Universität Stuttgart
IER Institut für Energiewirtschaft
und Rationelle Energieanwendung

Forschungsbericht

Recognising the Change in Land Use Patterns and its Impacts on Energy Demand and Emissions in Gauteng, South Africa

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Band 132

Recognising the Change in Land Use Patterns and its Impacts on Energy Demand and Emissions in Gauteng, South Africa

Von der Fakultät Energie-, Verfahrens- und Biotechnik der Universität Stuttgart zur Erlangung der Würde eines Doktor-Ingenieurs (Dr.-Ing.) genehmigte Abhandlung

Vorgelegt von

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geboren in Mumbai

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Tag der Einreichung:	05. Juli 2016
Tag der mündlichen Prüfung:	24. April 2017

Institut für Energiewirtschaft und Rationelle Energieanwendung

Der Universität Stuttgart

2017

ISSN 0938-1228

D 93 (Dissertation der Universität Stuttgart)

Acknowledgement

Firstly, I would like to express my sincere gratitude to my advisor Prof Dr Voß for his continuous support of my Ph.D., for all his patience, motivation and immense knowledge. I could not have imagined having a better advisor and mentor for my PhD study.

Besides my advisor, I would also like to thank my thesis committee: Prof Dr Hochschild and Prof Dr Resch, for their insightful comments and encouragement, as well as for the hard questions that helped me to widen my research from various perspectives.

My sincere thanks also go to Dr Ludger Eltrop, who provided me with an opportunity to join his team, for believing in my capabilities, as well as his support and guidance. Without his support, it would not have been possible to conduct this research.

I would like to thank my fellow colleagues at the SEE for making such a friendly atmosphere possible, where criticism is always constructive. I totally appreciate it and know that this is not to be taken for granted.

Last but not least, I would like to thank my family, especially my father, Late Mr Dattatraya Tukaram Marathe, my mother, Mrs Jayshree Dattatraya Marathe, and my sister, Ms Manisha Dattatraya Marathe. Their love and unconditional support provided me with energy and encouraged me to attain my studies.

Stuttgart, 24. April 2017

Sheetal Dattatraya Marathe

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List of Abbreviations

CS	Community Survey
CSIR	Council for Scientific and Industrial Research
DEAT	Department of Environmental Affairs and Tourism
GCRO	Gauteng City Region Observatory
GDARD	Gauteng Department of Agriculture and Rural Development
GSDF	Gauteng Spatial Development Framework
GSDP	Gauteng Spatial Development Perspective
GJ	Gigajoule
GWh/a	Gigawatt hours per annum
HH	Households
IDP	Integrated Development Plan
Kt	Kilo tonnes
MWh/a	Megawatt hours per annum
MJ	Megajoule
Mt	Mega tonnes
LU	Land use
NSDP	National Spatial Development Perspective
pa	Per annum
PJ	Petajoule
RSDF	Regional Spatial Development Frameworks
SDF	Spatial Development Framework
SEA	Strategic Environmental Assessment
Stats SA	Statistics South Africa
SWH	Solar water heater
TWh/a	Terawatt hours per annum
UNFPA	United Nations Population Fund
ZAR	South African Rand

Abstract

The economic powerhouse of South Africa, Gauteng, has seen rapid urban growth since its formation in the early nineties. Today, more than 90% of its population lives in urban areas. The sudden rapid urban growth over such a small period has resulted in dispersed spatial structure. The thesis aims at recognising the change in the land use pattern and its impacts on energy demand and emissions in Gauteng. Furthermore, based on a scenario analysis, recommendations were drawn with regard to future urban sprawl and emission mitigation measures. At the moment, there is no scientific research available which deals with the complex phenomenon of urban growth and its impact on energy and emissions in Gauteng.

In the thesis, the change in land use patterns between 1991 and 2009 in Gauteng was analysed which confirms that the region is affected by urban sprawl. Furthermore, based on two scenarios, the future urban developments in the region till 2040 were simulated using a cellular automata model. The scenario analysis concludes that the outward expansion of Gauteng must be restricted within the existing urban boundary to stop further sprawl.

In Gauteng, the residential sector is the third largest energy consumer and has the second largest share in greenhouse gas (GHG) emissions. Heavily coal-based electricity generation (around 93%), a high share of fossil fuels used by the households and use of inefficient energy technologies are the main reasons for high GHG emissions in the residential sector in Gauteng. Furthermore, the income disparity is also mirrored in the energy consumption patterns in Gauteng. Most of the poor households are struggling to gain access to electricity, whereas the rich communities are met with frequent power cuts. As the government tries to reduce the share of coal and other fossil fuels to achieve mitigation targets, reduction in energy consumption plays a major role in Gauteng. A comprehensive analysis, based on various income groups and dwelling types was carried out to understand the energy consumption patterns in the residential sector. The scenario analysis also reveals how the share of different energy carriers used by households and their share in the final energy consumption affect the GHG emissions.

The spatial distribution of the final energy demand in the residential sector helped in identifying energy intensive as well low energy demand areas in Gauteng. Energy intensive areas are located near the economically developed regions such as central business districts (CBD) in Johannesburg and Pretoria. The spatially explicit energy consumption could be a valuable tool for determining policies for implementing energy efficiency and renewable energy programs at the local level. Though the residential sector is not the highest energy consumer in Gauteng, the consumption and emissions in this sector can be easily influenced by the government by introducing various subsidies and incentives for renewable energy which would also help in minimising the high share of direct emissions by 2040.

In addition, a thorough potential analysis for energy generation from woody biomass, energy crops, photovoltaic (rooftop and open space), solar water heaters and wind energy was carried out at the municipal and the provincial level which exhibits various possibilities to implement the use of renewable energy in the region.

To sum up the thesis, the developed simulation model has been proven suitable to understand future urban patterns of a fast growing region like Gauteng. The simulated land use pattern would help in understanding what problems will occur in the future, as well as preparing the government to tackle these issues and develop new energy policies and strategies for Gauteng. Additionally, the spatial distribution of energy demand and renewable energy potential, which was assessed using a GIS-based model, helped in providing energy efficient and renewable energy-based solutions at the local level. It can be concluded that the constantly rising residential energy demand is not heavily influenced by the urban pattern and can only be reduced by increased use of efficient technologies and energy saving measures.

Kurzfassung

Die Region Gauteng ist das ökonomische Zentrum Südafrikas und seit ihrer Gründung Anfang der 1990er Jahre durch ein sehr hohes städtisches Wachstum gekennzeichnet. Heute leben mehr als 90% der Bevölkerung Gautengs in den urbanen Gebieten. Das schnelle Bevölkerungs- und Wirtschaftswachstum in kürzester Zeit hat die Ausbreitung städtischer Agglomerationen und Zersiedlung in der Region verursacht. Ziel der vorliegenden Dissertation ist es, die Landnutzungsänderungen und deren Auswirkung auf Energiebedarf und Treibhausgasemissionen (THG-Emissionen) in der Region Gauteng zu analysieren. Des Weiteren werden aufbauend auf Szenarioanalysen mögliche künftige Entwicklungen der städtischen Agglomerationen und Maßnahmen zur Emissionsminderung am Beispiel des Wohnsektors aufgezeigt. Derzeit liegen keine Forschungsergebnisse vor, die sich mit dem komplexen Phänomen des städtischen Wachstums in Gauteng und dessen Auswirkungen auf Energiebedarf und Emissionen beschäftigt haben.

In der vorliegenden Arbeit wurden die Landnutzungsveränderungen zwischen 1991 und 2009 und die Landnutzungsformen in der Region analysiert. Die Analyse bestätigt, dass die Region von einer Zersiedelung betroffen ist. Anhand von zwei Szenarien und durch Anwendung eines zellulären Automaten Modells, wurde die zukünftige Stadtentwicklung in der Region bis 2040 simuliert. Die Szenarioanalyse zeigt, dass um eine weitere Zersiedlung der Region zu vermeiden, das zukünftige Wachstum der Region sich innerhalb der bestehenden städtischen Grenzen vollziehen muss.

In der Region Gauteng ist der Wohnsektor der drittgrößte Energieverbraucher und nimmt den zweitgrößten Anteil der THG-Emissionen in Gauteng ein. Eine kohle-basierte Stromerzeugung (ca. 93%), ein hoher Anteil der fossilen Brennstoffe in den Haushalten und die Nutzung ineffizienter Energietechnologien sind die Hauptgründe für hohe THG-Emissionen des Wohnsektors in Gauteng. Darüber hinaus spiegeln die Energieverbrauchsmuster Einkommensdisparitäten wider. Die Mehrheit der armen Haushalte hat keinen Zugang zu Strom. Die reichen Haushalte sind dem gegenüber von häufigen Stromausfällen betroffen. Die Regierung versucht den Anteil der fossilen Brennstoffe zu minimieren und den Klimaschutz voranzutreiben. Damit verbunden spielt die Minderung des Energieverbrauchs eine bedeutende Rolle. Daher wurde eine umfassende Analyse, basierend auf verschiedenen Einkommensgruppen und Gebäudetypen durchgeführt, um die Energieverbrauchsmuster im Wohnsektor zu verstehen. Die Szenarioanalyse verdeutlicht auch, wie sich der Anteil der verschiedenen Energieträger und deren Anteile im Endenergiemix auf die THG-Emissionen auswirken.

Anhand einer GIS-basierten räumlichen Darstellung des Endenergiebedarfs im Wohnsektor wurden energieintensive Kommunen in Gauteng sowie solche mit niedrigem Energiebedarf identifiziert. Energieintensive Kommunen befinden sich in der Nähe der ökonomisch-entwickelten städtischen Bereiche wie Industriegebiete und Firmenviertel in Johannesburg und Pretoria. Die räumliche Darstellung des Energieverbrauchs kann ein wertvolles Instrument für Umsetzungsmaßnahmen für Energieeffizienz und erneuerbare Energien auf lokaler Ebene sein. Obwohl der Wohnsektor nicht der größte Energieverbraucher in Gauteng ist, kann die Regierung den Energieverbrauch in diesem Sektor gezielt durch die Einführung von Fördergeldern beeinflussen damit die höheren direkten Emissionen bis zum Jahr 2040 deutlich reduziert werden.

Zum Schluss wurde eine umfassende Potenzialanalyse für die Energiebereitstellung aus holzartiger Biomasse und Energiepflanzen, für Photovoltaik (Dach- und Freiflächen), solare Wasser-Heizung und Windenergie auf der kommunalen Ebene und der Ebene der Region Gauteng durchgeführt. In einem integrierten Ansatz werden die Potenziale der erneuerbaren Energien der räumlichen Energienachfrage gegenübergestellt und analysiert.

Zusammenfassend wurde im Rahmen der Dissertation ein Simulationsmodell entwickelt um künftige Agglomerationen und Zersiedelungen in der schnell wachsenden Region Gauteng zu identifizieren. Auf dieser Grundlage und anhand der simulierten Landnutzungsmuster können Regierung und Stadtplaner künftige räumliche Probleme auf lokaler Ebene und in der Region identifizieren, Vorbereitungen treffen, um künftige Probleme zu bewältigen, und eine neue Energiepolitik und Strategien für Gauteng entwickeln. Weiterhin wurde die räumliche Verteilung der Energienachfrage und des Potenzials erneuerbarer Energien mit Hilfe einer GIS-basierten Modells analysiert und die künftigen Anteile, die erneuerbare Energien einnehmen können, dargestellt. Es wurde auch festgestellt, dass die künftig wachsende Energienachfrage im Wohnsektor nicht nur durch Einflussnahme auf die städtische Siedlungsstruktur beeinflusst werden kann, sondern ausschließlich durch den Einsatz effizienter Technologien und Energiesparmaßnahmen.

1. Introduction

1.1. Problem statement

Rapid urban growth is a recent phenomenon: in 1900, only 15% of the world's population lived in cities, compared with more than half of the world's population in 2008 (UNFPA, 2009). With the global urban population growing at more than six percent per year, there will be a constant flow of people moving towards urbanised areas, especially in Asia and Africa. Urbanisation is linked with social, economic and environmental transformations. Along with resource efficiency and economic growth, cities are also prone to an increasing number of informal settlements.

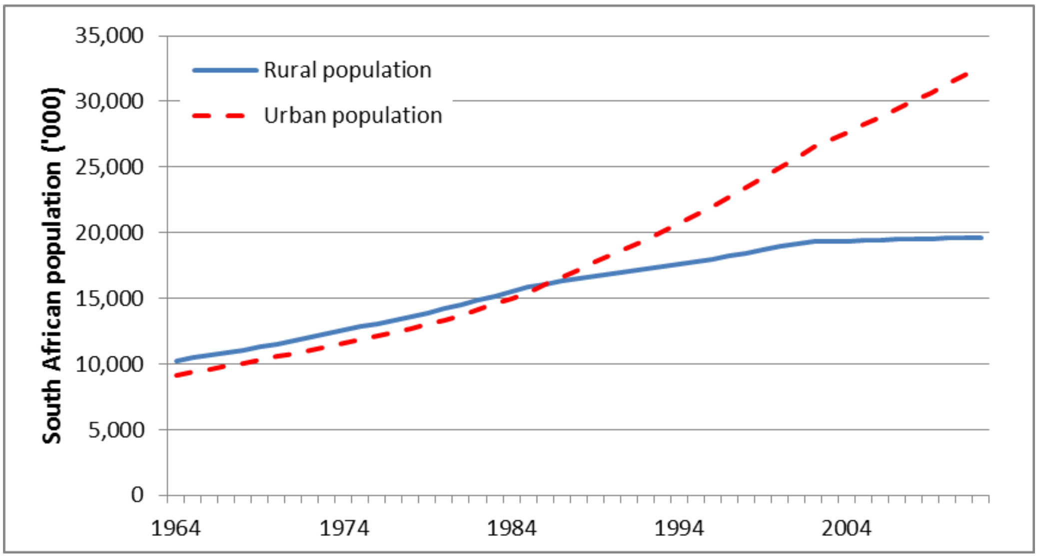

Figure 1: Urban and rural population in South Africa (1964 – 2012) (World Bank, 2013)

By 2030, around five billion people will be living in urban agglomerations in Asia and Africa (UNFPA, 2009). South Africa (or Gauteng) is no exception to this phenomenon (Figure 1). Like the rest of the world, more than half of Gauteng's population is living in urban areas (Stats SA, 2012). Gauteng is one of the nine provinces of South Africa. Though it is the smallest province in the country, this landlocked province is the economic hub of South Africa. It produces more than one-third of the national Gross Domestic Product (GDP) and inhabits more than one-fifth of the country's population (Stats SA, 2012).

With constantly growing population, urbanisation – or the increase in the urban share of the total population – is inevitable. The settlement preferences of incoming population result in various spatial patterns such as compact cities (growth around water or city/business centre), zonal development (development based upon various zones such as industry, residential, etc.), polycentric cities (growth around various small centres) and most recent urban sprawl[1] (outward development or continuous expansion of the city). Compact cities, zonal development and polycentric are considered to be ideal types of urban development, whereas urban sprawl is argued to be wasteful and inefficient urban growth due to a high urban footprint (Hasse, 2002).

In developed countries like the United States of America (USA) and Canada, many cities are affected by urban sprawl, although there is a growing awareness of this phenomenon, as can be seen through the number of studies conducted (Batty et al, 1999; Torrens and Alberti, 2000; Barnes et al, 2001; Hurd et al, 2001; Cheng and Masser, 2003). Developing countries like India, China and South Africa are recently facing the similar problem; indeed, many studies have also been conducted for the sprawling cities in Asia (Jothimani, 1997; Lata et al, 2001; Yeh and Li, 2001; Cheng and Masser, 2003; Sudhira et al, 2003). By contrast, while Africa has a handful of cities where sprawl has been evident in recent years, no studies have demonstrated this to date. This study will analyse the urban form/structure of Gauteng and find out if Gauteng is sprawling.

Besides traffic congestion and outward development, sprawling cities are best known for their wasteful use of land and resources due to consumption of a larger area by fewer people. Various studies have been conducted to ascertain the causes and consequences of urban sprawl (Harvey and Clark, 1965; Peiser, 1989; Song and Knaap, 2004; Bhatta et al, 2010), although very few have tried to understand the relationship between land use change and its impact on energy consumption, especially in the residential sector. Accordingly, one of the main aims of this study is to analyse and understand this relationship in detail.

With more than 12 million people living in Gauteng, it is the most populous province in South Africa (Stats SA, 2012). The residential sector in Gauteng is the third largest consumer (10%) of final energy. In the residential sector, income and standard of living affect the amount of energy consumed and the technologies used to fulfil the energy demand. Not only Gauteng but the whole of South Africa is afflicted with income inequality[2] which is reflected through consumption patterns.

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[1] Urban sprawl: Urban sprawl describes the expansion of human populations away from central urban areas into previously remote and rural areas, often resulting in communities reliant upon heavy automobile usage.

[2] The Gini-coefficient[2] – used as a measure of income inequality (on a scale from 0 to 1) – lies at 0.63, confirming the unequal distribution of wealth in South Africa (see Appendix O).

Additionally, the vast economic differences in various communities across Gauteng have led to multiple uses of fuels in households in Gauteng (Stats SA, 2008; Stats SA 2012). Especially households belonging to the poor and low-income groups tend to use more than one fuel to fulfil their energy needs compared to the mid- and high-income groups. Constantly growing population and high energy consumption in Gauteng have resulted in high energy-related carbon emissions. The direct emissions due to increased use of coal and paraffin in lower income groups are enormous. Accordingly, an increased share of clean and environmentally friendly fuels would help in reducing the emission levels in the residential sector. One of the main challenges in Gauteng is to reduce fossil fuel-based energy consumption and the resulting emissions. The government introduced subsidised efficient stoves (DME, 2004) and free basic electricity (FBE[3]) schemes to help the poor and low-income groups. The efficient stoves are comparatively expensive than the conventional non-efficient stoves. The introduction of more affordable and efficient appliances will play a major role towards achieving energy reduction goal.

The constantly rising energy demand in Gauteng is challenging the existing energy supply system with frequent power outages. Moreover, Gauteng's electricity generation is heavily coal-based (around 93%), resulting in high carbon emissions. Gauteng's energy mix has a negligible share of renewable energy (DLGH, 2010). Renewable energy solutions would help in tackling the energy issues in Gauteng and in achieving mitigation targets. The government in Gauteng has realised this problem and developed the 'Gauteng Integrated Energy Strategy' (GIES) which focuses on sustainable use of energy (DLGH, 2010). Unfortunately, there is a lack of information concerning the spatial distribution of energy demand on a spatial level and its relation to urban development.

A GIS-based spatial distribution of energy demand will not only reveal the high energy areas in Gauteng but also the degree of energy efficiency in various parts of the region. Furthermore, illustrating the energy demand on a spatial scale would expose the energy-poor areas and help towards finding better energy solutions for the poor. Moreover, at the provincial level, there have been no attempts to map the renewable energy potential for the region. An integrated approach including the spatial energy distribution and renewable

[3] The rationale of the Free Basic Electricity (FBE) Policy was to provide "electricity to all" through the provision of a 'limited' amount of free electricity to poor households. Subsequently, government decided on an amount of 50kWh per household per month, available only to those who have a legal connection. Some municipalities, e.g. Ekurhuleni provided 100kWh FBE to all households (Ferrial, 2010).

energy potential (e.g. solar or biomass) will help the government and urban planners in terms of locating suitable renewable energy solutions within the region.

The Gauteng 2034 development strategy (Ward and Schäffler, 2008) summarised energy security, energy poverty, carbon mitigation, environmental impacts and spatial development as the key energy issues in Gauteng, whereby the residential sector is most affected by these issues. This study tries to understand the mechanism, how these issues are inter-related and seeks to find better solutions to eliminate the same.

1.2. Aims and objective of the study

The main objective of this dissertation is to recognise the change in land use patterns and its impacts on energy demand and emissions in Gauteng, South Africa. Based on the aforementioned problem statement and the main objective, the study aims:

1. **To analyse and evaluate the spatial pattern and the land use changes in Gauteng**

   The dissertation intends to propose an innovative approach to understand and analyse the urban development in Gauteng through the recognition of spatial patterns, analysing the driving forces and impacts of urban development.

2. **To investigate the effect of land use change on energy demand and greenhouse gas emissions**

   The dissertation investigates how the changing land use pattern affects energy demand in the residential sector, including related GHG emissions.

3. **To illustrate spatial distribution of energy demand and renewable energy potential in Gauteng**

   With the help of GIS, the spatial distribution of the final energy demand and technical potential of various renewable energy carriers were illustrated. This will help in terms of finding suitable renewable energy solutions for the residential sector within the region's boundary.

4. **To simulate future spatial development in Gauteng under different scenarios**

   Based on two different scenarios, the future urban developments in Gauteng are simulated to exhibit the impact of various parameters on Gauteng's spatial development by 2040.

The findings of this study are expected to provide significant contributions in terms of understanding the spatial pattern of Gauteng, future energy demand and the related emissions, as well as suggesting solutions to reach mitigation targets.

1.3. Structure of the study and approach

This study includes cellular automata based simulation model, geostatistical methods as well as scenario analysis at the micro- and macro-geographical level. The thesis starts by giving background information on the political and legal framework in Gauteng and in South Africa (chapter 0). Furthermore, the geographic, demographic, and socio-economic parameters relevant to Gauteng are analysed in detail. Chapter 3 deals with land use change and spatial structure of Gauteng. In addition, the important definitions used in this study such as land use, land cover, land use/cover change and cellular automata, along with GIS and its various formats are described in this chapter.

Analysis of Gauteng's spatial pattern was a key parameter in the scenario development. Accordingly, it was envisaged to analyse the current spatial form of Gauteng. The trend in Gauteng's land use is explained in detail in chapter 4. The scenario analysis is undertaken at the macro- and micro-geographical level. Macro-geographical scenario analysis is conducted at the administrative (municipality) level and analyses economic, ecological, demographical and technical parameters, which are explained in detail in this chapter. At the micro-geographical level, a GIS and cellular automata-based model is used to visualise and analyse the spatial patterns in Gauteng, which is also described in chapter 4. The results of the simulation model (micro-geographical level) are illustrated at the end of chapter 4.

Chapter 5 deals with the spatial distribution of energy demand in the residential sector and the potential of renewable energy in Gauteng. The findings of this study are summarised among the conclusions in chapter 6. Furthermore, recommendations for policy implications and an outlook for future research are also presented at the end.

Table 1 shows the timelines used in the study, along with the objectives belonging to each timeline and the method or tool used to achieve the expected results. The historic data (1991-2001) is used to analyse the changes in land use pattern. A spatiotemporal simulation model based upon cellular automata and GIS was developed to predict the possible future developments under various framework conditions. These various framework conditions are described under scenario analysis (Chapter 4). The model was validated by comparing the simulated image for 2009 and the real image available for the same year. The model simulates future land use patterns (for two different scenarios) until 2040.

As seen in Table 1, GIS and cellular automata are the main tools used for this study. GIS is used to illustrate and analyse the land use patterns, whereas cellular automata is used to predict the land use patterns until 2040.

Table 1: Timelines used in the scenario analysis

Timeline	Objectives/Results	Method/Tool
Past (1991-2001)	Land use pattern analysis	Geographic Information System (GIS)
Present (2009)	Validation + Simulation	GIS + Statistical analysis
	Spatial allocation of energy balance + GHG emissions	Geo-statistics
Future (2009-2040)	Simulating urban development scenarios	Cellular automata
	Energy demand + GHG emission projections	Geo-statistics

The approach to reach the aims is illustrated in Figure 2. Various spatial (shapefiles, raster images, satellite images) and non-spatial (census survey data, energy-related data, etc.) data were analysed in this study. Besides the land use images, most of the available data were in non-spatial format. Hence, these data had to be converted into the spatial format to feed them into the model.

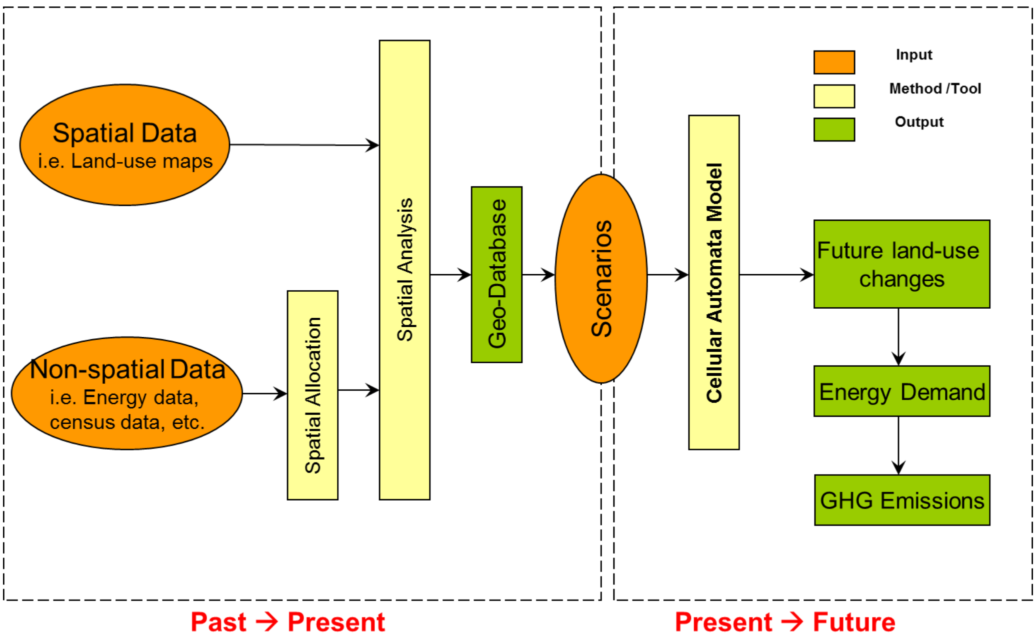

Figure 2: Approach for the land use simulation and the energy model

Together with spatial data and spatially allocated point data, a geodatabase for Gauteng was created, including demographic, socio-economic, environmental and energy-related data. The approach comprises two time periods, the first of which observes the period from past to the present, i.e. changes between 1991 and 2009. Figure 2 shows how various data from the past is combined together to form a geodatabase, a databank for the simulation model. The model scenarios are also based upon this databank. The second period observes the time period between the present and the future, i.e. 2009-2040. It comprises the cellular automata-based simulation model (micro-geographical level) and the macro-geographical model to predict the future land use patterns in Gauteng, energy demand in the residential sector and the resulting emissions, which are illustrated using GIS.

2. Background

This chapter reviews how Gauteng has developed in the recent past and describes various aspects, such as geographic, socio-economic and political aspects, which have influenced Gauteng. Finally, the energy consumption in the residential sector is described in detail.

2.1. Geographic structure

Gauteng is one of the nine provinces in South Africa – as depicted in Figure 3 - sharing its borders with the North-West province to the West, Limpopo to the north and Mpumalanga to the East. On the southern border is the Vaal River, which separates Gauteng from the Free State. It is the only landlocked province of South Africa without a foreign border (Figure 3; Gauteng, 2007a). Most of the province is located on the Highveld, high-altitude grassland (ca. 1,500 m above sea level). Between Johannesburg and Pretoria, there are low parallel ridges and undulating hills, some part of the Magaliesberg Mountains and the Witwatersrand. The north of the province is more sub-tropical due to its lower altitude and it is mostly dry savannah habitat.

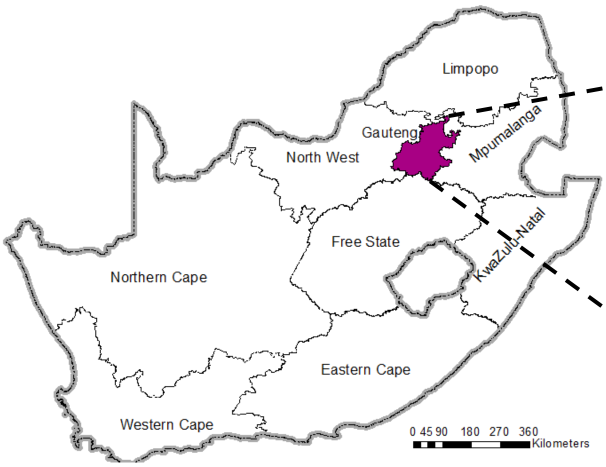

Figure 3: South Africa with provincial boundaries

Figure 4: Enlarged map of Gauteng, divided into metros & outer municipalities

Gauteng's climate is mostly influenced by its altitude. Although the province is at sub-tropical latitude, the climate is comparatively cooler, especially in Johannesburg; at 1,700 m above mean sea level (Pretoria lies at 1,330 m). Most precipitation occurs as brief afternoon thunderstorms. Winters are crisp and dry with frost occurring often in the southern areas. Snow is rare, although it has occurred on some occasions in the Johannesburg metropolitan area.

With 18,170 km² or 1.5% (Stats SA, 2006) of the total area, Gauteng is the smallest province, yet it supports more than 20% of the South African population, which makes it the most densely populated region in the country (Stats SA, 2012). According to the 2011 census, Gauteng is home to 12.3 million people. It comprises three metro municipalities – Johannesburg, Tshwane and Ekurhuleni – and other non-metro (outer) municipalities, such as Sedibeng or West Rand (Figure 4).

Johannesburg was found around a gold mine region in the late-1800s (Reid and Lane, 2004). Today, Johannesburg is the provincial capital of Gauteng and also the world's largest and only city not situated on a river, lake or coastline. It also accounts for one of the 50 largest agglomerations in the world (City population, 2010). Ekurhuleni is home to the international airport O. R. Tambo and is an important manufacturing centre in South Africa, famously known as 'the workshop of the country' (City Report, 2011). Tshwane is the northernmost and largest metropolitan municipality in Gauteng, which includes one of South Africa's three capitals,[4] Pretoria. Besides being an important political centre of Gauteng, Pretoria has been the traditional centre of government and commerce and it houses many corporate offices, small businesses, shops in Pretoria's central business district (CBD).

2.2. Demographic structure and development

Being an economic powerhouse of South Africa, Gauteng attracts migrants from within South Africa and across the African continent. Gauteng's population has shown constant growth since its formation. Figure 5 shows the population growth between 1996 and 2011, along with the number of households and household size. Between 1996 and 2001, the population in Gauteng grew at a rate of 28% and subsequently by about 31% between 2001 and 2011. The urban area grew by 25% between 1991 and 2001, although this rate suddenly declined between 2001 and 2009. In terms of urban area, only a 7% increase took place during this period (Marathe, 2014). The household size decreased from 3.62 persons per household in 1996 to only 3 persons in 2011. One of the reasons for this could be the shift from poor/low-income groups to mid income groups, whereby the size of households tends to reduce as they become more affluent.

[4] South Africa has three capitals: **Pretoria** serves as the executive (administrative) and de facto national capital, **Cape Town** as the legislative capital and **Bloemfontein** as the judicial capital.

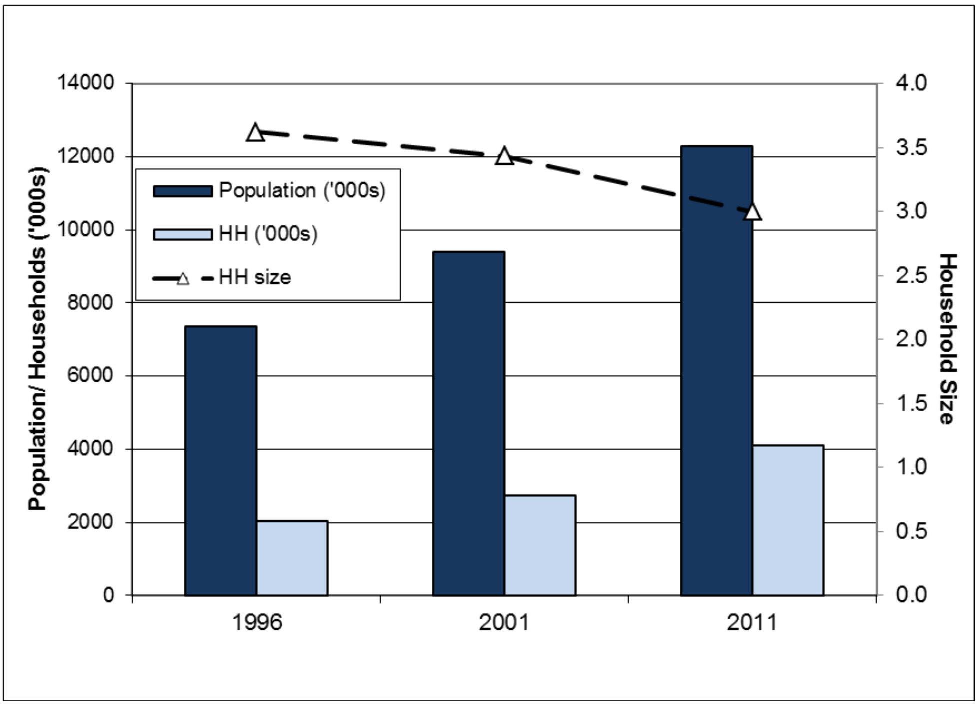

Figure 5: Population growth and the average household size in Gauteng (1996 – 2011) (Stats SA, 2012 and own calculations)

Like South Africa, Gauteng hosts a highly diversified population. Due to the strong fertility rate, HIV deaths, in-migration and out-migration of working adults, Gauteng's population is relatively young. 28% of the population is under 15 years of age and only 4% of the population is over 64 (Landau and Gindrey, 2008). This means 68% of Gauteng's population can be classified as a productive population (population of working age, i.e. 15-64). Moreover, the dependency ratio (people who are below 15 years old and more than 64, divided by the 15-64-year-old population) is only 39% in Gauteng, compared to 62% in the other provinces (Stats SA, 2012). Gauteng's population comprises various ethnicities, as illustrated in Table 2. Almost 78% of the population is black, followed by Indians/Asians with almost a 16% share of the population. Whites and coloured are in the minority in the province.

Table 2: Ethnic composition in Gauteng, 2011 (Stats SA, 2012)

Ethnicity	Share of total population
Black	77.9%
Indian/Asian	15.7%
White	3.5%
Coloured	2.9%

The population density per square km is illustrated in Figure 6 and Figure 7 for 1996 and 2011, respectively. The diverse population is spread quite unevenly in Gauteng, whereby higher population densities are observed in the metro regions of Johannesburg and Pretoria and along the main roads, whereas lower population densities are observed in the outer municipalities. The growth in population density between Johannesburg and Pretoria is also quite evident from these two figures. The darkest parts (purple and blue) of the figure depict the highest population density in the region, which is observed in informal settlements like Soweto and Alexandra.

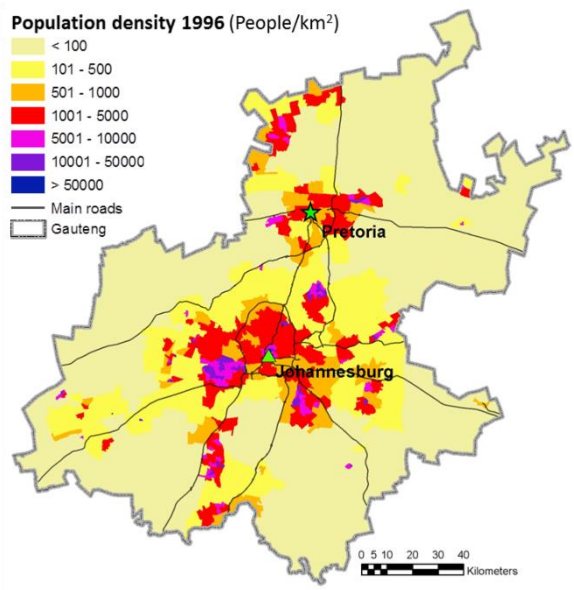

Figure 6: Population density in Gauteng at the ward level, 1996 (Stats, SA 1997 and own calculations)

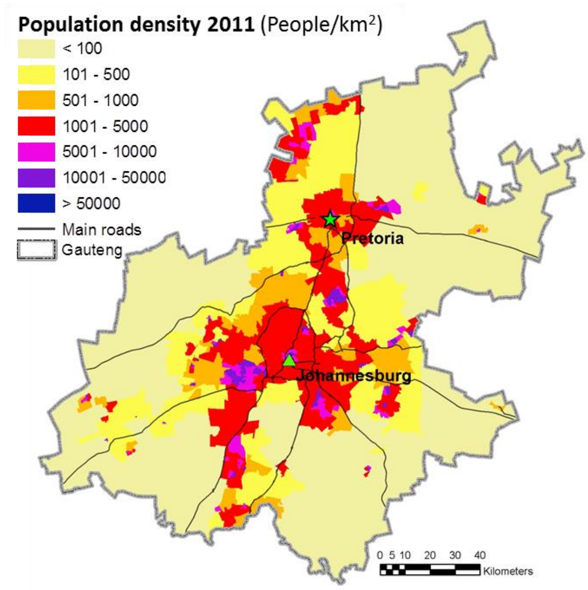

Figure 7: Population density in Gauteng at the ward level, 2011 (Stats, SA 2012 and own calculations)

2.3. Political and legal framework of the spatial development

South Africa's planning system reflects British planning practice from the time when it was a British colony. Racial discrimination existed in most of the planning framework during the Apartheid government which lasted until 1994 (Verna, 2009). During this period, an emphasis was placed upon racial segregation and unequal development, which has resulted in a strangely distorted, fragmented, unequal and inefficient spatial pattern (South Africa, 2001). As a result, the post-Apartheid spatial planning faced various problems, such as overcrowded homelands[5], a lack of public transportation, huge inequality between racial groups and the establishment of residential areas far away from economic, educational and cultural centres.

After 1994, as Apartheid came to an end, various laws, ordinances, etc. related to spatial issues were approved to address minority interests. These laws and policies sometimes led

[5] A homeland is the concept of the place with which an ethnic group holds a long history and a deep cultural association.

to confusion as disparate land use management systems existed in different former ‘race zones’. As a result, a disjuncture between inherited schemes and newly drawn up plans (MALA, 2001) was created. There has been no clear government position on the desirability of urbanisation, nor have government policies been based upon clear spatial assumptions or arguments (Pillay et al, 2006). There has been an attempt to address these problems through the white paper on ‘Spatial Planning and Land Use Management’ (MALA, 2001) and the recent ‘Land Use Management Bill’ (2008).

The current political framework of the spatial development framework in South Africa is divided into three administrative levels, as shown in Figure 8.

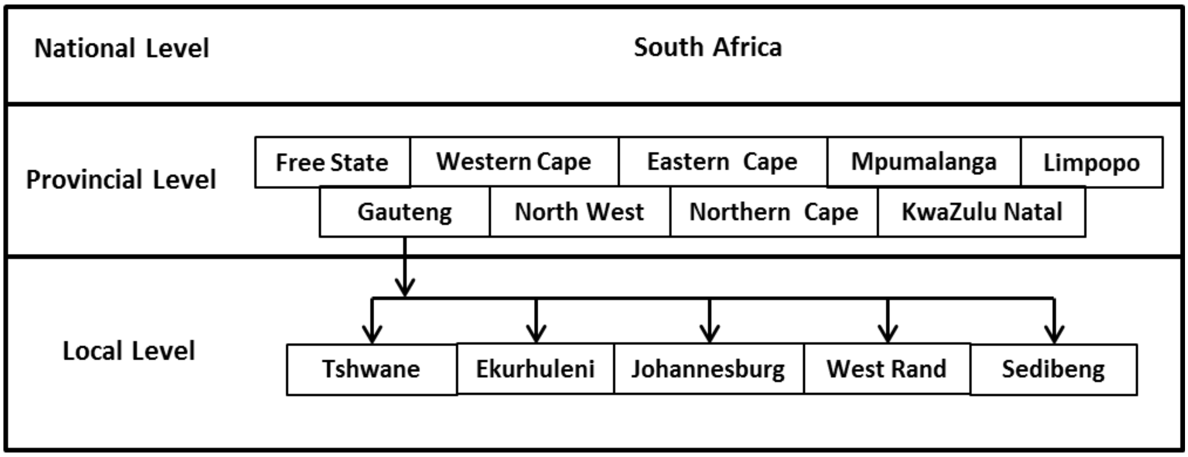

Figure 8: Administrative structure of the spatial development framework in South Africa (own diagram)

The South African spatial development framework is guided by various regulations and guidelines at the national, provincial and local government level, although it effectively operates at the local government level (Verna 2009). The ‘National Legislation’ and the provincial ‘Planning and Development Act’ both act as the important guidelines for the provincial development framework, as seen in Figure 9. Only the provincial (for the Gauteng province) and the local level (with Johannesburg as an example) frameworks are explained below.

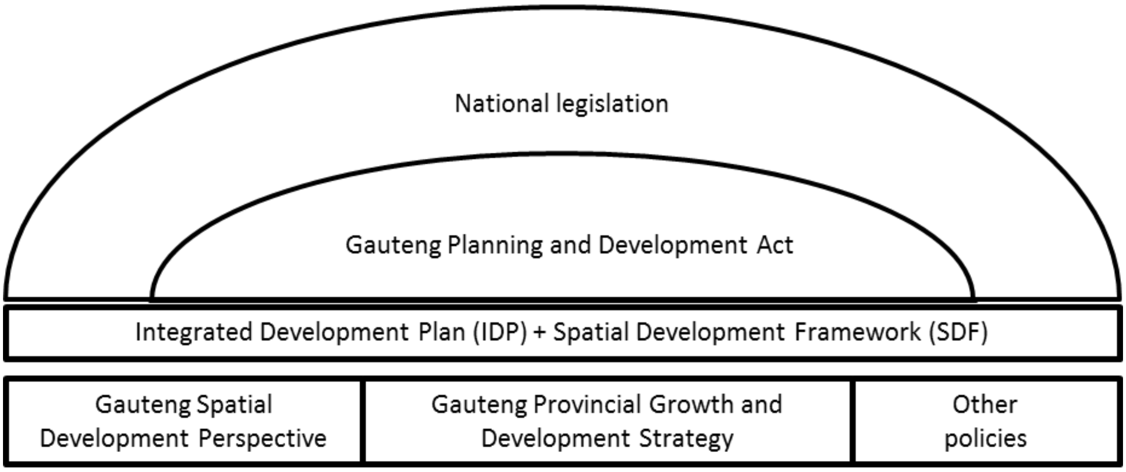

Figure 9: Spatial planning at the provincial level (Gauteng) in South Africa (own diagram)

Spatial framework at the provincial level

The provincial level in South Africa is explained using the example of Gauteng. As seen in Figure 9, the national legislation forms an umbrella over all provincial legislation and policies, whereby the provincial legislation and policies have to be aligned with the national legislation.

The ‘Spatial Development Framework’ (SDF) or the ‘Gauteng Spatial Development Framework’ (GSDF) for Gauteng province represent Gauteng’s most important spatial plan, included in Gauteng’s Integrated Development Plan (IDP). The GSDF is the uppermost level of spatial development planning and provides a spatial structure for Gauteng, which:

- accommodates growth and sustainability within the province;
- specifies a clear set of spatial objectives for its various municipalities, and
- proposes a set of plans these municipalities have to prepare in their pursuit of these objectives.

Along with the spatial issues of land management, the GSDF also focuses on integrated issues like energy and climate. Reducing car-dependency, encouraging public transport, reducing the usage of fossil fuel and promoting sustainable environment are elaborated in the GSDF. Important drivers that affect spatial development such as water, energy, pollution and environmental degradation are also encompassed in the GSDF.

It promotes sustainable and compact urban structure with open spaces, mixed-use development, efficient energy consumption and the protection of the natural environment. Furthermore, it advises the usage of ecological principles within the spatial development to bring the natural environment and the urban system into an integrated relationship, which would enable the communities to minimise their ecological footprint.

Moreover, the mandatory 'Strategic Environmental Assessment' (SEA) delivers an important opportunity to ensure that environmental concerns are considered and integrated into spatial planning. Although the GSDF provides a lot of information on climate and environmentally relevant topics, due to its broader scale it does not go into detail; rather, it builds a frame for further planning, which is also relevant for the local level.

The Department of Environmental Affairs and Tourism (DEAT) has acknowledged that a gap exists between planning, environmental management and sustainable development (Plessis et al, 2003; Harris and Krueger, 2005; Todes, 2005; Todes et al, 2009). As a result, a national framework document has been published, entitled "Strengthening Sustainability in the Integrated Development Planning Process". It appeals to planners to use scarce resources and limited capacity wisely, as well as re-orientating approaches and management tools to achieve a greater level of equity, service provision and sustainability in the country. It serves as a discussion platform that provides basic information and approaches. It does not provide any specific principles or solution processes and it mentions that detailed sustainability guidelines still have to be developed.

The **Gauteng Spatial Development Perspective (GSDP)** can be compared to the National Spatial Development Perspective (NSDP). Supporting economic growth in the province, improving livelihoods of the people, better mobility and accessibility are the ultimate goals of the GSDP (Gauteng, 2007b). GSDP has declared "ensuring sustainability" as a main challenge for the province. It postulates general sustainability approaches but does not provide detailed information about environmental contents such as population density, energy efficiencies, urban sprawl, etc. For detailed information on such topics, it refers to the provincial State of Environment Report. Furthermore, it serves as an input into the GSDF.

Local level planning

The local level planning framework functions at the municipality/metro level. Gauteng comprises three metros and two municipalities. The local level is described using the example of Johannesburg. The municipal regulations, by-laws, plans and frameworks have to be aligned with propounding national and provincial legislation. Figure 10 shows the different levels of local spatial planning:

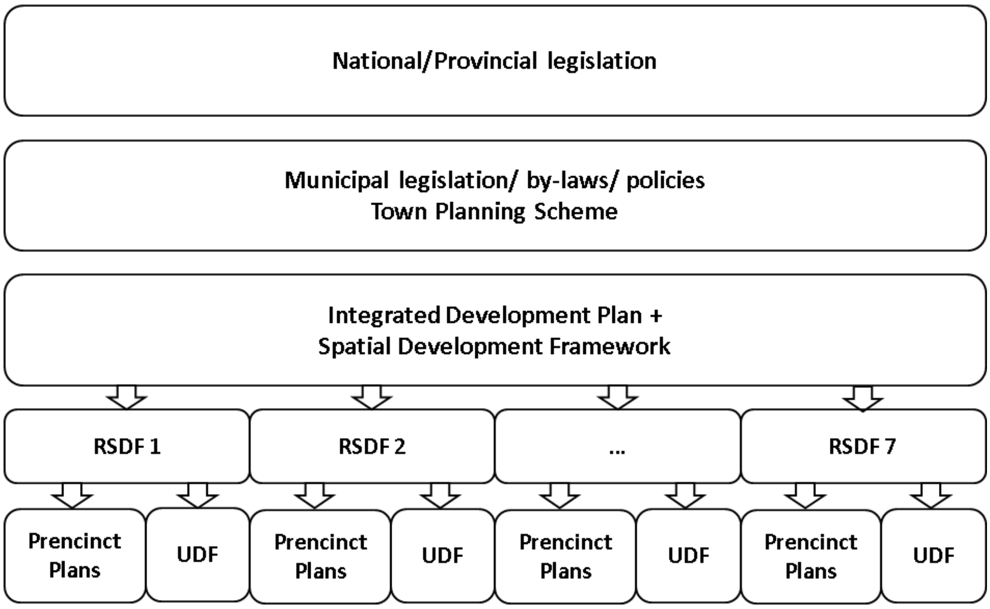

Figure 10: Spatial planning at the local level in South Africa (Adapted from Huck et al, 2011)
(RSDF: Regional Spatial Development Framework, UDF: Urban Development framework)

The Johannesburg **Town Planning Scheme 2010** (Draft) was compiled with the purpose of facilitating the comprehensive management of all property through the implementation of general guidelines. Possibilities for determining the type and degree of building and land use are provided. Additionally, developers are also encouraged to consider alternative forms of energy, renewable sources of energy and a building design paradigm that embraces energy efficiency.

The **Johannesburg Spatial Development Framework (SDF)** is an obligatory component of the integrated development plan (IDP), which helps to integrate the spatial perspective into the developing process of the municipality. It includes a capital investment programme – linked to the local government’s budget – to provide guidance for private investors as well as public infrastructure development (Nel, 2009). Besides, it is also supposed to show favourable land use patterns, directions of growth, urban edges, spatial development areas and conservation areas (Jones et al, 2005). Various SDF strategies focus on densification, infill[6] and brownfield [7]development, the implementation of an urban development boundary as well as nodal and corridor development, combined with public passenger

[6] Infill development means using land within a built-up area for further construction.
[7] Brownfield development uses land previously used for industrial or commercial purposes for property development.

transport efforts to achieve climate change mitigation. “Sustainability” and “efficiency” are two of the SDF principles. Moreover, SDF strategies include the support of environmental management, an efficient transport system, strong viable nodes and corridor development, densification of strategic locations, the management of urban growth and the facilitation of sustainable housing environments.

A detailed outlook of the SDF objectives and strategies is found in the **Regional Spatial Development Frameworks (RSDF)**, which presents a brief overview of the region’s current state and its main challenges. Regional characteristics such as wetlands and natural reserves, conservation areas and threats to the natural habitat/environment are described in detail. Additionally, environmental problems such as the poor environmental awareness in the public, the threat to existing water resources from pollutants and informal settlements’ dumping issues are dealt with in the RSDF.

The city of Johannesburg is divided into seven administrative regions. The RSDFs of these regions recognise the environmental issues in different sub-areas, outlining the key structuring elements and proposing projects to overcome such issues. The identification of nodal development areas and areas for densification and infill opportunities are a few of these examples. A few of these RSDFs propose densification together with the provision of housing solutions for low and mid-income households, in so-called mixed-use development. Moreover, issues like urban sprawl are also mentioned in a few of them. To overcome such issues, residential development is expected to have the ultimate goal of achieving a compact city form. Although some have defined various guidelines for an efficient environmental management[8], sadly the expressions “climate change”, “energy efficiency”, “mitigation”, “global warming”, “heat island effect”, etc. are still missing from the RSDFs.

“**Sub-Region Precinct Plans**” are prepared for existing sub-regions below each administrative region. In Johannesburg, most precinct plans have been developed at the precinct (zonal) level, which is comparable to sub-regions in the RSDFs. Moreover, a few important nodes and central business districts (CBD) have developed the Urban

[8] Some examples of these guidelines are: “Buffer zones should be applied around reserves and conversation areas”; “Where wetlands/rivers/drainage lines occur on sites, a detailed wetland delineation indicating all zones of the wetland must be submitted together with the project proposal to the relevant authorities”; “Protect all rivers and drainage lines. No development must be allowed within the 1:100 year flood line or 32m from the centre of the stream whichever is the greatest”; “All development proposals must include ecological assessments in order to identify sensitive features occurring on sites”; “The area should be reserved for eco-focused type of developments that incorporate and protect the sensitive environmental features. The area is thus earmarked for residential development where the primary focus is the conservation of the natural resource (eco-village)”; “Open space must be provided in developments.

Development Frameworks (UDF) for their respective zones or districts. These plans incorporate the ideas and development goals from the RSDFs. They partially demonstrate environment- and climate change-related objectives and guidelines. The **Northern Development Framework** (which comprises a further nine development frameworks at the precinct level) recognises that South Africa's current development path is not sustainable. This has resulted in the recognition of important sub-regional development objectives such as "create mix-use environment", "efficient urban form", "increase density and compactness" and "protection of open space". A new development boundary is suggested with more space for new urban development while also protecting endangered environmental areas and high potential agricultural land. Furthermore, each sub-region identifies ideal areas for densification.

The **Ikwezi Precinct Plan** concentrates on the Ikwezi railway station, using a SWOT (strength, weaknesses, opportunities, threats) analysis for planning. The long-term vision is "to develop an integrated and sustainable transportation node that promotes pedestrians, vehicle-friendly movement and economic growth of the region". Another example is the **Linbro Park Development Framework,** which incorporates the principles from the NSDF as well as the "Breaking New Ground Policy". This includes compact city development, promoting pedestrian movement, energy efficient settlements and design guidelines (Johannesburg, 2010).

Overall, Precinct Plans show stronger linkages to prominent environmental issues in the region. At times, there are indirect connections to climate change issues such as pedestrian movement, public transport, infill development, etc. However, climate change mitigation and adaptation and important issues like energy efficiency are usually not mentioned directly. Unfortunately, climate change and/or energy do not seem to play a crucial role in any development framework, neither while planning the new settlements nor within the rescheduling projects.

Incidentally, a national framework document (Guidelines for the Formulation of Spatial Development Frameworks) was published to support the municipalities with the preparation of the SDFs. This framework document describes both the contents and the procedure of compiling an SDF in detail and provides linkages (directly and indirectly) to achieve climate change mitigation and adaptation. Furthermore, some climate- and energy-relevant aspects such as mixed-use development, nodal development, corridors, infill development and densification, environmentally sustainable development, etc. are defined in detail. In addition, the guidelines refer to a range of sectoral plans that are critical for spatial mitigation or adaptation strategies and implicate targets or measures that have to be considered[9] (South Africa, 2010).

Nevertheless, it should not be forgotten that the important issues like climate change mitigation and adaptation or energy efficiency do not feature prominently in national policy development and the allocation of research funding. Thus, it is unsurprising that climate change does not play a major role in planning regulation and implementation mechanisms in South Africa and in Gauteng. For example, the building regulation does not promote energy or water efficiency, and in many cases, local by-laws prohibit urban densification (Plessis et al, 2003). A lack of sufficient capacity (both human and financial) for modelling and predicting the future climate – as well as for actually implementing mitigation and adaptation initiatives – is one of the greatest obstacles in the implementation process (Plessis et al, 2003).

2.4. Socio-economic aspects

As the economic powerhouse of South Africa, Gauteng contributes substantially to the financial, manufacturing, technology, telecommunications and transport sectors. The province is responsible for one-third of the country's gross domestic product (GDP). Moreover, Gauteng generates about 10% of the total GDP of Sub-Saharan Africa and about 7% of total African GDP.

Being the major contributor to South African GDP, Gauteng's economy is the backbone of the South African economy. The Gauteng Provincial Government's (GPG) policy framework is partially responsible for Gauteng's strong economy (Gauteng, 2008). With the national

[9] The most important sectoral plans are: **Strategic Environment Assessment (SEA)**: As a component of the SDF the SEA might have some sustainable objectives, criteria and indicators to be incorporated into the SDF. **Environmental Management Framework**: Identifies activities affecting natural resources and indicates how to manage these impacts. It thus serves as baseline information for SDFs. **Integrated Environmental Management Plan (IEMP)**: As a collection of various environmental management tools it provides a summary of possible activities for municipalities. **Integrated Transport Plan (ITP)**: Presents visions of transport systems and a description of the current traffic system and transportation needs. **Disaster Management Plan (DMP)** (local municipalities) **and Disaster Management Framework (DMF)** (metro municipalities): Aim at preventing, mitigating and reacting to possible future disasters. Identify potential disasters and areas, communities and households of risk, develop measures to reduce their vulnerability, provide prevention and mitigation strategies and prepare contingency plans and emergency procedures in case of disaster. For the SDF DMPs / DMFs provide crucial information on no-go areas for development or for restricted development (only special types or forms of development). Furthermore, they provide information on infrastructure requirements for large scale evacuations.

policy decisions influencing provincial directives, the national and provincial economies in South Africa are closely intertwined.

Economic performance: Gauteng and South Africa

In 2011, Gauteng was the province with the largest share of contribution to South Africa's GDP at 35.6 % (Economic Outlook, 2012). Figure 11 compares Gauteng's real economic growth[10] rates to that of South Africa as a whole from 2000 and 2015. The economic growth for South Africa and Gauteng appear to be quite similar, albeit with the exception of 2001, as the Gauteng region had slightly superior growth during this year. The worldwide economic crisis (recession) – which also hit South Africa – in 2009 can be seen visibly through the negative economic growth in that year, for both South Africa and Gauteng. Nonetheless, the economic rate at both levels has been rising thereafter. Although Gauteng's economic growth is forecasted to grow up to 4.6% in 2015, this will not suffice to significantly reduce the high unemployment in the province (Gauteng, 2008; Economic Outlook, 2012).

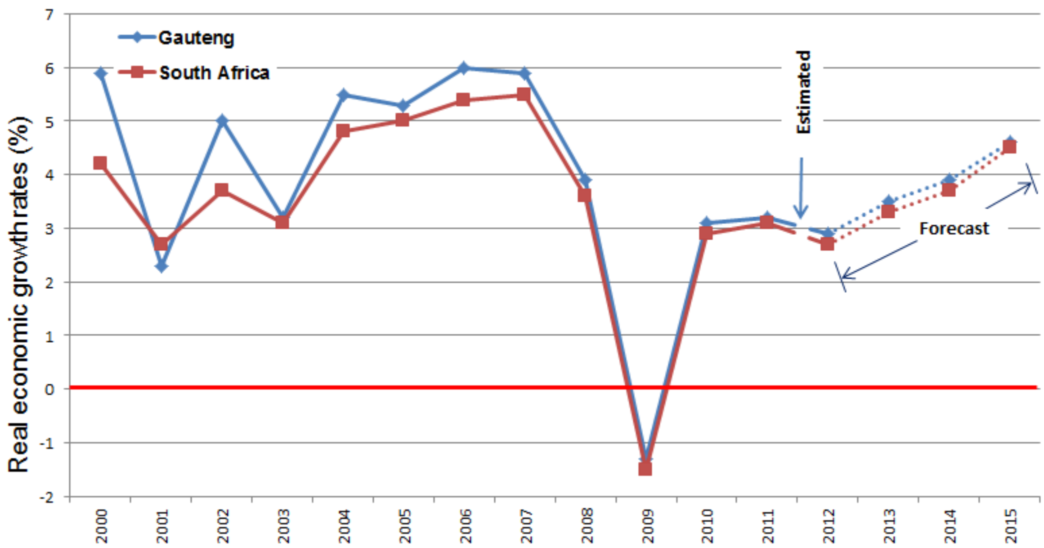

Figure 11: Real economic growth rates for Gauteng and South Africa (2000-2015) (own calculations based upon Gauteng, 2008 and Economic Outlook, 2012)

Spatial distribution of Gauteng's GDP

In 2011, the total GDP by region of Gauteng was ZAR[11]674.9 billion, with a growth rate of 3.2 %. A detailed look at Gauteng's economy shows that the economic activities are spread

[10] Real economic growth: A measure of economic growth from one period to another expressed as a percentage and adjusted for inflation (i.e. expressed in real as opposed to nominal terms). The real economic growth rate is a measure of the rate of change that a nation's gross domestic product (GDP) experiences from one year to another.

[11] ZAR: South African Rand is South African currency.

quite unevenly throughout the region. The three metropolitan municipalities in the province – Johannesburg, Tshwane and Ekurhuleni – contribute the major share of Gauteng's GDP. With the largest economy in the province, Johannesburg contributed ZAR313 billion in 2011 (almost half of the province's GDP) and is growing at 4 %. The major contribution in Johannesburg comes from banks, financial institutions (22%) and manufacturing (20%) (Stats SA, 2012). By contrast, Tshwane is known for being the fastest growing economy in the province, with an economic growth rate of 4.4%. It contributed ZAR184 billion to the total GDP in 2011. As the 'workshop' of the country, Ekurhuleni had a GDP of ZAR128 billion in 2011, with a growth of 3 %. Sedibeng and West Rand contributed 3.7 % and 3.5 % of GDP in 2011, respectively, or merely ZAR49.9 billion together. The GDP revenues from different municipalities are also clearly reflected in the job opportunities available in each district, which is illustrated in the following section.

Employment/Job opportunities

The spatial distribution of jobs is an important issue, given the social, environmental and economic impacts involved (Lang and LeFurgy, 2003). Kain argues that the development of job opportunities away from residential areas is harmful to the economically backwards social groups as daily travel becomes too expensive (Kain, 1992). Scattered jobs cause dispersed patterns in the residential sector, which subsequently results in an increase in land consumption per inhabitant (urban footprint). Another drawback is the dependency on private vehicles, as the scattered city structure makes it difficult to offer competitive public transport, which subsequently leads to higher CO_2 emissions (Newman and Kenworthy, 1989; Kahn, 2000; Camagni et al, 2002; Muniz and Galindo, 2005). Gauteng's scattered spatial job allocation is a consequence of dispersed development in the region. The development of the three metros during different time periods resulted in various industrial hubs in the region. Figure 12 and Figure 13 show job distribution over the region. Figure 12 shows the distribution of jobs (jobs/km^2) based on the data from census surveys and Figure 13 shows the 3-D representation of the jobs in Gauteng on the north-south axis. High employment opportunities concentrated around the Central Business District (CBD) areas in Johannesburg, Ekurhuleni, and Pretoria and around Orange Farm (located south of Johannesburg) are visible through the tall columns in Figure 13.

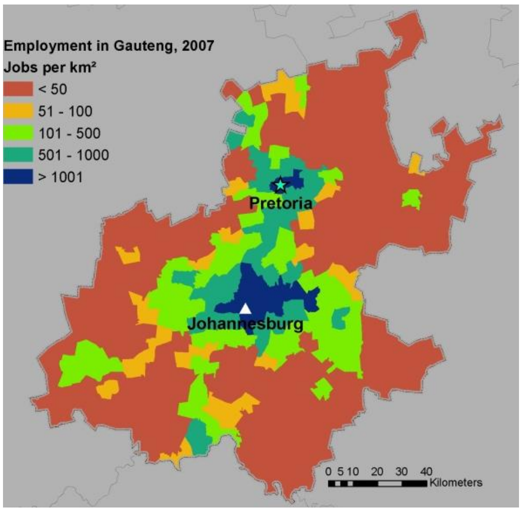

Figure 12: Spatial distribution of jobs in Gauteng (Stats SA, 2012)

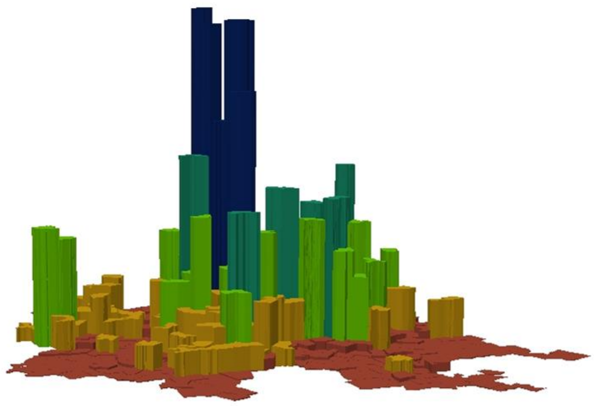

Figure 13: 3-D representation of Job distribution in Gauteng on the north-south axis

Migration

Migration not only involves a flow of people moving from one place to another; rather, it is often perceived as a cause of problems such as land and environmental degradation, health problems, political or social instability, declining law and order, a burden on infrastructure, etc. Migration affects population patterns and characteristics, social and cultural patterns and processes, economies and physical environments. As people move, their cultural traits and ideas diffuse along with them, creating and modifying cultural landscapes. Natural catastrophes, economic exploitation, political or civil tensions, violence and better opportunities are some of the major reasons why people migrate (De Haan, 2000 found in Kok and Collinson, 2006).

South Africa's political history and the mining roots of Gauteng's economic development have resulted in the province's heavy reliance on immigration to provide labour (Oosthuizen and Naidoo, 2004). Since the discovery of mineral wealth in the province, immigration has played an important role in the development of Gauteng. According to the 2011 census, only 54% of the population in Gauteng was born in Gauteng, while 9.25% were born outside South Africa (Stats SA, 2012). The ethnic composition of the incoming migrants is as follows: 81% of the migrants in Gauteng belong to black ethnicities, followed by Indian/Asians with 13%, 3% coloured and only 2 % whites.

Gauteng receives a major influx of migrants coming to South Africa. As seen in Figure 14, more than 70% of the total migrants end up in Gauteng. Most of these migrants tend to settle in one of the three metros of Ekurhuleni, Johannesburg or Tshwane due to better job prospects compared to Sedibeng and West Rand, which is visible through the high share of migrants in metros as seen in Figure 15.

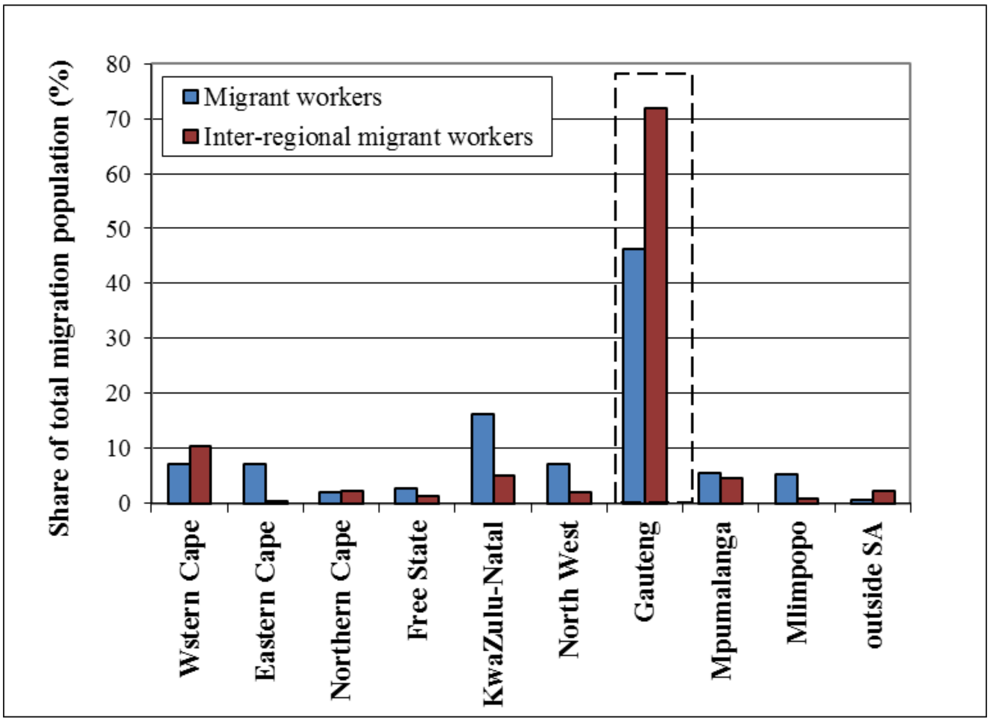

Figure 14: Share of total and inter-regional migration per province in South Africa, Stats SA 2002 (adapted from Oosthuizen and Naidoo, 2004)

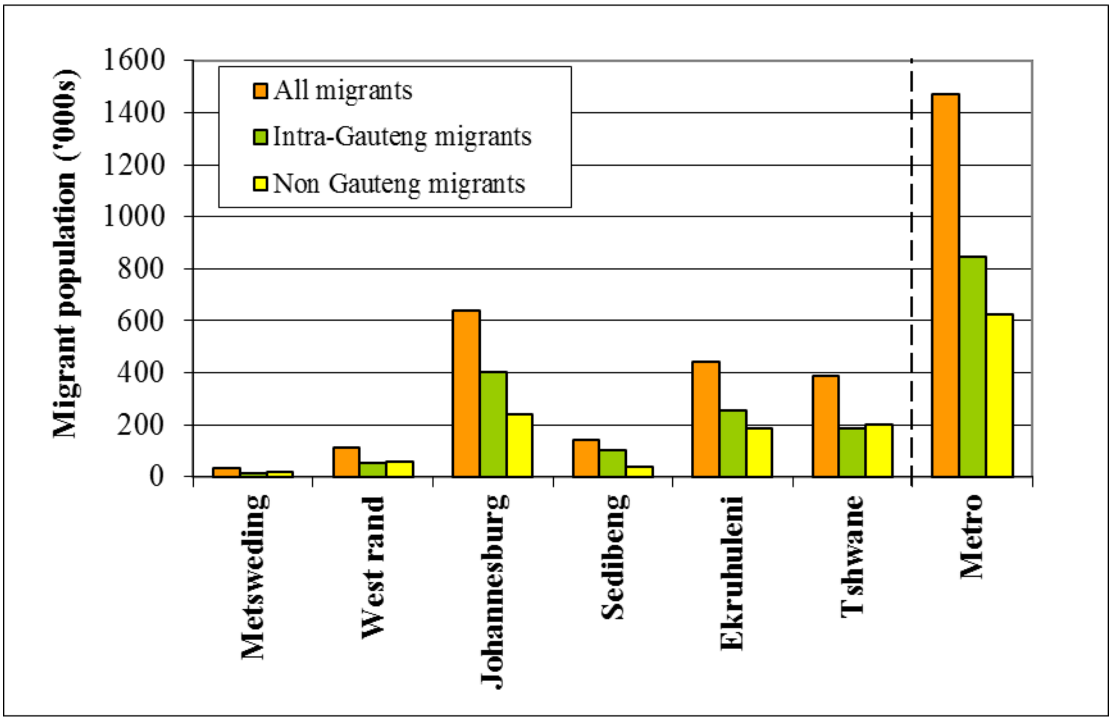

Figure 15: Total, inter-Gauteng and non-Gauteng migration within Gauteng, Stats SA 2002 (Adapted from Oosthuizen and Naidoo, 2004)

Apartheid: The racial segregation and its effects

Apartheid is an Afrikaans[12] word that means apartness or a state of being apart. The term refers to the legal racial segregation enforced by the 'National Party' government between 1948 and 1994. Although it had begun in colonial times, the official policy became effective after the elections in 1948. The population was divided into four main racial groups: black, white, coloured and Indians. The residential areas were also segregated, whereby non-white people had to carry identification proof – then called a 'pass book' – to enter the white areas.

The non-white races were deprived of better education, medical care and other public services. The government also practised 'forced removals' during the 1950s-1980s. It was a resettlement policy to force people (mostly non-white) and move them to their designated group areas. The most (in-) famous forced removal occurred in the 1950s in Johannesburg, when more than 60,000 people were moved to a new township, Soweto (South-Western Township), which is currently one of the largest informal settlements in Gauteng.

Apartheid legislation in South Africa involved a series of various acts and laws (started in 1949) that helped the Apartheid government to enforce the segregation of different races and cement the power and dominance by the whites over the other races. This legislation not only gave rise to a new social inequality, but it was rather the conclusion of a long historical development of racial segregation.

Besides socio-economic inequality, the impacts of Apartheid are visible through the spatial distribution of various ethnicities in and around Gauteng. Informal settlements such as Alexandra and Soweto are living examples of the remains of Apartheid. These communities lack basic necessities such as water supply and toilets, as well as proper public transportation, which makes it very expensive for people from poor and low-income groups to travel to their work on a daily basis.

Apartheid affected Gauteng's spatial development in more ways than simply by giving rise to informal settlements. As the poor were forced to live in informal settlements, the rich started putting fences around their property, creating 'gated communities', which can now be seen everywhere, including throughout South Africa. After the collapse of Apartheid, due

[12] Afrikaans is an offshoot of Dutch language developed in South Africa which gradually became a separate language

to crime and safety, gated communities became an integral part of South Africa's spatial development.

Although these gated communities are close knit, they lack in terms of providing a greater sense of community. These communities also prevent the co-existence of people from different income groups (mixed-use development). Sometimes, due to the 'closing off' of public roads (which run through these communities), they create inconvenience to the others living outside these areas. These aspects should be carefully incorporated in the future policy developments and are also included in the scenario analysis.

2.5. Energy consumption in Gauteng

Energy consumption plays an important role in any country's economy (Conners, 1998; Dzioubinski and Chipman, 1999). This section analyses current energy consumption trends (2007) in the residential sector in Gauteng. The focus of this study lies on household energy consumption, i.e. energy used for cooking, lighting, space heating and water heating. Energy consumption resulting from transport and manufacturing sector are not part of this study.

2.5.1. Current energy situation in Gauteng

Gauteng's primary energy source is mainly coal-based (93% of electricity generation). The energy planning and policy development in South Africa were driven by industry supply. Since the end of Apartheid in 1994, there have been some efforts to develop a more sustainable approach to coping with this situation (Wand and Schäffler, 2008). Gauteng hosts various industries and business centres, which makes energy an integral part of all economic and social activities in the province. In recent years, constantly increasing energy demand has led to frequent power outages in Gauteng. With 12.3 million inhabitants (Stats SA, 2012), the energy demand in Gauteng is constantly rising. By 2040, Gauteng will inhabit around 19 million residents, which means that the energy situation in Gauteng will worsen if appropriate measures are not taken in the near future. Given that most of the data on energy consumption and supply were available for 2007, it is the base year for this study.

Furthermore, 'energy poverty[13]' is a huge problem in Gauteng and needs to be eradicated to alleviate poverty. The South African Minister of Energy stated: "The use of energy is highly

[13] A person is in 'energy poverty' if he/she does not have access to at least:
• The equivalent of 35 kg LPG for cooking per capita per year from liquid and/or gas fuels or an improved supply of solid fuel sources and improved (efficient and clean) cooking stoves; and

correlated with the quality of life" (Peters, 2011). The standard of living is highly influenced by income. Additionally, South Africa has one of the worst or highest Gini-coefficients (refer Appendix O) in the world, at 0.63 (World Bank, 2009). More than half (approx. 67%) of the population in Gauteng belongs to poor or low-income groups (Hector et al, 2009) although they consume merely 26.5% of the final energy (see Figure 19).

As shown in Figure 16, total final energy consumption in Gauteng in 2007 was 767.8 PJ. The residential sector occupied third place with a 10% share in total final energy consumption, after industry (45%) and transport (35%) (EnerKey, 2010). Figure 17 shows the share of CO2-equivalent emissions by sector in 2007 (detailed information on emission factors is presented in Appendix J). The highest share of emission results from industry (53.8%), followed by the residential sector which has the second highest share of 16.5%. The final energy consumption by energy carriers in Gauteng is illustrated in Figure 18. Electricity (30.75%), mostly coal based, had the highest share in the final energy consumption by the carrier in 2007 in Gauteng. Coal (25.1%) and petrol (18%) also have a substantial share in the final energy consumption. The share of renewable energy is negligible and accounts for less than 1% in the final energy consumption.

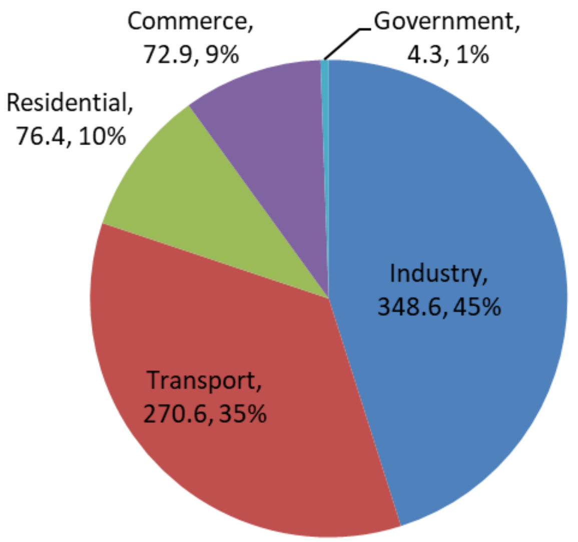

Figure 16: Final energy consumption in Gauteng by sector in 2007 (shown in PJ, %) (EnerKey, 2010)

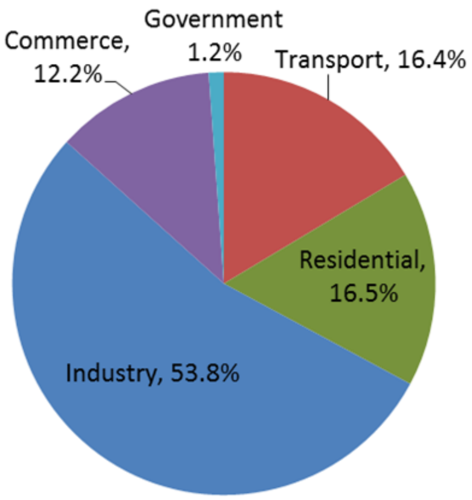

Figure 17: Share of CO_2-equivalent emissions by sector in 2007 (EnerKey, 2010)

• 120kWh electricity per capita per year for lighting, access to most basic services (drinking water, communication, improved health services, education improved services and others), plus some added value to local production (Tennakoon, 2008).

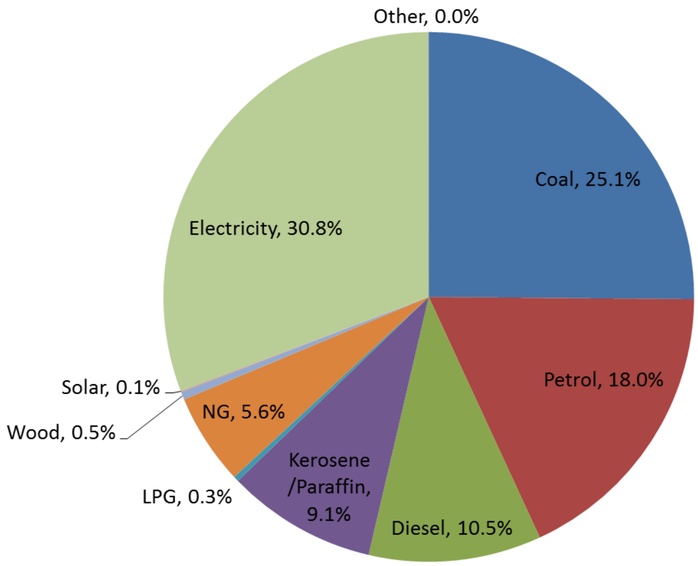

Figure 18: Final energy consumption by the carrier in 2007, (EnerKey, 2010)

2.5.2. Energy consumption in the residential sector Gauteng

In this section, energy consumption in the residential sector in Gauteng is described in detail, disaggregated based upon income groups and building types.

Income group distribution

The economic background of a household influences its choice of fuel and type of appliance used, which in turn affects its final energy consumption. In Gauteng, the economic diversity is vast which impacts the energy consumption in various strata of income groups. Household belonging to the higher income groups have the liberty to choose better, cleaner fuel and buy appliances equipped with better technologies, higher efficiency and safety. Moreover, these households can afford environmentally friendly technologies. By contrast, the households belonging to poor and low-income groups use various fuels (including gathering wood) to meet their ends. To cover these issues, the income classification was taken into consideration to calculate the final energy consumption, which is presented in Table 3.

Table 3: Income group distribution in households in Gauteng, 2007

Income groups →	Poor Income	Low Income	Mid Income	High Income
Annual Income (ZAR)	1 – 9,600	9,601 – 76,800	76,801 – 307,200	> 307,201
Number of households	705,224	1,430,872	651,292	388,191
% households	22.2%	45.1%	20.5%	12.2%

1 € = 10 ZAR (approximately)

The classification of income groups is based upon statistical data (Stats SA, 2008; Hector et al, 2009). The population was distributed into four income groups, namely the poor income group, earning up to 9,600 ZAR_{2007} per household per annum, households belonging to the low income group with an income between 9,600 ZAR_{2007} and 76,800 ZAR_{2007} per annum, the middle income group earning between 76,800 ZAR_{2007} and 307,200 ZAR_{2007} per annum and the high income group household with an income of more than 307,200 ZAR_{2007} per annum.

The share of energy consumption compared to the income group distribution is shown in Figure 19. The income disparity is reflected through the energy consumption patterns, as seen in Figure 19. The 22.2 % of households belonging to the poor income group use just above 4% of the total energy consumption, whereas the high-income group has only a 12.2% population share but uses almost ten times more energy than the poor income group. Accordingly, the poor and low-income groups (one-third share in the population) together use only 25% of the total energy consumption in Gauteng. This confirms the vast difference in energy consumption patterns between the rich and the poor. The development of future income distribution will be crucial for future energy consumption in the residential sector in Gauteng.

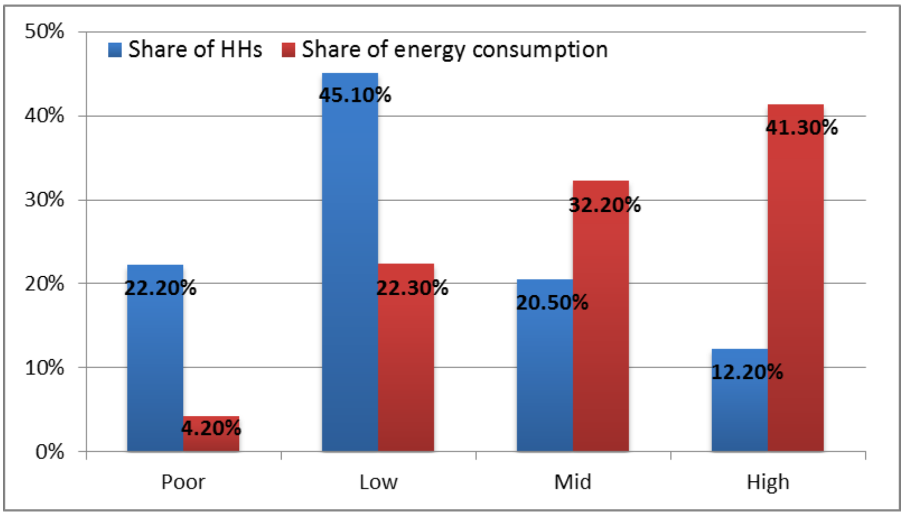

Figure 19: Share of energy consumption in households based upon income groups, 2007 (own calculations based upon Stats SA, 2008; Hector et al, 2010)

Dwelling type distribution

A dwelling type categorisation based upon Stats SA was used for this study as it exhibits the most standard building typology in Gauteng and South Africa (2008). Households in Gauteng are distributed across several types of residential buildings and include ten types according to the community survey (Stats SA, 2008). Table 4 show the classification of residential buildings in Gauteng along with four income groups and the number of households belonging to each income group and dwelling type. It is assumed that each household owns only one house/dwelling, i.e. the number of households is equal to the total number of buildings in Gauteng.

Table 4: Classification of residential dwelling types and income groups in percentage (%) (own calculations based upon Stats SA, 2008)

Dwelling type	Poor	Low	Mid	High	Total
House on separate stand	46.02	48.86	66.44	71.65	54.62
Traditional dwelling	0.47	0.40	0.25	0.24	0.37
Flat	4.88	6.06	11.41	6.67	6.97
Semi-detached houses	1.99	1.95	9.65	11.66	4.72
Flat in backyard	6.08	7.63	4.09	2.84	5.97
Dwelling in backyard	12.72	10.61	2.58	2.30	8.42
Informal dwelling in backyard	21.95	17.93	4.08	3.76	14.25
Dwelling in informal settlement	1.22	1.68	0.66	0.38	1.21
Hostel	4.16	4.38	0.56	0.30	3.05
Other* (boat, caravan, etc.)	0.50	0.51	0.27	0.21	0.42
Total	100	100	100	100	100

As seen in Table 4, ‘house on separate stand’ is the dominant type across all income groups. ‘Semi-detached house’ and ‘flat’ are the second and third most dominant dwelling types in the high-income group, whereas the situation in the mid-income group, is a little different, whereby the share of ‘flat’ is slightly more than ‘semi-detached houses’. The two lower income groups (low and poor) have ‘informal dwelling in backyard’ as the second most dominant dwelling type. Overall in Gauteng, around 55% of the households live in a ‘house on separate stand’, followed by just over 14% households living in the ‘informal dwelling in backyard’. In Gauteng (as well as South Africa), people prefer to live on a separate plot than in semi-detached houses or high-rise buildings, which is also proven through the statistics above. This is one of the reasons why Gauteng has dispersed urban growth.

The data used for energy consumption are based upon the EnerKey project database (EnerKey, 2010), TIMES-GEECO[14] model (EnerKey, 2013) and own calculations. For calculating energy demand in households, demand for cooking, lighting (indoor & outdoor),

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[14] TIMES is a technology rich, bottom-up model generator, which uses linear-programming to produce a least-cost energy system, optimized according to a number of user constraints, over medium to long-term time horizons. In a nutshell, TIMES is used for, "the exploration of possible energy futures based on contrasted scenarios" (Loulou et al., 2005). For the EnerKey Project, at IER an integrated energy system model TIMES-GEECO was developed for the region of Gauteng.

space heating and water heating were considered. This demand is further differentiated according to four income groups and ten dwelling types (See Table 61 in Appendix L).

Final energy consumption across income groups and building types

Final energy consumption is the energy which reaches the final consumer (e.g. household) and excludes that which is used by the energy sector itself. Final energy consumption heavily influenced by economic status of the household, type of energy carrier used, share of different technologies used and share thereof. To calculate the final energy consumption in Gauteng, different dwelling (building) types according to four income groups were considered. This resulted in a typical energy consumption profile for each of the different housing types and income groups. In 2007, an average poor household consumed 12.39 GJ compared to 52 GJ by an average high-income household. This means that an average high-income household consumes more than four times energy than a poor income household. Furthermore, in 2007, an average low-income household’s consumption was 16.91 GJ. By contrast, a mid-income household consumes three times more energy than an average poor household, i.e. 37.95 GJ in the same year. More detailed information on various fuels used by different income groups and their efficiencies can be found in Appendix L.

3. Land use and spatial structure

This chapter deals with the methodology used to analyse the land use pattern and changes in the land use pattern between 1991 and 2009 in Gauteng. The results obtained in this chapter are used as an input for the scenario analysis in the next chapter.

3.1. Definitions

3.1.1. Land use

Land use is defined as purposes for which humans exploit the earth's surface. It includes both the manner in which attributes of the land are manipulated and the purpose for which the land is used (Lambin et al, 2006). FAO defines land use as "the total of arrangements, activities, and inputs that people undertake in a certain land cover type" (FAO, 1997; FAO/UNEP, 1999).

Land use includes the management and modification of natural habitat into built environment such as cultivation, settlements, pastures, recreation, etc. Land use change at any location means a change or shift of present land use category into a different one. Unmanaged and unplanned land use can lead to unsustainable land use.

A single land use category usually corresponds to one land cover form, although a single category of land cover can support multiple land uses; for instance, the single land cover 'urban' can be further divided into multiple land use categories, such as residential, transport, recreation, industrial, park, etc. Figure 20 shows the land use for Johannesburg for 2007.

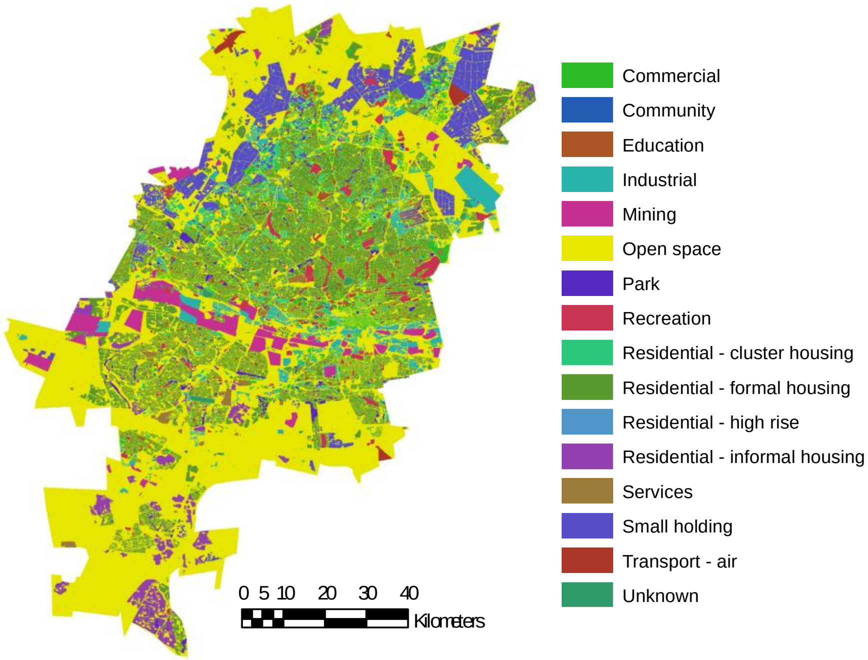

Figure 20: Detailed land use map of the city of Johannesburg, South Africa (2007)

3.1.2. Land use change

The concept of land use change emerged in the 1970s, prompted by concerns about the influence of land use changes on the climate (Ottermann, 1974; Charney and Stone, 1975; Sagan et al, 1979). The impact of land use change on global climate was first studied in the early-1980s (Woodwell et al, 1983; Houghton et al, 1985). Land use and land cover change (LULCC) – popularly known as land change – is a general term used for the human modifications of the Earth's surface. Although humans have been using the land for various purposes since the beginning of the human race, the extent and rate of land use change have rapidly risen in the recent past (Ellis, 2010).

Land use changes are the direct and indirect consequence of human actions to secure essential resources. It started with the burning of areas to enhance the availability of wild game or acquire land for agriculture, resulting in deforestation and the management of surfaces, which continues to date. In the recent past, industrialisation encouraged the concentration of human populations within urban areas and the desertion of rural areas, accompanied by the intensive usage of agriculture in the most productive lands. Land use changes can also occur due to natural phenomena such as earthquakes, floods or droughts. This study focuses on land use change caused by human beings and/or their activities.

3.1.3. Modelling land use change

The process of (urban) development is closely associated with land use change (both built and natural environments) over time. Fulfilling the increasing land demand for new residential sectors has been a huge challenge in many countries over the world. Various drivers of land use change such as natural processes, cultural, demographic, economic, political and technological factors are very complex in nature and inter-related in most cases (Veldkamp and Lambin, 2001; Lambin et al, 2003). Along with these factors, spatial policies designed at national, provincial, local and zonal level must be carefully integrated into the new urban plans to avoid unmanaged growth.

To understand and simulate this complex process between biophysical and human systems and foresee the impacts of various policies, a model that can be calibrated and validated is required. Such models help in terms of understanding and explaining the causes and consequences of land use dynamics. Modelling of land use changes is highly dependent on the availability and quality of the data.

Due to the poor connections between spatially explicit land studies (macro-level) and the socio-economic approaches (micro-level), there is a general lack of real integrated human-environmental approaches (Fox et al, 2002; Verburg et al, 2002; Nagendra et al, 2004). Aspinall and Kok (2004) demonstrate the need to address both of these approaches in a multi-scale approach to separate the environmental and socio-economic drivers of land use change. The outcomes of such a model are simulated land use maps that can be used to see the areas of future development and the impacts of environmental changes and can influence various regional/national energy, environmental and transport policies.

Land use change can be simulated using cellular automata (CA) models or agent-based models. CA models have many advantages such as realism, resolution, spatiality, easy linkage to GIS and object-oriented programming compared to agent-based models and they are described in detail later in this chapter. An agent-based model is a representation of a system (e.g. land use) in which agents interact with each other and their environment using a given set of rules. This model is a region-based model and the results can be hardly generalised. As agent-based models involve many agents and their interaction with the environment, the modelling processes are extremely computationally intensive and time-consuming. Compared to agent-based models, CA models require fewer data and hence are easily applicable to regions like Gauteng despite having fewer data.

3.1.4. Geographic information system (GIS)

A geographic information system (GIS) is a computer-based method for creating digital maps together with data, hardware and software to manage, manipulate, analyse and illustrate geographically referenced information. With the help of GIS, one can visualise and interpret data in various ways to demonstrate relationships, patterns and trends in the form of charts, maps and reports. Civil and military control systems, transportation network systems, architecture, land registration, civil engineering, urban development and census data management systems are few of the fields in which GIS is predominantly used.

Due to its multifaceted features, GIS has become popular in numerous fields. A few of the popularly used GIS techniques are:

- **Data representation:** The data must be geo-referenced in one of the available coordinate systems to represent the data without errors. The captured data is represented in vector or raster data. In the vector format, the GIS data is represented as points, lines or polygons. Satellite data is usually represented in raster format. In raster format, the image is divided into individual pixels. These GIS data types are further explained in the next chapter (see 3.1.5).
- **Data analysis:** GIS can be used to illustrate two- and three-dimensional characteristics of the earth's surface (e.g. wetlands, buildings, roads, etc.) and the atmospheric information (such as rainfall, temperature, etc.). For instance, contour lines are used to depict differing amounts of rainfall or the topography. A two-dimensional rainfall map created with the help of GIS can help in terms of providing data for water availability in the region.
- **Spatial analysis:** This includes the study of various features using their geographic, geometric or topological properties. Urban studies deal with large spatial data obtained from census, household surveys, etc. This data can be simplified with the help of GIS. Simulation models such as CA or agent-based models are widely used for spatial analysis.
- **Topographic modelling:** Topological relationships between geometric entities traditionally include adjacency, containment and proximity. A GIS tool can recognise and analyse the spatial relationships that exist within digitally stored spatial data.

Various software packages such as ArcGIS, GRASS-GIS and Quantum-GIS are used for spatial analysis. Due to its widespread use, strong customer support system and user-friendly interface, ArcGIS was used for this study (ESRI, 2012).

3.1.5. Data formats of GIS

GIS data is essentially spatial data that describes the absolute and relative location of geographic features. The attribute data describes the characteristics of the spatial features. The GIS data is available in either raster or vector format (see Figure 21), both of which are used to store and manipulate data/images on a computer. Most of the available GIS software programmes (both commercial and open source) are based upon either of the two aforementioned formats.

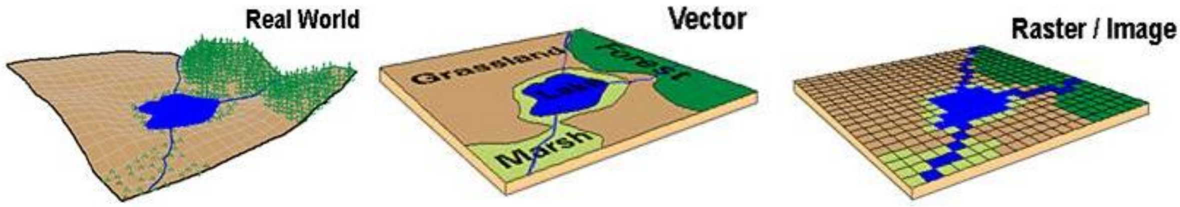

Figure 21: Representation of the real world in GIS with vector and raster format (Buckey, 1997)

Vector data is the simpler of the two formats. It comes in the form of points, lines and polygons, which are geometrically associated. For example, points are stored using two-dimensional coordinates, x and y. The points are joined together to form a line or joined into a closed loop to create a polygon. Vector data is usually more visually appealing than raster data, depending on the fineness/coarseness of the raster image. Gauteng's vector representation is illustrated in Figure 22. It shows various metros and municipalities in Gauteng, represented as polygons. The main roads are illustrated by (black) lines running through Gauteng.

Some of the advantages and disadvantages of the vector data are as follows:

Advantages	Drawbacks
1. It can be represented at its original resolution and form without generalisation. 2. The graphic output is aesthetically pleasing compared to raster data as no conversion is required. 3. Accurate geographic location of data is maintained. 4. Allows more efficient encoding of topology. 5. Requires lesser space on the hard disc.	1. The location of each vertex (point) needs to be stored explicitly. 2. For an effective analysis, the vector data have to be converted into a topographical structure. This is processing intensive and requires extensive data cleaning. 3. Algorithms for manipulative and analysis functions are complex, time-consuming and processing intensive. 4. Continuous data (e.g. elevation data) cannot be effectively represented. 5. Spatial analysis within polygons is impossible.

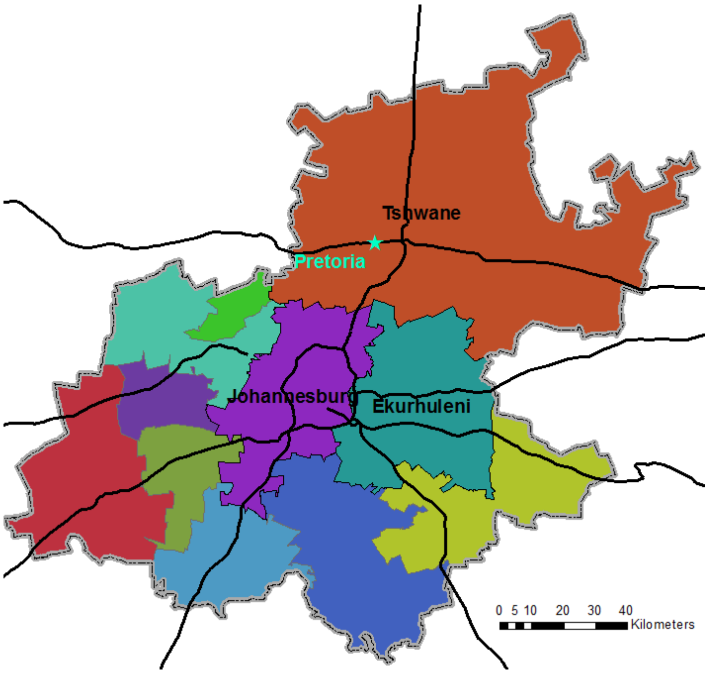

Figure 22: Vector representation of Gauteng (own diagram)

Raster data is represented in the form of individual pixels or cells containing a colour value, whereby each of these pixels indicates an attribute (e.g. elevation or land use type) associated with it. Each spatial location has a pixel associated with it. A raster image is a digital image represented by grids, i.e. rows and columns of cells. A raster-based representation of Gauteng's land use can be seen in Figure 23.

Raster data has following advantages and disadvantages:

Advantages	Drawbacks
1. It has a simple data structure. Each cell's geographic location is inferred by its position in the cell matrix. Other than an origin point no geographic coordinates are stored.	1. The pixel/ cell size of the image decides the resolution of the image. Changing this resolution results in loss of data integrity.
2. Due to the nature of the data storage technique data analysis is usually easy to program and quick to perform.	2. Representation of linear features such as rivers, transport network, etc. is difficult and depends heavily on the cell resolution.
3. Due to its inherent nature, e.g. one attribute maps, raster maps are ideally suited for quantitative analysis and mathematical modelling.	3. For large amounts of data, processing of the data can be cumbersome.
4. Discrete data such as forest can be represented equally well as continuous data, such as elevation data.	4. Raster maps represent only one characteristic/attribute of the area.
5. Facilitates the integration of the discrete and continuous data types.	5. As most of the data is available in vector format, the raster data must be always converted, which again results in the generalisation of the data and loss of data integrity.

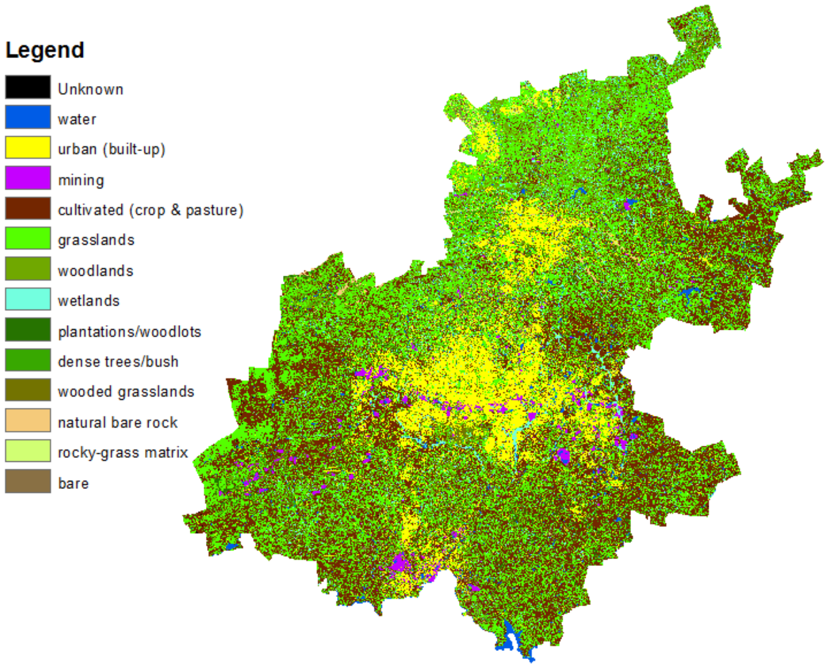

Figure 23: Raster representation of Gauteng's land use (own diagram)

A raster image stores data in pixel form, whereas in vector data only point coordinates are stored, which results in a smaller file size for vector data compared to raster images. Moreover, the finer the resolution, the larger the size of the raster image will be. Due to its simplicity, vector data is easier to handle on a computer. The vector data usually has fewer data items and can be adjusted to different scales. Data like satellite images are only available in raster format. Raster format enables the representation of continuous surfaces and performing the surface analysis. The raster format is more suitable for advanced spatial and statistical analysis, with the ability to uniformly store points, lines and polygons. With raster data, one can perform fast overlays with complex datasets, which is one of the reasons for choosing the raster data format for this study.

3.1.6. Cellular automata (CA)

Cellular automata (CA) are discrete dynamical systems that model complex behaviours based upon simple, local rules animating cells on a lattice. The concept of CA was invented by von Neumann and Ulam in 1948 to study reproduction in biology (von Neumann, 1951; Pickover, 2009). In the 1970s, when Conway's Game of Life – a two-dimensional model – was introduced, the interest in CA gained wider attention beyond academia (Gardner, 1970). Today, CA models are used in many fields of science and engineering.

A CA model comprises a regular grid of cells (raster format), with each cell in one of a finite number of states. A set of cells (surrounding the cell) – called its neighbourhood – is defined for each cell. An initial state (at time T=0) is selected by assigning a state for each cell. Based upon fixed transition rules, a new generation (at time T_1) is calculated. The transition rules – generally a mathematical function – determines the new state of the cell based upon its current state and the states of its neighbouring cells. The rules for changing the state of cells are usually the same for all the cells and do not change over time; moreover, they are applied to the entire grid simultaneously.

The most common types of the neighbourhood are the “von Neumann neighbourhood” (see Figure 24) and the “Moore neighbourhood” (see Figure 25). The von Neumann neighbourhood considers only four orthogonally adjacent cells (marked “red” in Figure 24) in the neighbourhood. Sometimes, as an extended neighbourhood, four more cells are taken into consideration, which is marked “pink” in Figure 24. By contrast, the Moore neighbourhood comprises all eight cells adjacent to the “black” cell, known as the “cell in question” (see Figure 25).

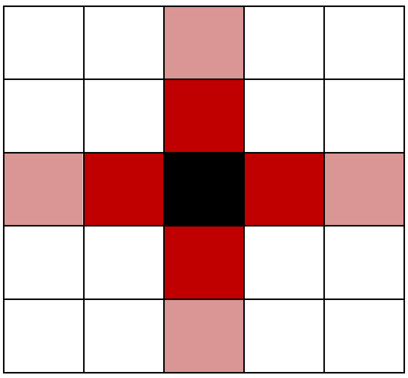

Figure 24: The von Neumann Neighbourhood formation

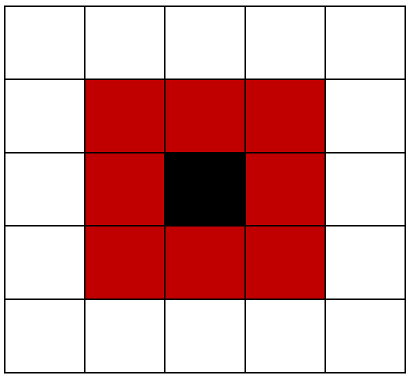

Figure 25: The Moore Neighbourhood formation

A CA model is usually simulated on a finite grid. The only problem with a finite grid is the boundary cells, for which two possible solutions exist. In one method, it is considered that the values in those boundary cells remain constant over time. Another solution would be to define a different neighbourhood for the boundary cells. How these cells are handled affects the values of all the cells in the grid.

3.1.7. Integration of GIS and CA

Modelling complex systems like cities or urban regions normally involves various spatial and temporal processes, which cannot be directly simulated using only GIS. Together with CA, it is possible to simulate the temporal processes. Like in CA, the probability of one land use types changing into another land use type strongly depends on the neighbouring land use patches due to neighbourhood effect. The neighbourhood effect includes the inertia of land uses over time, the conversion from one land use to another, and the attraction or repulsion of surrounding land uses (van Vilet, 2013). CA models are similar to the map algebra models (see Appendix C) in GIS.

Given that most of the available land use data (worldwide) are in raster format, it is easy to process them using a CA model. Due to the similarity in cell grids and neighbourhood effect, CA models are widely used for land use simulations (White and Engelen, 1993; White et al, 1996; Li and Yeh, 2002; Almeida et al, 2008). In GIS images, the objects are defined as pixels/cells that can take on various states and are influenced by neighbouring cells. The GIS representations form the basis of the landscape change models, which are based upon CA-like principles, especially in terms of the way in which the data can be combined through different spatial layers (Itami, 1994). Clarke et al (1997) and Yeh and Li (1998) state that availability of remote sensing data for monitoring urban change has prompted the development of simple models of urbanisation using GIS.

With the help of CA, it is easier to write software modules with special functionality that can be interlinked with GIS in various ways (Batty & Xie, 1994a and Batty & Xie, 1994b). Simulation models can be either loosely coupled to GIS (through their inputs and outputs) or strongly coupled through extensions to the ArcView package. There are commercially available packages which enable models to be developed based upon functions for conventional dynamic modelling and computing with raster data (Burrough, 1998). Nonetheless, these packages generally fail to deliver an appropriate environment for dynamic urban models based upon CA.

According to Tamayo and Hartman (1989), CA models are essentially based upon very simple reaction–diffusion equations. The state of any cell depends upon some function that reacts to what is already in that cell, as well as some function that relates the cell to what is happening in its immediate neighbourhood, namely the diffusion component. In some senses, all dynamics are based upon such a representation. For instance, population growth in a city is dependent upon the reactions such as births, deaths and existing population with diffusion from that stock taking place through migration (Batty, 1971).

CA-based models are capable of reproducing complex global patterns and behaviour through simulating local interactions among individual cells (Wolfram, 1984), and are used for modelling various spatial phenomena such as land use change (Li and Yeh, 2002; Wu, 2002; Almeida et al, 2003; Ménard and Marceau, 2007; Wang and Marceau, 2013) and urban growth (White and Engelen, 1993; White et al, 2000a; Dietzel and Clarke, 2006), among others.

The raster-based CA models are rather sensitive to the cell size. Their results vary according to the cell size and the neighbourhood configuration. Use of two different cell sizes for the urban expansion creates significantly different land use patterns (Jenerette and Wu, 2001). The impact of cell size and neighbourhood in a raster-based CA model was investigated by Chen and Mynett (2003). Various other studies validated that the CA models are sensitive to the cell size and neighbourhood configuration (Jantz and Goetz, 2005; Ménard and Marceau, 2005; Kocabas and Dragicevic, 2006; Marcau et al, 2008)

3.1.8. CA Simulation Model: Dinamica

A land use pattern results from a succession of circumstances developed over a period (Forman and Gordon, 1986; Soares-Filho, 2002). A constant evolution of such a system leads to remarkable impacts on the environment. The development of a simulation model helps in terms of understanding the interaction between nature and human activities. The simulation model attempts to replicate the future land use patterns and thereby evaluate the environmental implications in the future.

The micro-geographical analysis for Gauteng comprises a simulation model to predict the future land use patterns. This analysis is conducted to assess the impact of various geographical parameters (factors directly affecting land use change) and observe the neighbourhood effect (see section 2.1.6). The Dinamica[15] “Environment for Geoprocessing Objects” (EGO) – a GIS and CA-based simulation model – is used in this study to conduct the micro-geographical analysis.

The Dinamica model involves a multiple time step stochastic simulation with dynamic spatial transition probabilities calculated within a cartographic neighbourhood. As the CA local rule, its core engine employs transitional functions specially designed to reproduce the dimensions and forms of land use changes, such as urban development patterns produced by different agents of change. For the model parameterisation, logistic regression is applied to indicate the most favourable areas for each type of transition, by using data obtained

[15] Dinamica is a C++ and Java based cellular automata model.

mainly from satellite imagery. The CA model structure of Dinamica used in this study is discussed in the following section.

CA Model structure

Every conventional cellular automata model comprises the following (White et al, 2000b):

1. A Euclidean space divided into an array of identical cells;
2. A cell neighbourhood of a defined size and shape;
3. A set of discrete cell states;
4. A set of transition rules, which determine the state of a cell as a function of the states of cells in a neighbourhood; and
5. Discrete time steps, with all cell, states being updated simultaneously.

The Dinamica model represents the aforementioned concepts by using a sequence of specially developed algorithms, which are described in Figure 26:

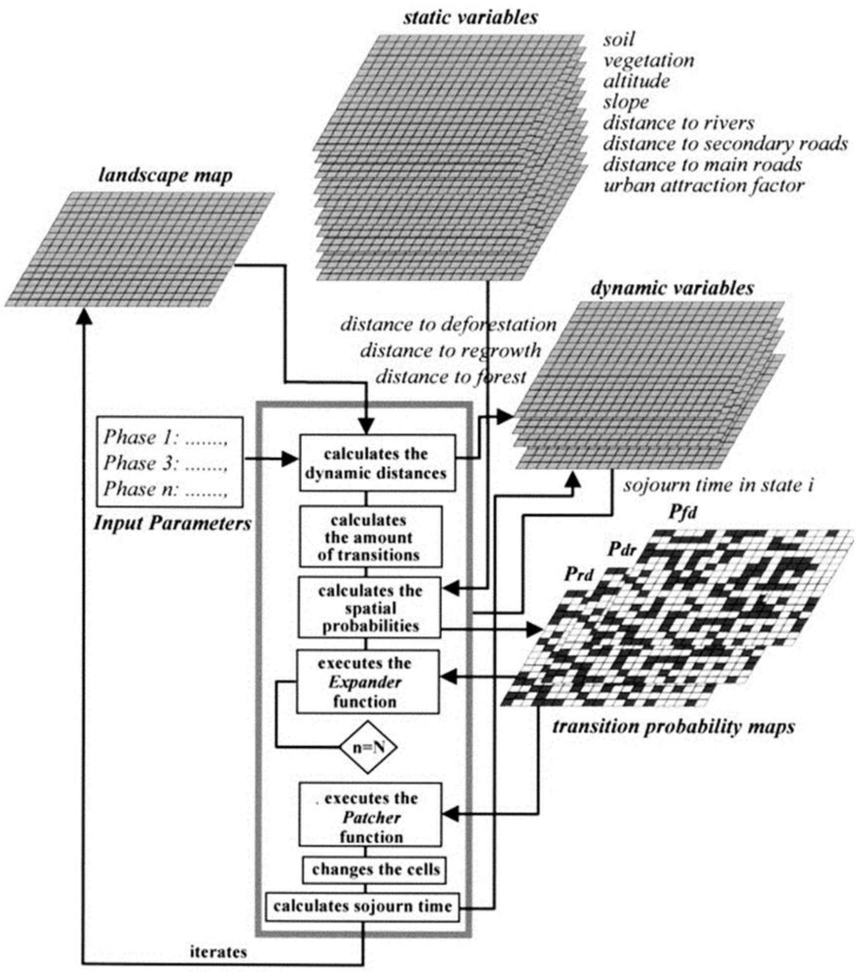

Figure 26: Flowchart of a Dinamica Model (Soares-Filho et al, 2002)

A land use map is a main input of the Dinamica model. Along with the land use map, various spatial variables, static and dynamic are also selected as inputs. As an output, the model generates spatial transition probability maps showing the probability of a cell at a position (x, y) to change from *I* to *j* state, the dynamic spatial variable maps and a simulated land use map (one for each time step).

The model iterates in phases to run the simulation. Each phase has its own parameters, such as:

- number of time steps
- transition matrix
- saturation rates for each land use category
- minimum sojourn time [16] for each type of transition before a cell changes its state
- coefficients of the logistic model applied to calculate each spatial P*ij*
- percentage of transitions executed by each transitional function together with the parameters mean patch size and patch size variance of each type of land use category

Thus, the model can be run using multiple phases, each of which comprises several steps.

3.2. Land use changes in Gauteng

Worldwide urban areas accompanied by cropland, pastures and plantations have expanded due to increasing demand for energy, food and water; indeed, Gauteng is no exception to this phenomenon. To understand Gauteng's spatiotemporal evolution, it is important to analyse the land use change in Gauteng.

3.2.1. Land use change in Gauteng, between 1991 and 2009

The data[17] used for Gauteng for 1991, 2001 and 2009 is based upon the GeoTerra[18] images. All the images have a resolution of 30 x 30 m and were classified in fourteen different categories, as shown in Table 5. These categories are explained in detail in Appendix A. This table depicts the area belonging to each category (in km²) for each year (1991, 2001 and 2009) and the change in each category between 1991 and 2009. The fifth and the sixth

[16] Sojourn time: The (mean) sojourn time for an object in a system is a mathematical term for the amount of time an object is expected to spend in a system before leaving the system for good.
[17] All the data (satellite images) were made available by the University of Johannesburg, detailed information on land use categories can be found in Appendix A.
[18] GeoTerra: GeoTerra IMAGE (Pty) Ltd is a privately owned company, which has been providing geographical information services and products to a wide range of public and commercial sectors in support of business intelligence and planning decisions since 1999.

columns show the change in km^2 and as a percentage, respectively. Negative values show a loss, whereas positive values show a gain.

The category ‘urban’ had the highest gain (861.78 km² or 41.07%) in 18 years, followed by grasslands (1070.19 km² or 18.64%), natural bare rock (4.33 km² or 4.03%) and cultivated area (212. 85 km^2 or 3.65%). By contrast, the dense tree had the highest loss (365.56 km² or 75.56%), followed by woodlands (1223.14 km² or 71%) and plantation (191.40 km² or 58.89 %).

Due to high extraction rates (mining) in the past, mining has drastically declined in recent years, especially, above-ground mining. Table 5 also verifies this fact. Initially between 1991 and 2001, there was an increase of 115.58 km² (47 %), but subsequently a decrease of 178.47 km² (49 %) in the following decade (2001-2009). The mining area shown in this table includes only the surface mining and not the underground mining areas.

Table 5: Change in land use categories in Gauteng between 1991 and 2009

Category	Area (km²)			Change (1991-2009)	
	1991	2001	2009	(km²)	(%)
Unknown/open	16.05	3.62	6.71	-9.34	-58.18
Water	308.58	301.29	280.30	-28.28	-9.16
Urban (built-up)	2098.40	2573.56	2960.18	861.78	**41.07**
Mining	248.86	364.44	185.97	-62.88	-25.27
Cultivated	5832.22	6012.71	6045.07	212.85	**3.65**
Grasslands	5740.46	6022.63	6810.65	1070.19	**18.64**
Woodlands	1722.72	694.85	499.57	-1223.14	-71
Wetlands	581.99	232.72	561.43	-20.56	-3.53
Plantation	325.00	392.25	133.61	-191.40	-58.89
Dense tree	483.80	271.08	118.24	-365.56	-75.56
Wooded grass	296.37	590.16	240.72	-55.65	-18.78
Bare rock	30.86	30.86	35.19	4.33	**14.03**
Rocky grass	171.97	154.46	146.85	-25.13	-14.61
Bare	313.00	525.64	145.78	-167.22	-53.42

A model simulation for an area of 18,170 km² with fourteen categories (with a resolution of 30 m x 30 m, i.e. more than 20 M cells) was not possible due to the cellular automata model constraints[19]. Hence, these 14 categories had to be reduced to six categories. An attempt was made to keep all the categories with similar characteristics in one group, to avoid

[19] The CA Model used in this study cannot process 14 land use categories in the simulation process.

compromising the data quality. The cell size was not altered as it results in losing spatial accuracy. The resulting six categories are shown in Figure 27.

As seen in Figure 27, water and wetlands are combined and reclassified as ‘water’, (842 km² in 2009), urban and mining were combined under ‘urban’, (3146 km² in 2009), open, bare and bare rock were reclassified as ‘open space’ category (188 km² in 2009) and cultivated and plantation were combined under the category ‘cultivated’ (6179 km² in 2009). The new ‘grass’ category (6957 km² in 2009) includes grasslands and rocky grass, whereas the ‘forest’ category (895 km² in 2009) includes woodlands, dense trees and wooded grass. All three images were reclassified using ArcGIS 10 Model-Builder (see Appendix C). Figure 28 shows an example of reclassification of the satellite imagery for 1991. The area under new six land use categories is shown in Table 6.

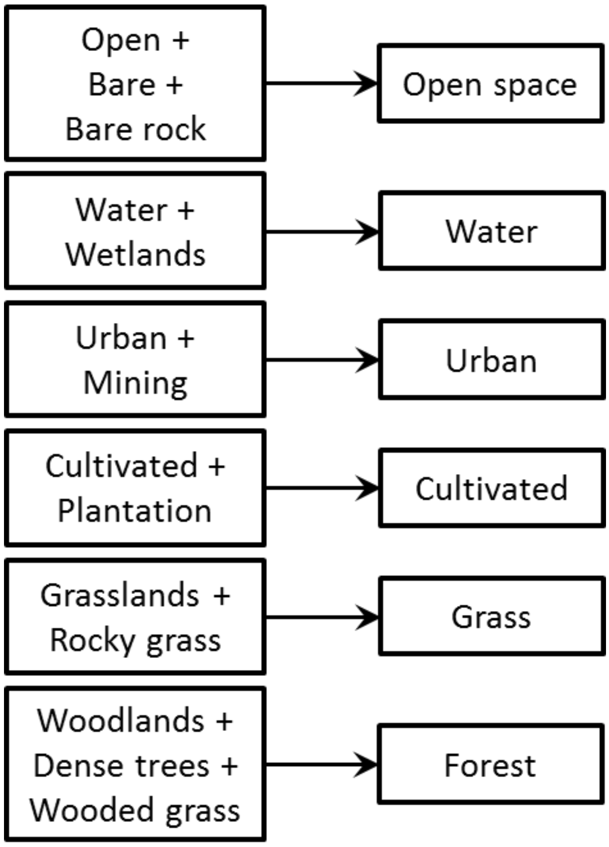

Figure 27: Reclassification of the land use categories

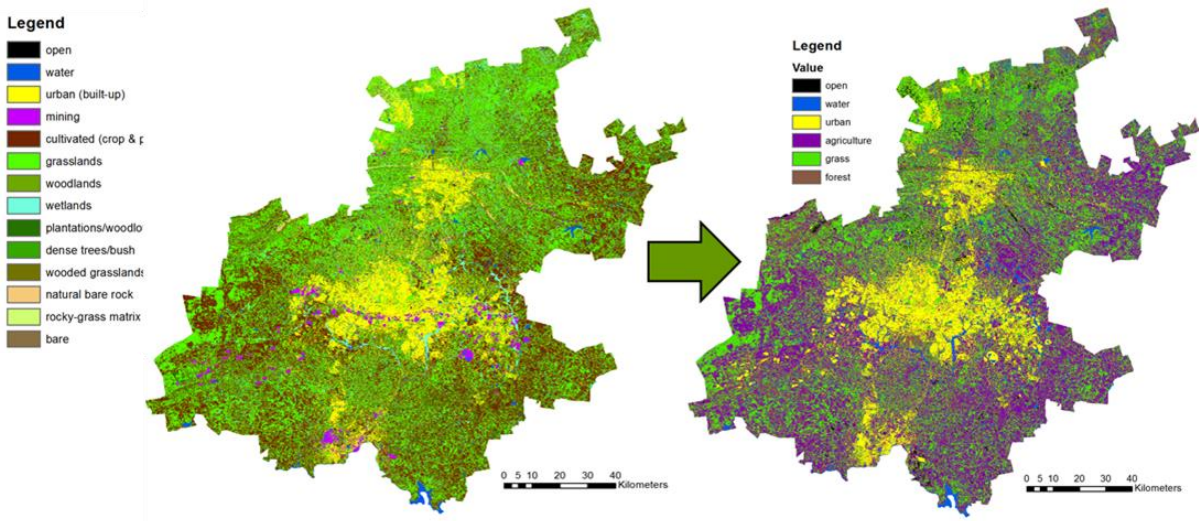

Figure 28: Land use categories after reclassification, Gauteng (1991)

Table 6: Area under new land use categories (1991 – 2009)

Land use category	Area (km²)			Change (km²)	Change (%)
	1991	**2001**	**2009**	**1991-2009**	
Open space	360	560	188	-172	-47.85
Water	891	534	842	-49	-5.48
Urban	2347	2938	3146	799	**34.04**
Cultivated	6157	6405	6179	-21	-0.35
Grass	5912	6177	6957	1045	**17.68**
Forest	2503	1556	895	-1644	-65.70

Table 6 shows the change in the six aggregated land use categories between 1991 and 2009. Land use categories most affected by the urbanisation are 'open space' (ca. 48% reduction) and 'forest' (ca. 66% reduction). Land use category 'urban' shows the highest increase (34%). Besides the urban area, the grass is the only land use category that has increased in the last two decades.

Along with the land use change patterns, it is important to understand the urban footprint of Gauteng. The urban footprint reveals how efficiently the urban land is being used within a region. Moreover, it is also an indicator of compactness of a city. The Urban footprint is not just a multiplicative inverse of population density, namely the population divided by the total area; rather, the urban footprint is calculated using built-up area, not the total area. Hence, a better measure to compare the change in urban (built-up) area as the total area of a region (usually) does not change over time.

The Urban footprint[20] of Gauteng: Due to mining and the economic boom, Gauteng has been receiving a constant influx of people; indeed, Gauteng's urban area grew by 34% between 1991 and 2009. Table 7 displays the changes in the urban and non-urban area along with the population growth and urban footprint (m²/capita) for the Gauteng region. Due to a stronger increase in population, the urban footprint has reduced from 313 to 299 m²/ capita.

Table 7: Urban footprint of Gauteng (own calculations)

Parameter	Unit	1991	2001	2009
urban area	km²	2347	2938	3146
Population[a]	No.	-	9,388,854[b]	10,531,300[c]
Urban footprint	m²/capita	-	313	299

a: As Gauteng was formed in 1994, the population for 1991 does not exist.
B: Source: Census 2011 Key results, Stats SA 2012
c: Mid-year population estimates, for 2009, Stats SA 2010

Table 8 compares the urban footprint of three metros around the world (London, Cape Town and Atlanta) with Gauteng. As a classic example of a compact city, London has a very small urban footprint compared to Cape Town and Atlanta. Although Gauteng's urban footprint is not as high as Cape Town or Atlanta, with its constantly increasing population and increasing urban area, this situation might soon change.

Table 8: Urban footprint of Gauteng and other metros, 2009 (own calculations)

Region	Urban Area (km²)	population	Urban footprint m²/capita
London	1,738	8,631,325	201
Gauteng	3,144	10,531,300	299
Cape Town	2,454	3,404,807	720
Atlanta	4,280	4,691,356	1,096

3.2.2. Understanding spatial structure of Gauteng

A city form is generally quantified using the impervious/built-up area (Torrens and Alberti, 2000; Barnes et al, 2001; Epstein et al, 2002). Integrated use of GIS and a geodatabase enables measuring, monitoring and predicting the sprawl or compactness of the city. However, monitoring urban land use change using the techniques of GIS and its subsequent modelling to arrive at a conventional approach is lacking in the context of Gauteng or South Africa in general.

Various forms of spatial structure can be found in the world. London, Jakarta and Paris are few examples of compact cities (Bertaud, 2008), whereas Chicago is an example of a zonal

[20] Urban footprint: Urban footprint denotes how much built-up area is used by each human being (m²/capita).

model[21] (Burgess, 1924) and Calgary of Hoyt's sector model[22] (Hoyt, 1939). In most of these models, higher population densities are observed around the city centre or the business sector. By contrast, regions like Gauteng, Brasilia and Moscow have rather dispersed, low-density spatial structures (also known as urban sprawl), where the densities increase along with the distance from city centre (Bertaud, 2008). A lack of public transport and the presence of crime-related safety issues are the major reasons why people in Gauteng have deserted the city centres. Two central business districts (CBD) in Johannesburg and Pretoria and scattered industry all over the region have also influenced dispersed job distribution in Gauteng.

Another special characteristic of Gauteng's spatial pattern is segregation based upon race, which came in effect with the Apartheid era (Gauteng, 2001). Most of the poor non-white people lived in the informal settlements such as Alexandra and Soweto, on the outskirts of white settlements (Western, 2002). Figure 29 shows the dispersed population distribution in Gauteng. Besides a few population pillars in Johannesburg's CBD, most of the population lives on the outskirts, away from the CBDs.

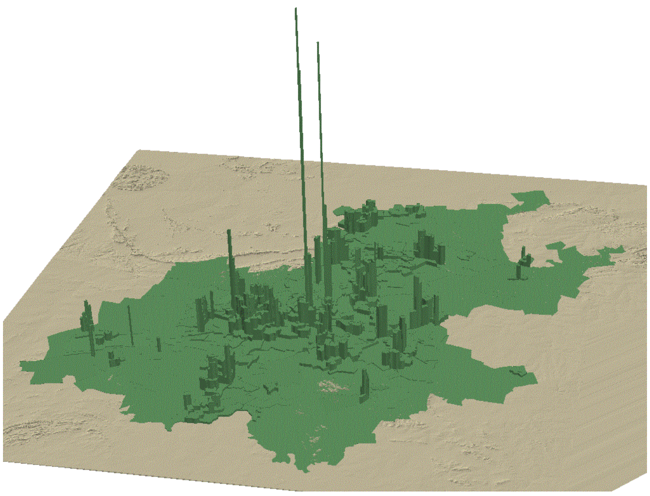

Figure 29: Scattered population distribution in Gauteng (own diagram based on data from Stats SA 2012)

A detailed analysis was conducted (see next section) to recognise the city structure of Gauteng and identify dynamics of its spatial structure to suggest appropriate management strategies. Understanding such a phenomenon and its pattern helps in terms of effective planning of natural resources and infrastructure facilities.

[21] Zonal model: According to this model, a city grows outward from a central point in a series of rings. The innermost ring represents central business district (Burgess, 1924)
[22] Sector model: Hoyt's sector model proposed that a city develops in sectors instead of rings (Hoyt, 1939)

3.2.3. Quantifying spatial structure with Shannon's entropy

Urbanisation is an unavoidable process, although efforts can still be made through urban planning to direct it in the most appropriate way (Soffianian et al, 2010). This has given rise to the increased importance of accurate mapping of urban environments and monitoring urban growth at the global level (Guindon and Zhang, 2009). As conventional mapping techniques are fairly expensive and time-consuming for the estimation of urban growth, computer-based statistical techniques along with GIS have gained popularity as an alternative (Yeh and Li, 2001; Sudhira et al, 2004; Punia and Singh, 2011; Deka et al, 2012).

Shannon's entropy factor was used in this study to quantify Gauteng's urban form (Yeh and Li, 2001). Significant research has been conducted in recent years concerning the integrated use of satellite data and GIS for recognising urban growth patterns using Shannon's entropy approach (Sudhira et al, 2004; Joshi et al, 2006; Sun et al, 2007; Sarvestani et al, 2011). Studies have shown that the entropy factor is a good statistical measure for recognising and understanding the spatial distribution of various geographic phenomena (Batty, 1972; Thomas, 1981, Yeh and Li, 2001). Shannon's entropy is an indicator of spatial concentration or dispersion and can be applied to investigate various geographic entities. Spatial and temporal variations are taken into account to measure the sprawl/compact patterns (Yeh and Xia, 1998).

Shannon's entropy factor was calculated for 1991, 2001 and 2009. Shannon's entropy (H_n) was used to measure the degree of spatial dispersion or concentration of a geographical variable (x_i) among n zones (Theil, 1967; Thomas, 1981; Yeh and Li, 2001). It is calculated as follows:

$$H_{n=}\sum_{i}^{n} p_i * log(1/p_i) \qquad \textbf{Equation 1}$$

Where P_i is the probability or proportion of a change occurring in the i_{th} zone

$$p_i = x_i/\sum_{i}^{n} x_i \qquad \textbf{Equation 2}$$

x_i is the observed value of the change in the ith zone and n is the total number of zones. The entropy values vary from zero to log (n). The lowest value - zero - will occur when the distribution is concentrated in one zone, whereas an even distribution will have the maximum value of log (n). To scale the entropy values between zero and one, relative entropy is used. Relative entropy (H'_n) (Thomas, 1981) is defined as:

$$H'_n = \sum_{i}^{n} \log(1/p_i)/\log(n)$$ **Equation 3**

Entropy can be used to indicate the degree of urban sprawl by investigating whether the urban development in the city is dispersed or compact. If the value is large (close to one), the urban development is dispersed/sprawl, whereas values tending towards zero indicate a compact city form.

Entropy calculations for Gauteng

The land cover data used for the study was obtained from GeoTerra Image for three different time periods, namely 1991, 2001 and 2009. The raster images have a resolution of 30 x 30 m. Other data such as province boundaries, highways, etc. were acquired from various project partners in South Africa. The land cover images were processed and geo-referenced with ArcGIS 10 software.

The original land cover was categorised into fourteen different categories (see Figure 30). As the entropy factor takes only the built-up area into consideration (see Equation 3), the land use maps for all the three periods were subsequently reclassified into two categories – urban (built-up) and non-urban (non-built-up) areas – as shown in Figure 31.

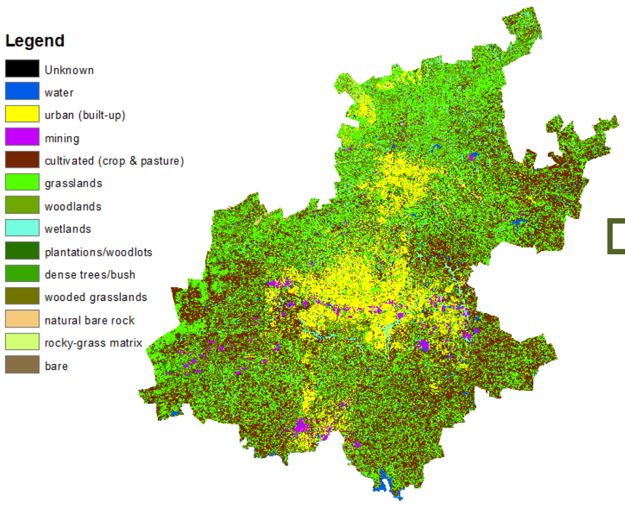

Figure 30: Land cover map of Gauteng, 1991 (own diagram based upon GeoTerra Image)

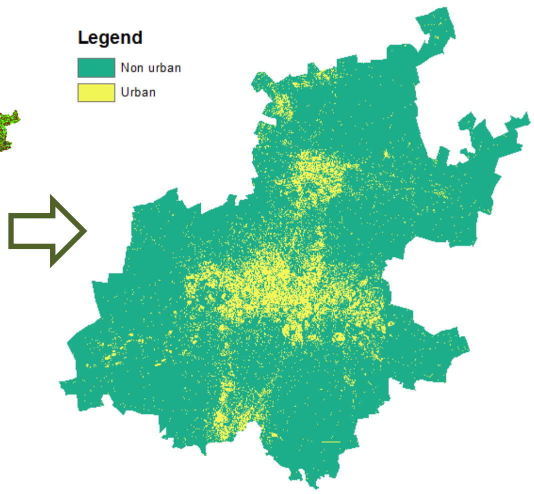

Figure 31: Processed land cover map of Gauteng, 1991 (own diagram based upon GeoTerra Image)

Urbanisation usually takes place on the periphery or along highways (easy accessibility), giving rise to urban sprawl. In addition, the size of the zone (Equation 3) also affects the entropy factor. Taking these issues into consideration, three different levels were finalised for the analysis:

- **Region Gauteng**: In this case, the entire region is considered as one entity.
- **Municipalitie**s: In Gauteng each municipality is unique, e.g. Johannesburg inhabits many financial institutions and Tshwane has major industries. Hence, to observe the effect of employment opportunities in each municipality, the administrative boundaries of the region are taken into consideration. The region is divided into twelve municipalities. Figure 32 shows the various municipalities within the region.
- **The area in the close proximity of the main roads:** A city usually grows around business centres or near transport lines/nodes (accessibility). To analyse the impact of the main roads on the urban development in Gauteng, a buffer of 5 km was created around the main roads and only the buffered area was considered for the entropy calculations. Figure 33 shows main roads (also called freeways or highways) in Gauteng with a buffer of 5 km around them.

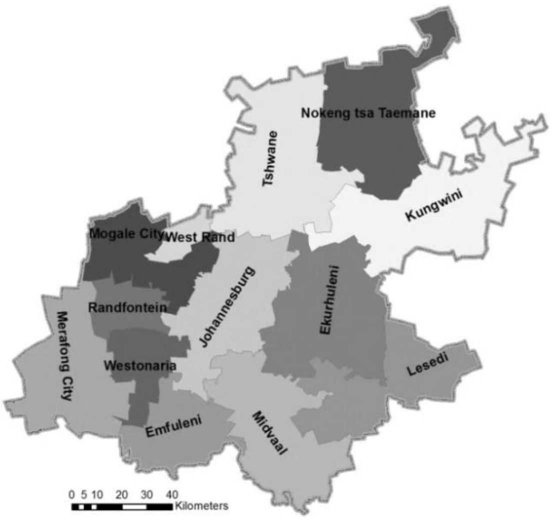

Figure 32: Gauteng with administrative boundaries (own diagram)

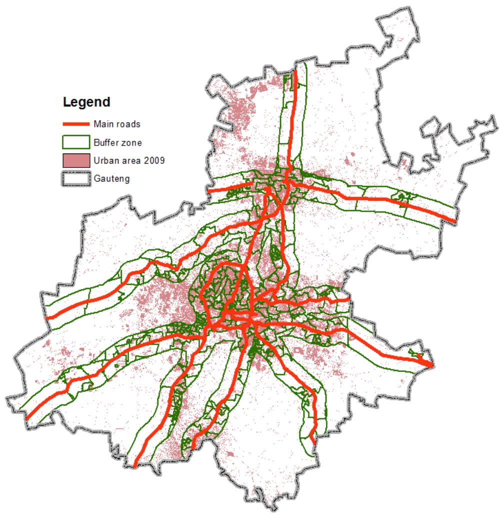

Figure 33: Main roads in Gauteng with a 5 km buffer (own diagram)

Shannon's entropy measures the share of built-up area in the specified zone. For Gauteng, the administrative zones at the municipality level (for case 2 mentioned above) were selected as the boundary condition for the entropy calculations. The model, created in ArcGIS 10 – Model-Builder - shown in Figure 34 - was used for reclassification of the raster images and to calculate the percentage of built-up area in each zone.

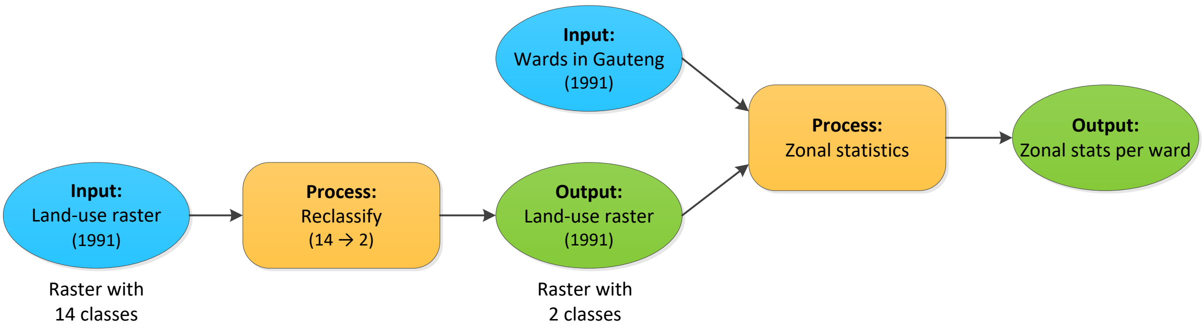

Figure 34: Model-Builder flowchart showing reclassification and zonal statistics process

The model presents a two-step process involved in the reclassification of the raster map: in the first step, the model reclassifies the image to reduce the number of categories from fourteen to two (urban or built-up and non-urban); and in the second step, it combines the resulting raster with the wards to carry out the zonal statistics. The tool 'zonal statistics' counts the number of pixels belonging to the built-up category in each zone in the raster. Based upon the results from the zonal statistics (built-up area in each zone), the total area and Equation 3, the entropy factors for three different cases were calculated. The consequences of urban sprawl are described later in section 6.1.2. The results are presented in Table 9.

Table 9: Entropy factors in Gauteng (1991, 2001 and 2009)

Built-up area (km²)			Total Area	Entropy factor			Category
1991	**2001**	**2009**	**(km²)**	**1991**	**2001**	**2009**	
2,348.94	2,940.11	3,143.66	18,170	0.95	0.97	0.97	Gauteng
48.85	85.71	73.71	1629.31	0.80	0.86	0.86	Merafong city
43.65	65.12	63.84	1967.07	0.73	0.81	0.78	Nokeng
177.90	227.34	183.92	965.27	0.96	0.98	0.98	Emfuleni
72.66	107.38	90.24	1724.55	0.87	0.84	0.89	Midvaal
42.91	60.38	50.08	1485.67	0.84	0.83	0.87	Lesedi
58.11	81.28	89.84	2201.95	0.85	0.85	0.82	Kungwini
93.49	127.38	126.00	1098.49	0.90	0.94	0.94	Mogale city
40.46	48.05	50.88	476.76	0.91	0.92	0.93	Randfontein
43.80	60.80	59.27	637.17	0.82	0.85	0.85	Westonaria
633.28	728.39	805.38	1923.63	0.97	0.98	0.99	Ekurhuleni
646.99	758.99	866.57	1644.05	0.97	0.99	0.99	Johannesburg
440.32	579.83	679.67	2173.57	0.96	0.97	0.98	Tshwane
-	-	-	-	0.95	0.97	0.97	Roads
				-	0.91	-	Calgary, Canada[a]
				-	0.98	-	Pune, India[b]
				0.73_{1990}	0.83_{2000}	0.88_{2006}	Setubal, Portugal[c]

a: Sun et al (2007), b: Shekhar (2004), c: Araya and Cabral (2010)

Most of the factors lie in the range of 0.80–0.99. Besides Kungwini and Nokeng, all other categories show an increase in the entropy factor between 1991 and 2009. This means that there is a trend of increasing dispersed growth in Gauteng. As Kungwini and Nokeng municipalities do not have major industrial or financial centres, they have a low share of population and hence lower entropy values. The reduction in entropy factor is a result of either manual error in satellite image processing or a change in the mining areas (which are included in 'built-up' category), which have turned into bare rock or rocky grass areas, hence reducing the built-up area in this region. Otherwise, once an area is turned into a built-up area, it cannot be changed into another category, given that it is an irreversible process.

In other municipalities – e.g. Johannesburg, Mogale city and West Rand – the entropy factors have remained unchanged since 2001. The constant entropy factor confirms that most of the available land for development is already in use, reaching saturation of the urban areas. Another reason for constant entropy factors is the desertion of the city centres in Johannesburg and Pretoria, as people move away due to security reasons to find safer living areas in the gated communities on the periphery.

Table 9 also compares Gauteng's entropy factors with three other cities around the world. Due to vast land availability and car-dependency, countries like the USA and Canada are already affected by urban sprawl, although cities like Pune in India and Setubal in Portugal are also affected by this same phenomenon. It can be concluded that urban sprawl is not just a phenomenon in the developed countries any longer; rather, it has also been recognised in various cities in developing countries.

The sprawl or the dispersed nature of Gauteng is also evident from the satellite images superimposed in Figure 35. The figure below shows the urban area in 1991, 2001 and 2009. Through yellow and red coloured regions, the outward expansion of Gauteng is quite evident.

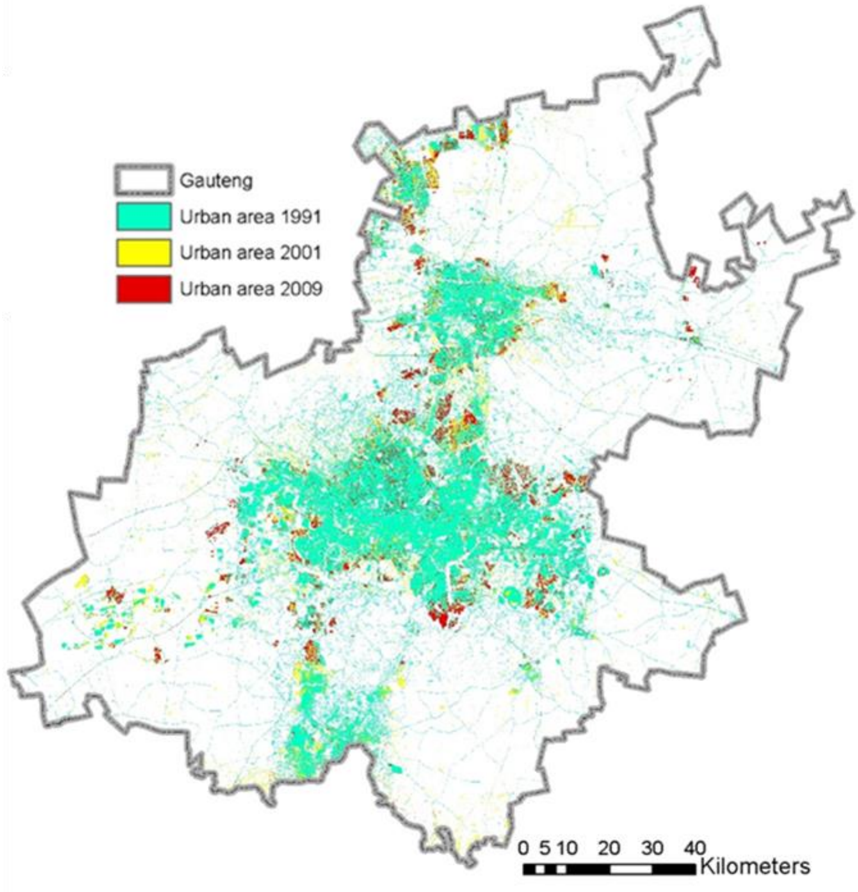

Figure 35: Expansion of the urban areas in Gauteng between 1991 and 2009 (own diagram)

4. Scenario analysis

Scenario analysis is a process of analysing possible future developments based upon various assumptions and possible outcomes. In this study, a simulation model was run to predict the future developments in Gauteng under various 'Spatial Development Framework' (SDF) policies. Besides understanding the urban development process, the scenario analysis helps in terms of understanding the behaviour of the energy system in the residential sector in Gauteng.

Before conducting the analysis, it is important to set the scale for the model. Many scales have been proposed to describe regions and at which level they function. Generally, two distinct sub-categories are considered: national or state regions, and sub-state or zonal regions (Lombaerde, 2010). In this study, the scenario analysis is conducted at the macro-geographical and micro-geographical level. Macro-geography is an approach to human geography that examines large-scale patterns in the spatial distribution of observed phenomena, e.g. regions within the provincial or municipality boundary. For the macro-geographical scenario analysis, Gauteng is divided into twelve zones based upon the administrative boundaries of the municipalities (see Figure 36), as most of the socio-economic data is available at this level. By contrast, micro-geography involves or is concerned with strict geographic localisation, i.e. detailed empirical geographical study on a small scale of a specific locale, e.g. zones or parcels in a region. For the micro-geographical scenario analysis, a grid of cells was chosen (see Figure 37).

Macro-geographical analysis traces the outcomes of an interaction - such as economic interactions - over a large group of the population, e.g. Johannesburg or Tshwane. Moreover, the framework data such as socio-economic parameters (e.g. population, GDP, employment, etc.) or technology/policy-related parameters (e.g. share of renewable energy, urban development policies) cannot be directly applied to the cells at the micro-geographical level due to its miniature cell size; hence, a scenario analysis at the macro-geographical level is necessary. It helps in terms of understanding the demographical and the economic interactions in the region.

Figure 36: Gauteng divided into municipalities (for macro-geographical model)

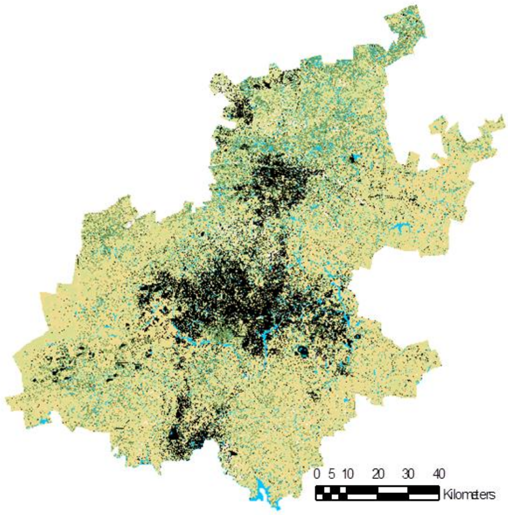

Figure 37: Gauteng represented as a grid of cells (for micro-geographical model)

In the micro-geographical analysis, the model results are highly dependent on the resolution of the available imagery. Optimum cell size varies from region to region and from study to study. The smaller the cell size, the greater will be the resolution and accuracy although it will require more processing time and more space for the database storage. The cell size in the micro-geographical analysis is kept the same as the cell size (30 x 30 m) in the GeoTerra images to preserve the data structure. Although such a finer resolution for an area of 18,170 km² results in higher costs in terms of disk space, processing speed and simulation time, changing the cell size (from finer to coarser scale) will result in a loss of data structure, as the larger cells will contain more than one attribute value from the fine-scale data.

4.1. Macro-geographical scenario analysis

The scenario analysis at the macro-geographical level is conducted to assess the impact of various economic, ecological, political and technical parameters on the future development in Gauteng. The administrative boundary of Gauteng is considered as the borderline for this scenario analysis. In the entropy calculations in the previous chapter, it was established that Gauteng is affected by urban sprawl; hence, two scenarios 'business as usual' (BAU) (upper bound scenario) and 'planned urban growth' (lower bound scenario) developed for this study consider sprawling and constrained urban growth, respectively.

Business As Usual (BAU) scenario:

The BAU scenario is the reference scenario, based upon the assumption that there will be no significant change in people's attitudes and priorities (e.g. choice of energy carrier) or no major changes in technology, economics or policies, whereby existing developments are expected to continue. The existing policies along with likely-to-be-implemented policies in the future are included in this scenario. The BAU scenario for Gauteng aims to illustrate possible future urban developments in Gauteng under the current special development framework without major changes or developments. The scenario can be seen as the upper bound scenario as is takes fast growing dispersed spatial structure into considerations.

This scenario is not seen as a prediction of the future, but rather a simulation of how the system would develop until 2040 if the developments continued from the past without major changes. It is a projection of the future energy system, which does not include policies to reduce energy consumption or GHG emissions. Moreover, it does not include increased penetration of new technologies or renewables. The BAU scenario results are presented in the section 4.6.1.

'Planned urban growth' (PUG) scenario:

If Gauteng's urban development continues to grow at the current rate, the region will continue to grow outwards (sprawl), adversely affecting infrastructure, basic utilities, energy consumption and the provision of cost-effective public transport. To avoid further dispersed development and to achieve a more compact urban form, the PUG scenario was developed, in which the outward expansion of the region is restricted. Due to the construction constraints considered in this scenario, it is a lower bound scenario. Based upon the data published by GDARD in 2011, the urban boundary[23] (explained late in Geographical factors) of Gauteng is taken as a boundary condition for this scenario. Future developments in Gauteng are considered to take place within this boundary. When all the empty and available areas (suitable for built-up category) are used, only then outward expansion is allowed in the model.

In comparison with the BAU scenario, the PUG scenario considers that several plausible mitigation measures (based upon Gauteng Integrated Energy Strategy) will be implemented in the future (DLGH, 2010). Higher penetration of solar water heaters, increase in energy efficiency – in both, technologies and buildings - and a higher share of renewable energies are the main distinguishing factors considered in this scenario. The PUG scenario results are presented in section 4.6.2.

[23] Urban boundary: Boundary of Gauteng's existing built-up area.

4.2. Key assumptions for the two scenarios

The key modelling assumptions applied to both scenarios are described below. These assumptions are grouped under three topics, namely as socio-economic, geographical and technology-related parameters. Most of the data used for the residential sector comes from the national statistics 2001 & 2011 (Stats SA, 2002; Stats SA 2012) and community survey 2007 (Stats SA, 2008). This data is further supplemented with the information from local institutions, research organisations (e.g. CSIR[24]), government departments and EnerKey[25] data (EnerKey, 2010; EnerKey, 2013).

4.2.1. Socio-economic factors

General assumptions based upon socio-economic factors applied to both scenarios are explained below. The socio-economic parameters are kept the same for both scenarios:

a. **Population growth:** The projected population growth until 2040 was calculated based upon various factors such as birth rate, fertility rate[26] mortality rate and life expectancy[27]. Gauteng had a fertility rate of 2.8 in 2001. Due to various social issues (e.g. crime, migration) and alarming rates of HIV, the fertility rate is expected to reduce to 2.4 by 2040. The life expectancy factor is the same as for South Africa, 59.5 years for males and 67.8 years for females.

   As seen in Figure 38, Gauteng will have a total population of 19.1 million in 2040. There have been various studies and forecasts projecting Gauteng's population. Landau and Gindrey (2008) developed three different scenarios that predict a population projection between 19 (low growth) to 21 million (high growth) by 2040. The projected population in this study is in line with the low growth scenario suggested by Landau and Gindrey (2008). The aforementioned calculations for the population development were conducted with the help of 'Spectrum 4' software[28] (see Appendix M).

[24] CSIR: Council for Science and Industrial Research based in Pretoria, South Africa.
[25] EnerKey project: A German-South African collaboration project which aimed at finding sustainable solutions for Gauteng region in South Africa. More information available at: http://www.enerkey.info/
[26] Fertility rate is the average number of children that would be born alive to a woman during her lifetime if she were to pass through all her childbearing years confirming to the age-specific fertility rates of a given year.
[27] Life expectancy is the average number of years a new-born can expect to live based on the mortality conditions at the time.
[28] Spectrum 4 is a freeware used for calculating the population projection. It consists of several sub-models including DemProj (demography), FamPlan, LiST, AIM and GOALS. It is developed by the Futures institute in the USA and can be downloaded for free at: http://www.futuresinstitute.org/software.aspx

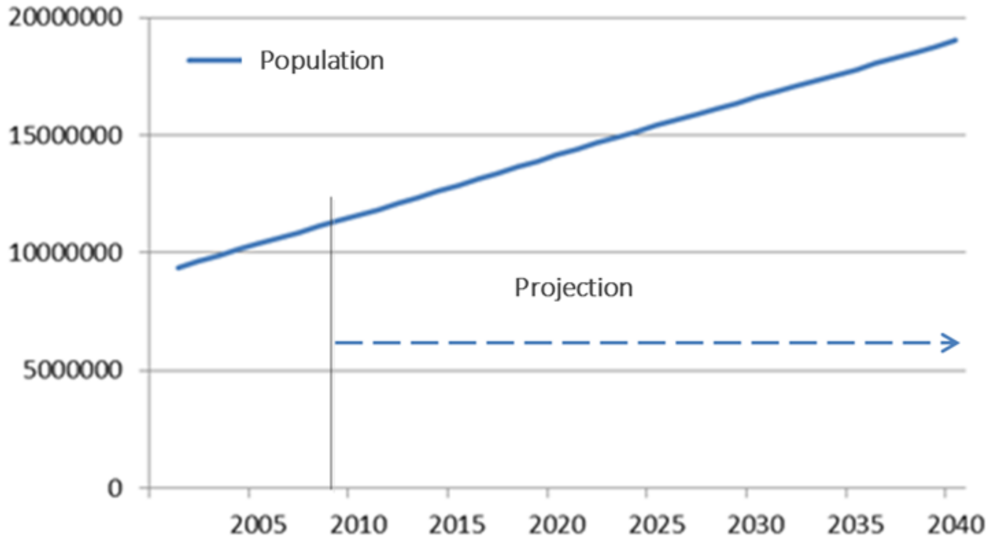

Figure 38: Population development in Gauteng between 2001 and 2040 (own calculations)

b. GDP growth: Being the economic powerhouse of South Africa, Gauteng plays a major role in the South African economy, producing more than one-third of the country's GDP. The economic growth in the province has been quite volatile in the past. In the last eight years prior to the economic crisis in 2009, it was 4.6%. Economic growth patterns of Gauteng and South Africa are generally comparable and aligned (see Figure 11). Most of the time, the economic growth in Gauteng has been slightly higher than in South Africa (except in 2001).

On this basis, long-term economic outlooks for South Africa can be used to determine the margin in which economic growth is expected to happen until 2040 in Gauteng. The GDP development until 2040 is shown in Table 10. The historical economic growth is expected to continue until 2009. In the short term – namely, until 2014 – the forecast of PERO (2009) will be met, whereas economic growth until 2020 will remain at the level of 4.6%. After 2020, the annual growth rate will slowly decrease with an average of 4.3% for 2021-2030 and a 4% average from 2031-2040. Although the GDP rates seem higher than international scenario forecasts (BMI, 2009), the scenario assumptions considered here are rather optimistic (see Appendix N for detailed information on the GDP development).

Table 10: Scenario assumptions for GDP (own calculations, Wehnert et al, 2011)

Timeframe	Assumptions for Scenarios
up to 2009	4.6% Historical data
2009 – 2014	4.5% (Short-term outlook according to PERO 2009)
2015–- 2020	4.6 %
2021 – 2030	4.3 %
2031 – 2040	4 %

c. **Income groups & energy consumption**: Besides the high poverty levels, income disparity is extremely high in South Africa. South Africa is among the countries with the highest Gini-coefficient in the world. Surprisingly, the income disparity has even increased in post-Apartheid South Africa. According to a study, the Gini-coefficient rose by 0.04 between 1993 and 2009 (Leibrandt et al, 2010). As the income status of a household influences its energy consumption, it is important to understand and study the income group distribution in Gauteng. Based upon the community survey (Stats SA, 2008) and study conducted by Hector et al (2009), Table 3 shows the income distribution in Gauteng in 2007. Merely 12% of the population in Gauteng belongs to the high-income group. Around 67% of the population in Gauteng earns less than 6400 ZAR (640 €) per month. The mid-income group counts for around one-fifth of the population.

Social and income equity is one of the key factors to achieve poverty alleviation in Gauteng. It is assumed that in the first decade (until 2020) no significant changes will take place and the historic development of the income groups will continue (Figure 39). There is a small share of households shifting from the poor to low-income group, which is achieved by government programmes. Between 2020 and 2040, a major shift from low-income to mid- and high-income is expected. The mid-income group will remain relatively constant and the high-income group will double in size by 2040. This will have a visible impact on the total energy demand from the residential sector in Gauteng as the mid- and the high-income group have relatively high energy demand.

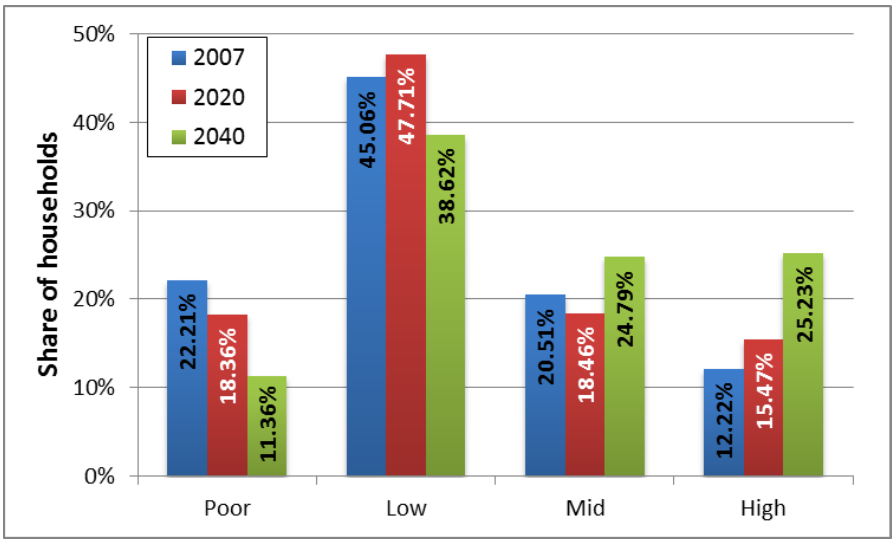

Figure 39: Development of income groups between 2007 and 2040 (Wehnert et al, 2011; own calculations)

The future development of different socio-economic parameters considered in the scenario analysis is depicted in Table 11. The table shows the development of population, households, GDP and the number of jobs available for both scenarios. Population, household size and the number of jobs available will almost double in size, whereas GDP will experience an almost fourfold increase by 2040.

Table 11: Future development of socio-economic parameters (2007-2040)

Parameter	Year	BAU & Planned urban growth
Population(M)	2007	10.5
	2010	11.3
	2020	14.1
	2030	16.6
	2040	19.1
Households (M)	2007	3.2
	2010	3.5
	2020	4.6
	2030	5.6
	2040	6.8
GDP (Bn. Rand)	2007	681
	2010	734
	2020	1134
	2030	1723
	2040	2550
Employment (M)	2007	3.9
	2010	3.7
	2020	4.8
	2030	6
	2040	7.2

4.2.2. Geographical factors

The geographical factors considered in this study include factors that are directly associated with the geography, such as protected areas or urban boundary. These factors do not change during the model simulation period. Hence, they can be used as constraint parameters for the simulation. These geographical factors are described below in detail:

a. **Protected areas:** The local Gauteng Department of Agriculture and Rural Development (GDARD) first introduced the 'conservation plan' (popularly known as the C-plan) for the Gauteng region in 2000. Since then, the C-plan has been revised on several occasions, with the latest C-plan (version 3.3) released in October 2011. Among others, it included areas under protection, bioclimatic zones and land cover for the year 2009. One of the main purposes of the C-plan is to serve as a basis for the development of bioregional plans in municipalities within the province. This C-plan was used as the guideline for conservation/protection areas considered in the micro-geographical modelling for both scenarios. Figure 40 shows the conservation areas, which include wetlands, reserved areas, irreplaceable areas and important areas considered for the modelling. Any encroachment (for built-up purposes) in these areas is prohibited in the simulation model.

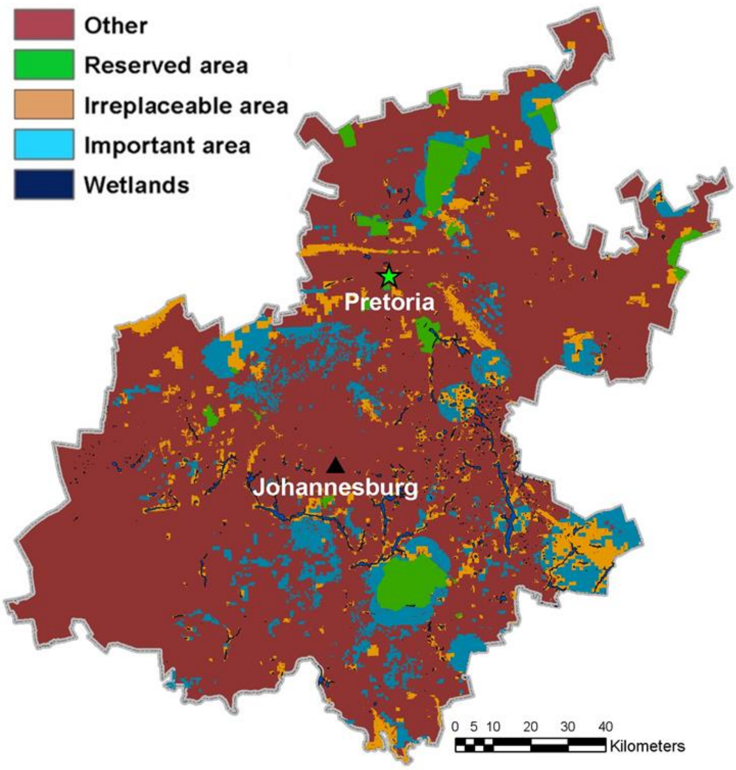

Figure 40: Conservation areas in Gauteng (Own diagram based upon data from C-Plan 3.3)

b. **Spatial development framework:** The political and legal framework in Gauteng has been described in detail in the previous section 2.3. Various policies mentioned in the spatial development framework are integrated into the simulation model. Moreover, it is also envisaged that in 'planned urban growth', stricter laws and regulations against deforestation will be enforced.

c. **Urban boundary:** The urban boundary (also known as 'Urban edge') is the boundary of Gauteng's urban area (built-up area) in 2009 (GDARD, 2011). Figure 41 illustrates the urban boundary sub-categorised as 'inside edge', i.e. within the urban boundary in 2009 and 'additional approved', i.e. areas additionally approved in 2009 for further urban development. This parameter is taken as a 'constraint factor' for the PUG scenario. In this scenario it is considered that the urban development will take place only within the urban boundary till no more suitable area is left within the boundary, only then the urban areas can spread outside this boundary. By constraining the future developments within this boundary, the existing brownfield and infill areas can be utilised efficiently without outward expansion of the region. Examples of brownfield areas in Gauteng include abandoned city centres and closed mining sites.

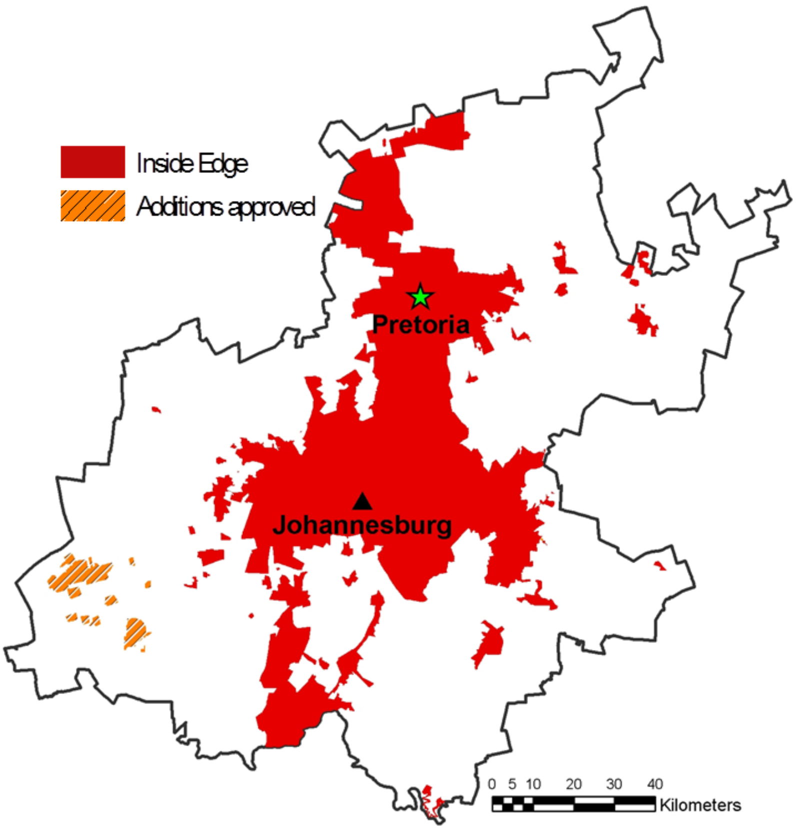

Figure 41: Gauteng's urban boundary in 2009 (GDARD, 2011)

4.2.3. Technology related factors

As the community survey conducted in 2007 provides the initial distribution of the energy carriers in Gauteng (Stats SA, 2008), 2007 was chosen as the base year for the energy demand calculations. Additional data such as main energy carriers was extracted from the 'Income and Expenditure Survey' (2005) to supplement the community survey data. Missing data, such as data on water heating was gathered from the literature. The future demand was projected based upon the literature studies, expert interviews and stakeholder workshops conducted within the project EnerKey.

Various technologies used in the residential sector - along with their relevance to income groups - are described in this section. In Gauteng, technologies used for various purposes (cooking, lighting, space heating, water heating) are strongly influenced by the economic status of the household. The technologies used differ in energy carrier, efficiency, availability, investment costs, durability (lifetime of an appliance) and emissions. The energy carrier or share of different energy carriers used to fulfil various needs (such as cooking, lighting, etc.) is also influenced by the financial status of the household. The high-income group usually use electricity to satisfy most of their energy needs, whereas households belonging to poor and low-income group need at least 2 -3 different energy carriers to fulfil their energy needs, depending on the availability of money and energy carriers (e.g. electricity, paraffin and wood) (Stats SA, 2008).

Technologies used in both scenarios - together with their efficiencies and their future share in the energy mix - are described in detail in Appendix L. Compared to the BAU scenario, the PUG scenario, considers higher share and higher penetration of efficient appliances, along with a higher share of renewable energy (e.g. solar energy) in the future energy mix compared to 2007.

Besides restricting urban sprawl, the PUG scenario also includes a higher share of houses constructed based upon the South African National Standard (SANS) norm (see Table 64). According to these norms, the newly built houses are passive houses, which are equipped with solar water heaters. The following section enlists various technologies considered in these two scenarios.

Figure 42 shows the average share of various households' demands in the final energy consumption. Energy consumption for water heating has the highest share of 42%, followed by cooking and space heating with 19% and 18 %, respectively. On average, a household in Gauteng spends 14% of its final energy on appliances and merely 7% on the lighting. The largest end-use category will have more potential of energy saving. The technologies to fulfil the largest part of end-use, water heating, therefore, offer the highest saving potential. Increasing the efficiency of the existing water heating technologies (e.g. electric geyser with a blanket) and introducing alternative technologies such as solar water heaters will help in reducing total energy consumption in the residential sector.

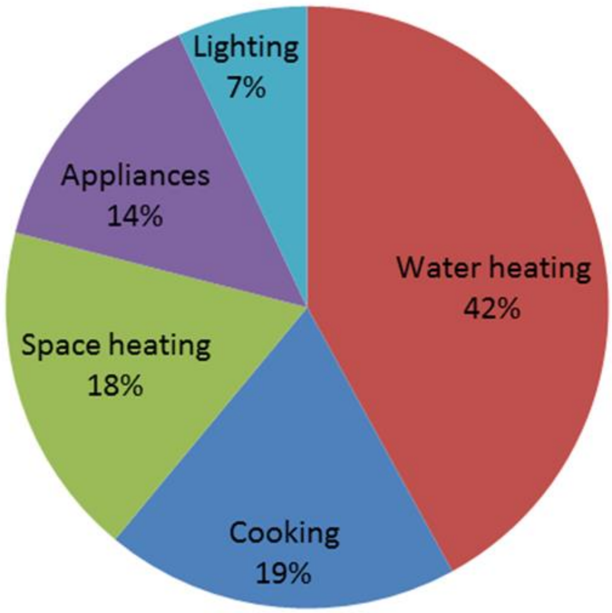

Figure 42: Share of energy consumption by end use in the residential sector in Gauteng (2007) (Stats SA, 2008, EnerKey, 2010)

<u>**Water heating technologies**</u>

In the residential sector, the highest share of energy is used to fulfil the hot water demand, especially in the high and mid income groups. The technologies investigated not only include currently available/used technologies (e.g. paraffin stove) but also technologies that might be used in the future in the Gauteng region.

The technology used for water heating depends on the income of the household. In 2007, the electric geyser was the most commonly used technology among high- (83.9%) and mid-income (77.9%) households. In low-income households, paraffin stove was the most used technology (24.46%), together with electric hot plates (24.46%). The dominating technology in poor households was the electric kettle. These households heat smaller quantities of water (up to 100° C) and mix it with cold water, using lesser electricity than the electric geyser as only a small amount of water is heated. Paraffin stove was the second most commonly used technology in the poor households.

Table 12 shows the various water heating technologies used across four income groups along with their efficiencies and share. Electric kettle, SWH (flat plate and evacuated tube) are the most efficient technologies, followed by LPG and natural gas heaters. Coal and wood stoves are the bottom two technologies with very low efficiency, at 40 % and 25 %, respectively. The table also shows the relevance of each technology to the income groups. The technologies that need high investment costs such as flat plate solar water heaters are only relevant to the high or mid income groups, as they are proven cost-effective (also lesser emissions) than the electric geyser or the paraffin stove (Oezdemir et al, 2012). The natural gas (NG) geyser is an upcoming technology in Gauteng as the pipeline network is only available in Johannesburg, although it is expected that this technology will have higher penetration in the future.

Table 12: Efficiency and share of water heating technologies in Gauteng, 2007 (own calculations based on Stats SA, 2008; EnerKey, 2010)

Technology	Efficiency	Poor	Low	Mid	High
Electric geyser	0.70	6.13%	24.19%	77.92%	83.91%
Electric kettle	1.00	39.50%	23.70%	-	-
Electric hot plate	0.65	20.39%	24.46%	-	-
SWH (flat plate)	*0.60*[29]*	-	-	2.14%	4.34%
SWH (Evacuated tube)	*0.60**	-	0.80%	-	-
LPG water heater	0.88	0.87%	0.87%	12.97%	9.18%
NG water heater	0.88	-	-	6.98%	2.57%
Paraffin heater	0.55	26.57%	24.46%	-	-
Coal stove	0.40	3.40%	0.99%	-	-
Wood stove	0.25	3.20%	0.55%	-	-

* This defines the conversion rate or conversion efficiency between heated water and electricity used in solar water heaters (EnerKey, 2013; Oezdemir et al, 2012, Tomaschek et al, 2012)

The market penetration[30] of the above-mentioned technologies depends on various factors such as preferability, comfort, price, availability and - most importantly - affordability. To calculate the possible share of electric technologies, the electrification rate of the high, mid, low and poor households is important. The development of the electrification rate for four

[29] The efficiencies for SWHs set into the model are 175% for flat plates and 190% for evacuated tubes, because they describe the conversion rate or conversion efficiency between heated water and electricity used in the solar water heaters. This efficiency therefore considers the electricity savings using a solar water heater, where solar energy is mainly used. Electricity is just used for electric backup.

[30] Market penetration: It is defined as the number of people who buy a specific brand or a category of goods at least once in a given period, divided by the size of the relevant market population. It is a measure of brand popularity.

income groups is illustrated in Figure 43. The high-income group is expected to reach a 100% electrification rate in 2015. It is estimated that the mid-income group will reach 99% electrification by 2030. The Gauteng government has to engage significant effort to increase the electrification rate in the poor and low-income households from 72% and 80% (2007) to around 90% in 2040. The 'technology ranges[31]' used for other technologies can be found in Appendix L. Furthermore, the share of water heating technologies used for scenario calculations till 2040 is presented in Table 65 to Table 68 for four income groups. For the share of each technology, an upper and a lower range (bound) were fixed. The final share of each technology per income group used in scenario calculations was derived from TIMES-GEECO model, an optimisation model which was developed for Gauteng (EnerKey, 2013).

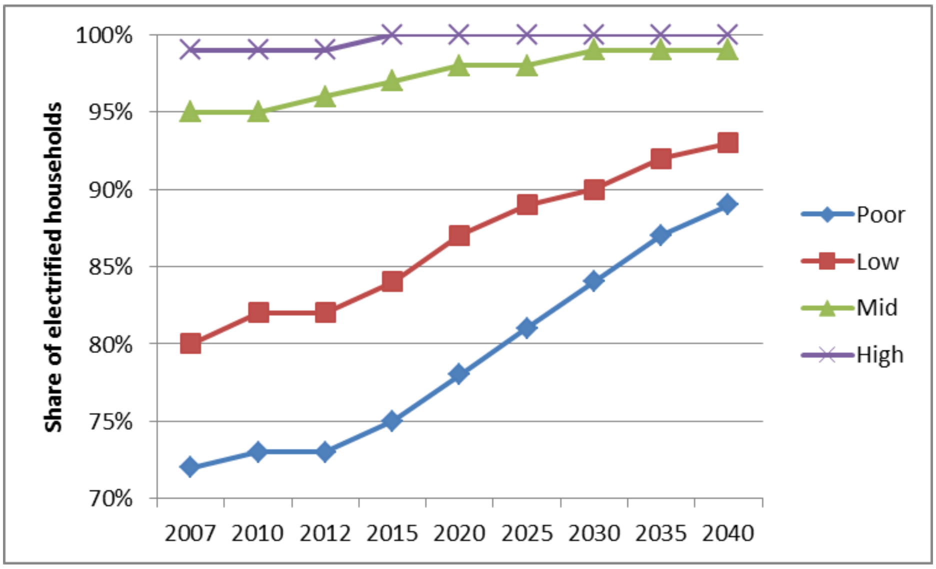

Figure 43: Electrification rate of households in Gauteng, 2007-40 (own calculations based upon Stats SA, 2008 and Stats SA, 2012)

Table 13 shows the SWH penetration for various income groups and both scenarios. In the BAU scenario, the solar water heaters will reach a penetration rate of only 25% in the poor and low-income group and the other two groups will have 50% penetration. In the PUG scenario, a little higher penetration of solar water heater is envisaged, namely, 30% for the poor and low income and 80% for the mid and high-income groups. The assumption considers the installation of solar water heaters in newly built and old houses.

[31] In the TIMES model, technology range is used to define the upper and lower limit range for each technology, within which a technology is expected to grow/reduce in the future. The upper limit makes sure that there is no rapid increase or dominance of one technology in the future, the lower limit on the other hand assures that some technologies don't vanish as they are relevant to that society due to cultural and/or economic reasons.

Table 13: SWH penetration rates in Gauteng (own assumptions; SEA 2009; DLGH 2010)

Income Group	Scenario	2007	2010	2015	2020	2025	2030	2035	2040
Poor and Low-income	BAU	0%	0%	0%	5%	10%	15%	20%	25%
	Planned urban growth	0%	0%	15%	20%	25%	30%	35%	50%
Mid and High-income	BAU	0%	0%	0%	5%	10%	15%	20%	30%
	Planned urban growth	0%	0%	20%	30%	40%	50%	60%	80%

Space heating technologies

Space heating in Gauteng had the third highest share in energy consumption in the residential sector in 2007 (see Figure 42). Table 14 shows various space heating technologies with their share in four income groups and efficiencies in 2007. All other technologies besides paraffin heater, coal stove and wood stove have an efficiency of one. Wood and coal stove are usually not used directly for space heating, although the heat produced during cooking or water heating is used to keep the room warm. The electric oil-filled radiator is the most used technology in the mid- and high-income households. Additionally, most of the poor and low-income households use the electric infrared heater.

Table 14: Efficiency and share of the space heating technologies in Gauteng, 2007 (own calculations based upon Stats SA, 2008; EnerKey, 2010)

Technology	Efficiency	Poor	Low	Mid	High
Electric infrared heater	1.00	65.75%	59.92%	4.57%	4.58%
Electric forced convection heater	1.00	-	11.53%	4.57%	4.58%
Electric oil filled radiator	1.00	-	-	82.23%	82.36%
Radiant liquefied petroleum gas heater	1.00	0.62%	0.76%	1.40%	2.06%
Radiant natural gas heater	1.00	-	-	3.74%	3.23%
Paraffin heater	0.55	20.41%	15.96%	3.49%	3.19%
Coal stove	0.40	8.12%	8.02%	-	-
Wood stove	0.25	5.10%	3.81%	-	-

The share of space heating technologies till 2040 can be found in Table 69 to Table 72 for four income groups. The technology ranges were used to calculate the future demands of various technologies and can be found in Appendix L. The LPG and natural gas space heaters are assumed to be relevant mainly for the mid and high-income groups. The LPG heater share is restricted to an upper limit of 15% for the high-income group and 16% for the mid-income group (Figure 111). The paraffin heater, coal stove and wood stove will still play a considerable role in space heating in the poor and low-income households. Their technology ranges are illustrated in Appendix L (Figure 110 and Figure 112).

Lighting technologies

The lighting technologies include indoor and outdoor lighting. Outdoor lighting is used predominantly in the mid and high-income households for security reasons. Incandescent bulbs are widely used in all income groups, as demonstrated in Table 15, followed by candles and paraffin pressure lamps. The paraffin wick lamp is used only in the poor and low-income households. Other technologies enlisted in Table 15, such as compact fluorescent lamps (CFL) and light-emitting diode (LED) has a negligible share in Gauteng in 2007, although in the scenario analysis the high and mid income groups are expected to change from incandescent bulbs to CFL or LED in the future. The future share of technologies till 2040 for different income groups is illustrated in Table 73 to Table 76. Moreover, the technology ranges for incandescent bulbs, CFLs and LEDs are elaborated in Appendix L (Figure 116 and Figure 117). The poor and low-income groups are expected to have an increased share of electric lighting as the share of electrified houses increases substantially by 2040 (Figure 43 and Figure 115). Paraffin lighting is expected to reduce by 2040, with an upper bound of 10% and lower bound of 1.3% (Figure 118).

Table 15: Efficiency and share of lighting technologies in Gauteng, 2007 (own calculations based on Stats SA, 2008; EnerKey, 2010)

Technology	Luminous efficacy (lm/W)	Poor	Low	Mid	High
Incandescent bulb	1.00	73.48%	79.47%	95.28%	95.46%
Compact fluorescent lamp	5.45	-	-	-	-
Fluorescent lamp	2.86	-	-	-	-
Light emitting diode (LED)	10.00	-	-	-	-
Candle	0.80	17.71%	13.59%	2.79%	2.64%
Paraffin pressure	0.58	8.06%	6.22%	1.93%	1.89%
Paraffin wick	0.06	0.75%	0.72%	-	-

Cooking technologies

Energy demand for cooking is one of the basic needs that every household need to fulfil. Energy carriers used for cooking are strongly influenced by income, as well as cultural influences. This is one of the reasons why the penetration of electric stoves is not very high. Table 16 shows different cooking technologies, their efficiencies and share for the four income groups in Gauteng in 2007. The technology used and its efficiency affects the total energy demand. The electric induction stove has the highest efficiency (0.84) compared to the other high-end cooking technologies such as electric stove (0.65), electric hot plate (0.65), LPG stove (0.53) and natural gas stove (0.53). Remaining low-end technologies such as paraffin stove (0.50), coal stove (0.40) and wood stove (0.25) have very low efficiencies and hence need more fuel to fulfil the same energy demand as compared to other technologies with higher efficiencies. Moreover, the share of these technologies which was used for scenario calculations till 2040 can be found in Appendix L (Table 77 - Table 80) for four income groups.

Table 16: Efficiency and share of the technologies used for cooking in Gauteng, 2007 (own calculations based on Stats SA, 2008; EnerKey, 2010)

Technology	Efficiency	Poor	Low	Mid	High
Electric stove and oven	0.65	-	6.32%	94.59%	92.33%
Electric induction stove and oven	0.84	-	-	-	1.89%
Electric hot plate	0.65	70.62%	70.63%	-	-
LPG stove and oven	0.53	0.87%	0.89%	0.82%	1.42%
NG stove and oven	0.53	-	-	0.42%	0.38%
Paraffin cooker	0.42	26.57%	20.62%	4.17%	3.99%
Coal brazier	0.08	0.48%	0.50%	-	-
Coal basintuthu stove	0.10	0.43%	0.50%	-	-
Wood stove	0.08	1.03%	0.55%	-	-

The usage of electric appliances for cooking is determined by the electrification level in each income group. The share of electricity-based appliances such as electric stove, electric induction stove and the electric hot plate is considered parallel to the electrification level (Figure 43). Gas stoves (LPG and natural gas) will also have a substantial share in future energy demand as the South African government has decided to switch to gas in the future (DME, 2005) to reduce electricity demand and increase gas consumption.

Based upon the above-mentioned parameters, the macro-geographical analysis was conducted. The results are presented later in section 4.6.

4.3. Micro-geographical scenario analysis

The cellular automata (CA)-based simulation model 'Dinamica' (see 3.1.8) was used for the micro-geographical scenario analysis. The CA model for Gauteng was simulated for the BAU and the PUG scenario. Under the 'BAU' scenario, the outward dispersed development of Gauteng will continue in the future without any spatial constraints. The PUG scenario evaluates the future spatial patterns of Gauteng under strict spatial development regulations. The future developments are allowed to take place within Gauteng's existing urban boundary (illustrated in Figure 41). An outward urban development can only take place when the currently available area within this boundary has been fully utilised (i.e.

encouraging infill and brownfield development). Different parameters used for both scenarios (see Table 17) along with various model constraints are described in detail in the following section.

Table 17: Parameters used for the micro-geographical analysis in the simulation model

Parameter	Unit	Remarks
Proximity to main roads	5 km	see Figure 90
Proximity to railways	2 km	see Figure 91
Proximity to existing settlements	10 km	see Figure 92
Proximity to jobs	10 km	see Figure 93
Conservation/Protected areas	No encroachment	see Figure 94
Slope	≤ 10%	see Figure 95
Urban boundary	-	see Figure 41

An overview of all the parameters considered for the micro-geographical analysis and the buffer used for each parameter are summarised in Table 17. The parameters chosen for the micro-geographical analysis are those factors that affect the movement of people in a region and their decision to choose a new location of residence. Hence, these parameters also influence the location of a new settlement in the region. Infrastructure plays a major role in the planning of new settlements/industrial and/or commercial areas, among others. No settlements can be planned without an easy access to existing roads or railways. People usually buy/rent houses near main roads (freeways) or railway stations due to convenience. A smaller buffer is used for railways (2 km) than roads (5 km) as people are expected to walk to the railway station from their home.

There is a higher chance of developing a new settlement near an existing settlement; hence, a buffer of 10 km around existing settlements is considered for the analysis. Another factor that affects the location choice is opportunity or availability of employment in the vicinity. Accordingly, a buffer of 10 km around the area with job opportunity is considered for the analysis. The area under buffer is the area that is the most favourable area for the future development of settlements. The main difference between BAU and the PUG scenario is spatial restriction through 'urban boundary' and strict law enforcement against encroachment into protected areas. In the PUG scenario, encroachment into the existing protected areas (Figure 40) is prohibited (GDARD, 2011). Developing/constructing a new settlement/urban areas in an area with steep slopes is rather avoided due to higher costs involved to level the ground; thus, a slope of less than 10 % was chosen for this study.

The simulation model receives the data in raster format, i.e. in GeoTIFF[32] format. For all the parameters, a stepped buffer of 1 km, 2 km, 5 km and 10 km is used (see Appendix B), whereby the smaller the distance, the higher the possibility of developing a new settlement. In the simulation model, this concept is used under the term ‘friction surface’. The closest areas (i.e. within 1 km buffer) have a friction value of 1 as these are the most favoured areas. The friction value increases with distance, whereby a friction value of 10,000 denotes a barrier for a new settlement, i.e. it is virtually impossible to develop a new settlement. For example, to construct a new road through a river is impossible without constructing a bridge, hence; the area with river will have the highest friction factor.

The simulation model: Dinamica

The main objective of the land use modelling was to run, calibrate and validate a model which will simulate the future urban growth in Gauteng. The simulation model used for this study is called ‘Dinamica’. The main input in the Dinamica is the historical land use maps (1991 and 2001). Furthermore, as an input, the model receives a series of spatial variables (see Table 17, Figure 44) as a rastercube[33]. Figure 44 shows the sub-model used in Dinamica for calculating the rastercube. The input maps for the Gauteng simulation model include parameters listed in Table 17.

[32] Geotiff is a public domain metadata standard which allows geo-referencing information to be embedded within a TIFF file.

[33] Rastercube: It is a form defined by the Dinamica model, in which various raster images of different static variables are fed into the model.

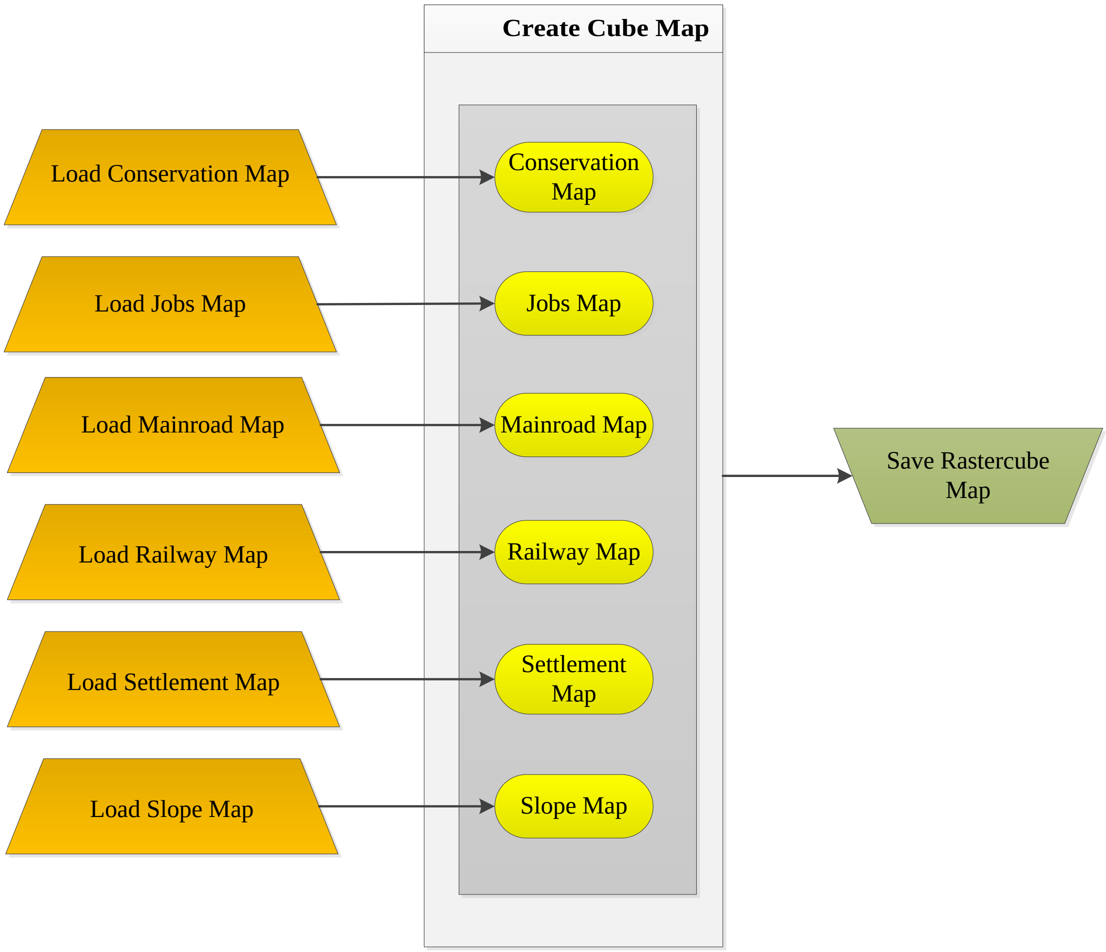

Figure 44: GIS-based sub-model for calculating the rastercube map

Dinamica supports only raster datasets/maps. All maps fed to the 'Create Cube Map' (see Figure 44) must have the same projection, registration-coordinates and the same number of lines and columns (exact same grid). Dinamica can read and write raster data in three formats: ER Mapper, GeoTIFF and ArcView ASCII. With the help of GIS, all maps for Gauteng were converted to the same cell type[34].

The 'Dinamica' model (simulation model) runs through eight steps (8 sub-models) to simulate the future land use maps for Gauteng, as presented in Figure 45. Each step is represented as a separate sub-model and is elaborated in detail in the following section.

[34] Cell types supported by Dinamica: 1 Bit integer [0,1], Signed 8 Bit Integer [-128, 127], Unsigned 8 Bit Integer [0, 255], Signed 16 Bit Integer [-32768, 32767], Unsigned 16 Bit Integer [0, 65535], Signed 32 Bit Integer [-2147483648, 2417483647], Unsigned 32 Bit Integer [], IEEE 754 32 Bit Real [-34028235E38, 34028235E38]

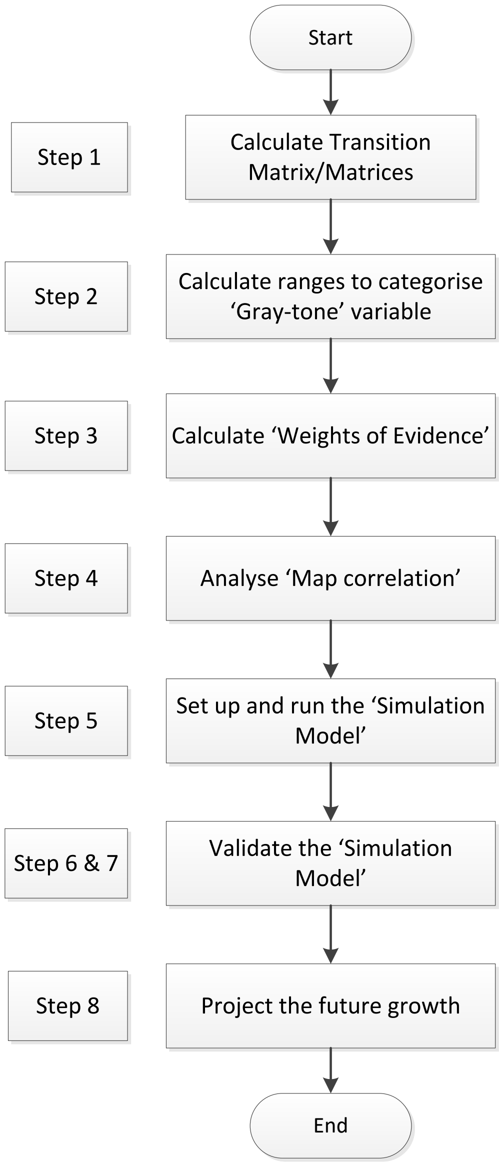

Figure 45: Flowchart of the land use change simulation model (Adapted from DinamicaEgo, 2013)

The simulation model uses the land use map for 1991 as the initial land use and the 2001 map as the final land use, whereby the simulated model results are validated against an image from 2009. All these maps are based upon land use categories shown in Table 6.

4.3.1. Step one: calculating transition matrices

Calculation of the transition matrix based upon historical land use maps (1991 and 2001) is the first step in the simulation process. The transition matrix defines a system that changes over discrete time increment. In transition matrix, the value of any variable in a given time period is the sum of fixed percentages of values of all variables in the previous time step. In transition matrix, its element in the i_{th} row and j_{th} column describes the probability of moving from state I to state j in one time step. The transition equation is shown in Equation 4.

$$\text{Transition rate } = \frac{\text{Transitions per category}}{\text{Total no. of cells per category}} \qquad \textbf{Equation 4}$$

Figure 46 illustrates the sub-model process for calculating transition matrices. Input data for the transition matrix are historical land use data for two different time periods. For Gauteng model, the historical data is taken for 1991 and 2001. Based upon this data, the model calculates two transition matrices, single-step matrix and multiple-step transition matrix. The single-step matrix denotes a time period represented as a single time step, i.e. for a model with initial land use for 1991 and final land use for 2001, the single-step matrix will consider these 10 years as a single time step. On the contrary, the multiple-step transition matrix corresponds to a time step specified by dividing the time period by a number of time steps; hence, for the Gauteng model, the time step will be one year. The transition rates set the net quantity of changes that will occur in a category (land use category) or the percentage of land that will change from one state to another. For detailed information on the transition matrix, see Appendix D.

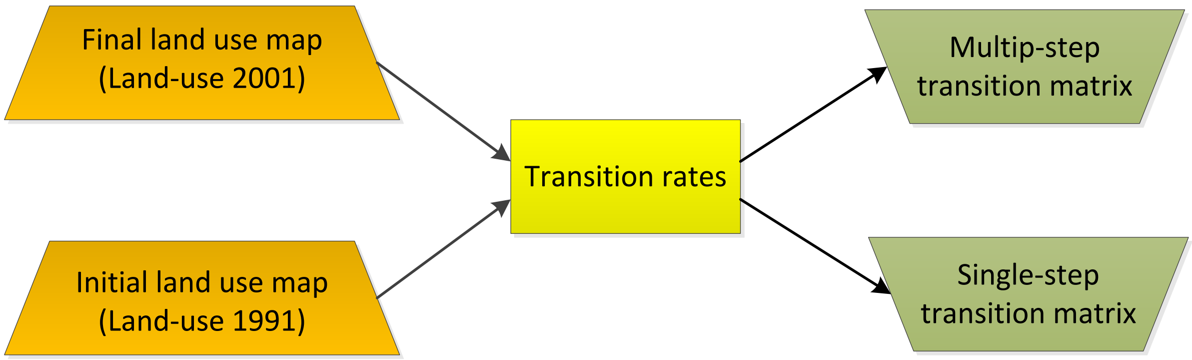

Figure 46: Sub-model 1 used for calculating the transition matrices for Gauteng

Results of sub-model 1:

Table 18 shows the number of cells and area (km²) available in each land use category at the beginning of the simulation model. The initial land use map for 1991 was used as the base year in the simulation model. Each cell is 30 x 30 m, with an area of 900 m² or 0.0009 km².

Table 18: Initial land use with six land use categories, 1991

Key	Category	Cells	Area (km²)
1	Open space	399,904	359.91
2	Water	989,524	890.57
3	Urban	2,608,068	2,347.26
4	Cultivated	6,841,357	6157.22
5	Grass	6,569,367	5,912.43
6	Forest	2,780,979	2,502.88

To calculate the transition matrix, the model first calculates the cell transition for each category which took place between 1991 and 2001. These transitions are shown in Table 19. Key 1 to 6 represents the land use categories (see Table 18). From 1 to 3 (1 → 3) means transition of land use category 1 to land use category in 3 over defined period (e.g. for the model, between 1991 and 2001). As seen in Table 19, 45,906 cells (41.32 km²) changed from category 1 (open space) to category 3 (urban/built-up area).

Table 19: Cells per transition in six land use categories (1991 – 2001)

		To (2001)					
		1	**2**	**3**	**4**	**5**	**6**
From (1991)	**1**	0	2798	45906	100126	106126	54746
	2	13666	0	23879	193241	254914	57319
	3	0	16	0	11	15	56
	4	131371	36928	175416	0	2297214	716599
	5	309917	41432	197702	2349123	0	557635
	6	77210	65666	213572	990286	1091605	0

Once these transitions are calculated, the model calculates the transition rates. Table 20 and Table 21 show the single-step and the multiple-step transition matrix respectively resulting from sub-model 1 (Figure 46).

The single-step matrix, shown in Table 20 is calculated based on an assumption that there is only one time step occurring between 1991 and 2001. The time step used for the Gauteng model is ten years, which means a sudden change in land use is expected.

Table 20: Single-step transition matrix for Gauteng (1991 – 2001)

		To					
		1	**2**	**3**	**4**	**5**	**6**
From	**1**	0	0.007	0.115	0.250	0.265	0.137
	2	0.014	0	0.024	0.195	0.258	0.058
	3	0	6.13E-06	0	4.22E-06	5.75E-06	2.15E-05
	4	0.019	0.005	0.026	0	0.336	0.105
	5	0.047	0.006	0.030	0.358	0	0.085
	6	0.028	0.024	0.077	0.356	0.393	0

The multiple-step matrix shown in Table 21 is calculated on an assumption that the time step is specified by dividing the time period by a number of time steps. For the Gauteng model, the time period is ten years, divided by 10 (number of time steps). Hence, the time step used for the model is one year, considering the gradual changes in land use.

Table 21: Multiple-step transition matrix for Gauteng (1991 – 2001)

		To					
		1	**2**	**3**	**4**	**5**	**6**
From	**1**	0	0	0.016	0.030	0.030	0.068
	2	8.59E-05	0	0.002	0.021	0.043	0.011
	3	0	7.19E-07	0	0	0	5.62E-06
	4	0.000	0	0.001	0	0.062	0.038
	5	0.014	0.001	0.002	0.077	0	0.015
	6	0.001	0.009	0.016	0.089	0.137	0

The simulation model (see Step five) was run for the single- and multiple-step matrices. The validation results showed that the multiple-step matrix predicts better results, as the gradual changes in land use categories are taken into account, which was the chosen for the simulation model. E.g. conversion of wetlands into urban areas happens gradually, if single-step matrix is considered, the conversion would appear to be a sudden change as the matrix takes only one step into account. The multiple-step matrix considers this conversion as a ten-year-step process and hence gives better results.

4.3.2. Step two: Calculating ranges to categorise continuous variables

The transition probability maps are produced based upon the 'Weights of Evidence' method (Agteberg and Bonham-Carter, 1990; Goodacre et al, 1993; Bonham-Carter, 1994). These transition probability maps illustrate the most favourable areas for change (Soares-Filho et al, 2002; Soares-Filho et al, 2004).

The 'Weights of Evidence' method comprises a Bayesian method, in which the effect of a spatial variable on a transition is calculated independently of a combined solution (Dinamica Ego, 2013). The 'Weights of Evidence' represents each variable's influence on the spatial probability of a transition *i* → *j*, calculated as shown in Equation 5 and Equation 6.

$$O\,\{D|B\} = \frac{P\,\{D|B\}}{P\,\{\bar{D}|B\}}$$ **Equation 5**

Equation 6

$$\log\{D|B\} = log\{D\} + W^{+}$$

Where, W^+ is the 'Weights of Evidence' of occurring event D, given a spatial pattern B. The spatial post-probability of a transition *i* → *j*, given a set of spatial data (B, C, D,…,N), is expressed as follows:

$$P\{i \Rightarrow j | B \cap C \cap D \dots \cap N\} = \frac{e^{\sum W_N^+}}{1 + e^{\sum W_N^+}}$$ **Equation 7**

Where B, C, D and N are the values of K spatial variables that are measured at location x, y and represented by its weights W^+_N.

Figure 47 shows how the calculation and application of 'Weights of Evidence' are undertaken to produce a transition probability map.

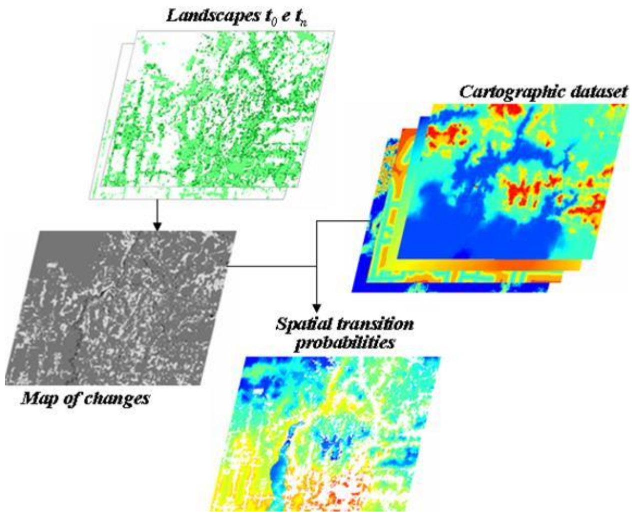

Figure 47: Calculation and application of 'Weights of Evidence' to produce a transition probability map (DinamicaEgo, 2013)

The simulation model receives different data (through rastercube) as an input. Few of these data are continuous data such as slope, rivers, roads and railway lines. As 'Weights of Evidence' can only be applied to categorical data, the aforementioned continuous data must be categorised before it is fed into the model. Figure 48 shows steps involved in calculating the ranges to categorise continuous maps. The model shown in Figure 48 calculates evidence ranges to categorise continuous variables. It selects the number of intervals and their buffer sizes to preserve the data structure. Along with the initial and final land use maps, the model is fed with a rastercube comprising various static maps as an input.

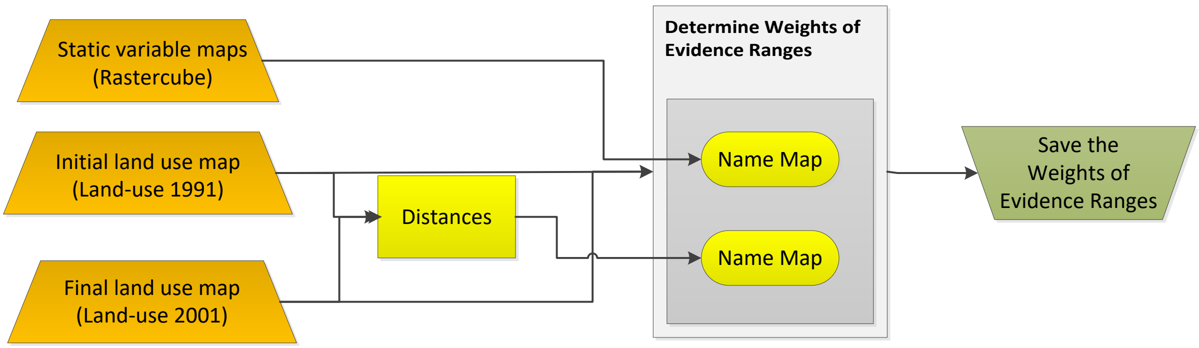

Figure 48: Sub-model 2 for calculating ranges to categorise continuous variables

Sub-model 2 results:

Table 22 shows the results of the categorisation of continuous variables. The first line depicts the ranges for each category (e.g. water/open/built-up, etc.) and the second line shows the transitions (1,3 means transition from category 1 to category 3, i.e. transition from open to built-up category) and their relative 'Weights of Evidence' coefficients (predicting the favourability for the occurrence of an event), which are set to zero in this step.

Table 22: Partial results of skeleton structure for the 'Weights of Evidence'

```
:distance/distance_to_3    0:60    60:90    90:120    120:150    150:210    210:330
330:3750
1,3   0   0   0   0   0   0   0
:static_var/Conservation   1:2   2:3   3:4   4:5   5:6
1,3   0   0   0   0   0
:static_var/Jobs   0:30
1,3   0
:static_var/Mainroad   0:30
1,3   0
:static_var/Railway   0:30
1,3   0
:static_var/Settlement   0:30
1,3   0
:static_var/Slope   0:2   2:3   3:17   17:18   18:92
1,3   0   0   0   0   0
```

4.3.3. Step three: Calculate 'Weights of Evidence'

The 'Weights of Evidence' method was originally developed for a non-spatial medical diagnosis, before being adapted for mineral potential mapping in Geology to predict the occurrence of the minerals in the late-1980s. In this study, it is used to spatially model land use change. The 'Weights of Evidence' method belongs to the group of methods used for multi-criteria decision-making. The 'Weights of Evidence' model (for combining evidence) involves an estimation of the response variable (land use change) and a set of predictor variables (distance to roads, railways, slope, etc.).

The sub-model shown in Figure 49 determines the 'Weights of Evidence' coefficients for selected spatial variables with respect to a transition or set of transitions.

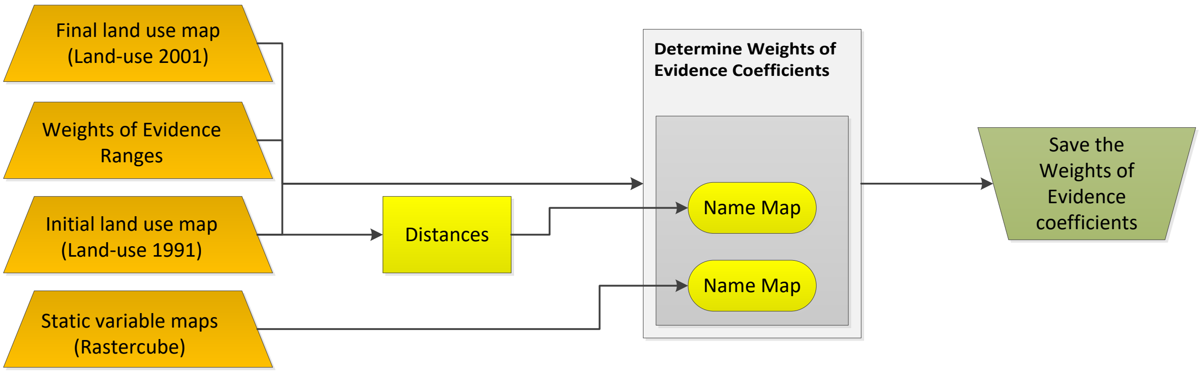

Figure 49: Sub-model 3 for calculating the 'Weights of Evidence' coefficients

Sub-model 3 results:

Table 23 shows the results obtained from the sub-model 3 illustrated above (see Figure 49). The table shows results for the transition 1 → 2 and variable: distance/distance_to_2. Transition 1 → 2 means transitions from land use category 1 to land use category 2. Variable distance/distance_to_2 means it analyses distance to land use category 2 (i.e. category water). The first column shows the ranges, the second the buffer size in cells, the third the number of possible transitions occurring within each buffer, the fourth actual transitions occurring within each buffer, the fifth the obtained coefficients, the sixth the 'contrast' measure and the last row shows the result of the statistical significant test.

The first few ranges in Table 23 show a positive association, favouring the change, especially the first, in the 'contrast' category. The final ranges show negative values, thus repelling the change/transition. The middle range shows values close to zero, which means that these distance ranges do not have an effect on the transition.

The 'contrast' measures the association or the repelling effect. The larger positive value of the 'contrast', the greater the attraction, whereas the larger the negative value, the greater the repelling effect. Values nearing zero do not have effect at all. Hence, if the 'contrast' is positive, the higher is the possibility of land use change between those two categories.

Table 23: Sub-model results for the ‘Weights of Evidence’ coefficient

Transition: 1->2 Variable: distance/distance_to_2							
Range			Possible Transitions	Executed Transitions	Weight Coefficient	Contrast	Significant?
0	<= v <	60	3227	367	1.42003717	1.528338	yes
60	<= v <	90	6709	345	0.55838425	0.616774	yes
90	<= v <	120	6897	278	0.30317376	0.331594	yes
120	<= v <	150	6908	226	0.0866146	0.093873	no
150	<= v <	240	20816	675	0.0774521	0.10085	yes
240	<= v <	300	9590	250	-0.1473484	-0.16304	yes
300	<= v <	570	20899	472	-0.2943816	-0.36631	yes
570	<= v <	630	1897	34	-0.5303306	-0.53897	yes
630	<= v <	990	6857	99	-0.7501102	-0.79192	yes
990	<= v <	1020	419	4	-1.1687319	-1.17191	yes
1020	<= v <	1050	443	3	-1.5149102	-1.51872	yes
1050	<= v <	1080	390	4	-1.0962908	-1.09915	yes
1080	<= v <	1170	1295	18	-0.7886449	-0.79644	yes
1170	<= v <	1200	384	3	-1.3709349	-1.37409	yes
1200	<= v <	1230	343	1	-2.3615585	-2.365	yes
1230	<= v <	1320	1110	9	-1.3334973	-1.34255	yes
1320	<= v <	1440	1120	5	-1.9339195	-1.94456	yes
1440	<= v <	1770	2230	4	-2.8484149	-2.87195	yes
1770	<= v <	4650	1542	3	-2.7670236	-2.78315	yes
			93076	**2800**			

4.3.4. Step four: Analyse map correlation

The advantage of ‘Weights of Evidence’ over other statistical methods is that this method is not constrained by the classical assumptions of parametric methods, which spatial data usually tends to violate. Moreover, the effect of each spatial variable can be calculated independently of a combined solution. The input maps used in the ‘Weights of Evidence’ method are assumed to be spatially independent. To verify the independence of these maps, a set of measures such as Cramer’s Coefficient (also known as Cramer’s V), Contingency Coefficient and the Joint Information Uncertainty is applied (Bonham-Carter, 1994).

The correlated variables must be either omitted or combined into a third, which will replace the correlated pair in the model, whereby the maps are spatially independent. The two former methods are based upon the chi² (chi-square) statistic while the latter is derived from the ‘joint entropy’ measure, whereby all methods are calculated from a contingency table produced by a cross-tabulating pair of maps. The sub-model shown in Figure 50 carries out pairwise tests for categorical maps to test the independence of those two categories. For the Gauteng model, chi-square, ‘Crammer’s test’, the ‘Contingency’, the entropy and the uncertainty joint information (see Appendix E) are used to verify the correlation between the two maps.

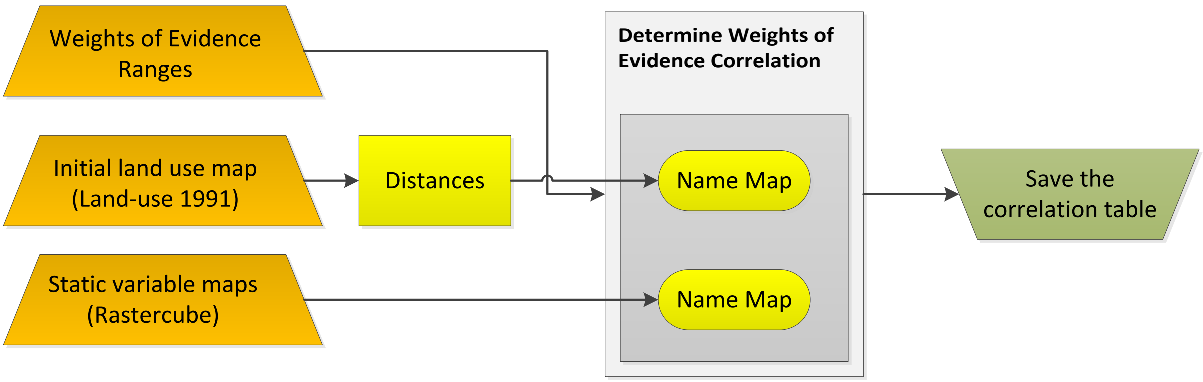

Figure 50: Sub-model 4 for calculating the ‘Weights of Evidence’ coefficients

4.3.5. Step five: Simulation model

Based upon a local CA rule, the model uses a transition engine comprising two complementary transition functions, namely the ‘expander’ (see Appendix F) and the ‘patcher’ (see Appendix G), specially designed to reproduce the spatial patterns of change. The first process is dedicated only to the expansion or contraction of previous patches of a certain category while the second process is designed to generate or form new patches through a seeding mechanism. The ‘Patcher’ searches for cells around a chosen location for a joint transition. The process is started by selecting the core cell of the new patch and subsequently selecting a specific number of cells around the core cell, according to their P_{ij} transition probabilities.

By varying their input parameters, these functions enable the formation of a variety of sizes and shapes of patches of change. The ‘patch isometry’ varies from 0 to 2. The patches assume a more isometric form as this number increases. The sizes of change patches are set according to a lognormal probability distribution. Therefore, it is necessary to specify the parameters of this distribution represented by the mean and variance of the patch sizes to be formed. The combination of Dinamica’s transition function presents numerous possibilities with respect to the generation and evolvement of spatial patterns of change.

The process behind creating the simulated land use is represented in Figure 51. The sub-model is fed with rastercube, initial land use, transition matrix (multiple-step) and coefficients of 'Weights of Evidence' as an input. The model can be run for more than one loop (through Functor: Repeat; see Figure 51). The model creates two output maps: probabilities map and the land use map (Figure 52).

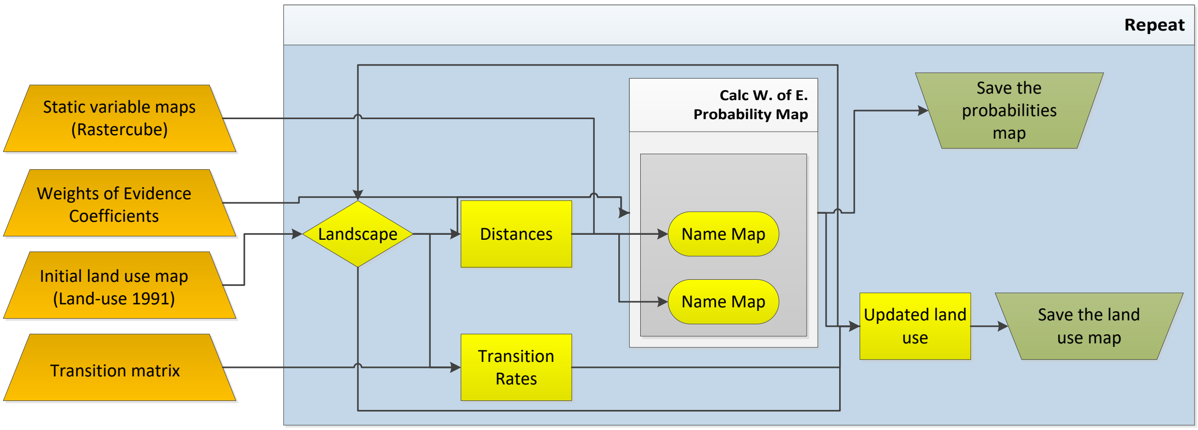

Figure 51: Sub-model 5 used for creating simulated land use map for Gauteng

The simulated land use map is subsequently compared with the final land use map. The probability map illustrates high probability areas for the future changes. The simulated land use map (Figure 52) is a result of a combination of all possible transitions. After the simulated land use map is created, the next step is to validate the simulation results with an existing map.

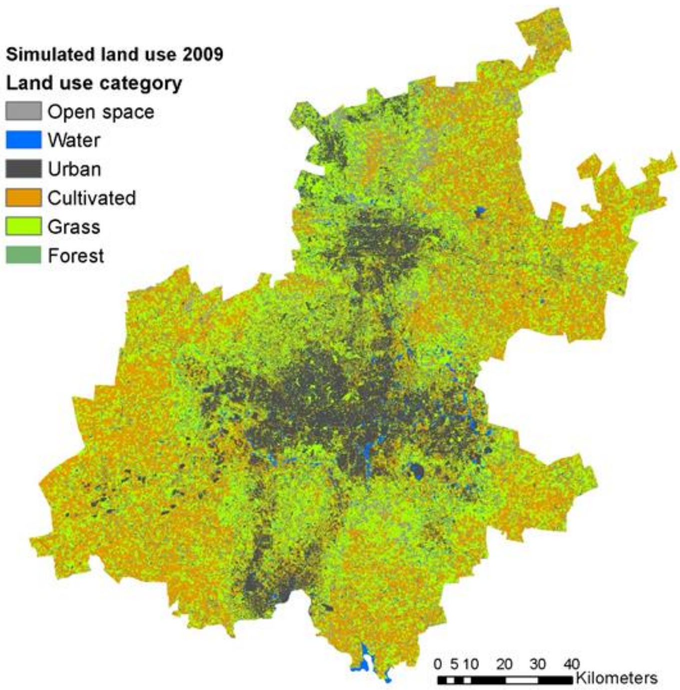

Figure 52: Simulated land use map of Gauteng, 2009

4.3.6. Step six: Validation using an exponential decay function

A visual comparison of spatial patterns can be misleading at times. To avoid this, the spatial models need a comparison within a given neighbourhood context. This helps in terms of recognising the spatial agreement within certain cell vicinity. Various vicinity-based comparison models have been developed to address this issue, such as 'the multiple resolution fitting procedure that compares a map fit within increasing window sizes' (Constanza, 1989). Similar to Constanza's method (1989), Pontius (2002) presented a method that differentiates errors due to location and quantity. Similarly, a comparison method based upon hierarchical fuzzy pattern matching was provided by Power et al (2001). By contrast, Hagen (2003) developed a new method to compare raster maps of the categorical data, which applies fuzzy set theory and involves both fuzziness of the location and fuzziness of the category. The method adopted in the Dinamica simulation model is a modification of the latter and is known as a 'Calc Reciprocal Similarity Map' functor (see Appendix H). This method employs an exponential decay function[35] with distance to weigh the cell distance distribution around a central cell. Figure 53 shows the sub-model that uses exponential decay function for the validation of the simulation model. This model receives initial land use, final land use and the simulated land use as an input. The similarities sub-model (see Figure 53) evaluates the spatial fit between maps of changes. A map of differences between the initial map (land use map 1991) and the final map (land use map 2009) and the differences between the initial map and the simulated map (simulated land use map 2009) is calculated.

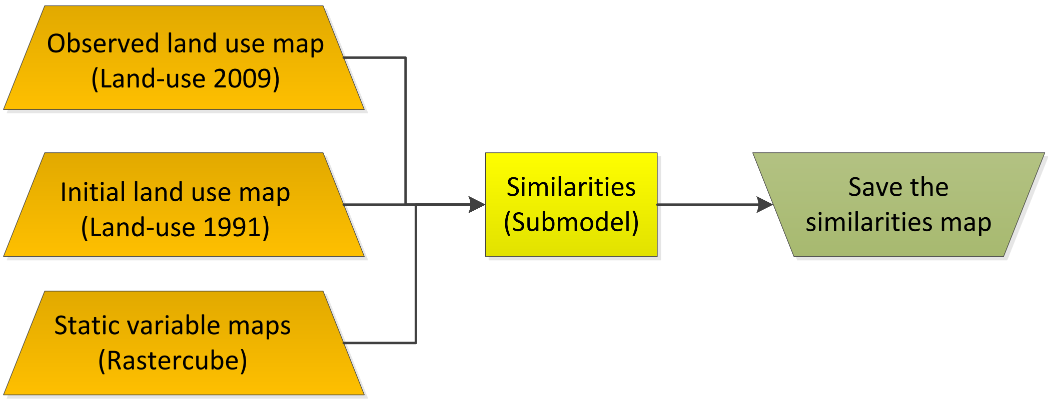

Figure 53: Sub-model 6 with exponential decay function for validating the simulation model

[35] In an exponential decay function, the similarity is calculated using an exponential decay function truncated by the window size.

4.3.7. Step seven: Validation with multiple windows constant decay function

The difference between the previous step and this one is that the former uses exponential decay function and the latter uses a constant decay function[36]. This sub-model is fed with the similar inputs as in the previous sub-model with exponential decay function. The window size used to verify the similarities must always be odd numbers. Hence, the windows range from 1x1, 3x3, 5x5, 7x7,…, nxn. The increment used to set the next step or model iteration is two. Figure 54 shows the sub-model used for in the validation with constant decay function.

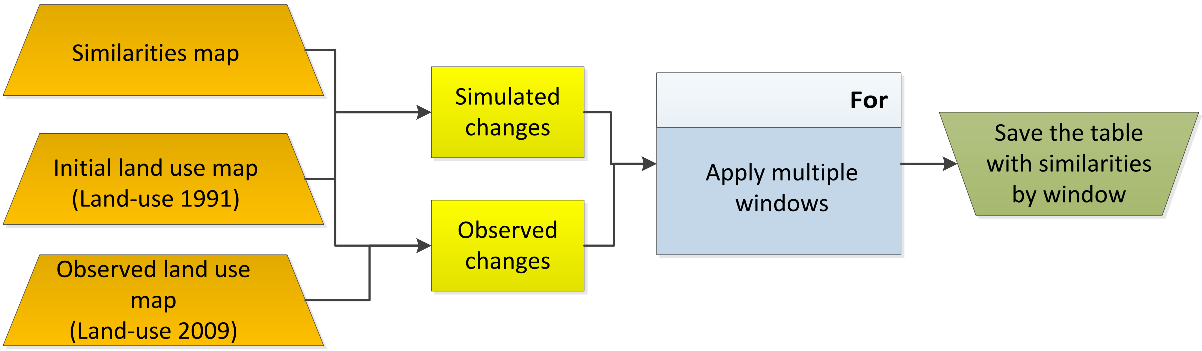

Figure 54: Sub-model 7 using multiple windows constant decay function for validating the simulation model

The sub-model results are shown in Figure 55. The model fitness goes from 31% at 1 x 1 cell resolution to 93% at 35 x 35 cell resolution. As the simulation receives, as input, a fixed transition matrix, only the model fitness with respect to the location of changes needs to be assessed. Taking into account that cell resolution is 30 metres and the window search radius is half of the resolution, a graph depicting model fitness per spatial resolution is drawn (see Figure 55).

[36] In a constant function, the similarity value is one if corresponding cells are found within the search window, and zero if not.

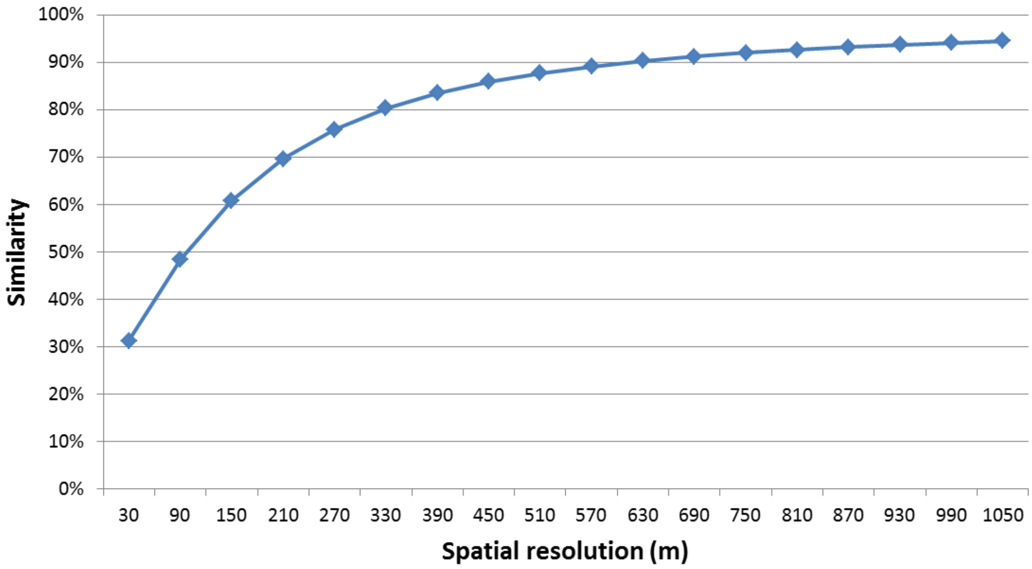

Figure 55: Model fitness (similarity vs. spatial resolution)

Model validation with 'Overall Accuracy (OA)' factor

Model validation is essential in any land use change simulation model. Validation is usually conducted by comparing the simulated results and the existing map for the same year to verify the model's predictability. For Gauteng, historical data was used to simulate a land use pattern for 2009. This simulated map was compared with an existing raster map of Gauteng for the same year. The validation was conducted using the 'overall accuracy' (OA) factor. The principle of the OA factor is explained with the help of Equation 8 and Figure 56.

$$OA = \frac{B+E}{A+B+C+D+E}$$ **Equation 8**

Where:
A is the area of error due to observed change predicted as persistence;
B is the area of correct due to observed change predicted as change;
C is the area of error due to observed change predicted as wrong gaining category;
D is the area of error due to observed persistence predicted as change; and
E is the area of correct due to observed persistence predicted as persistence.

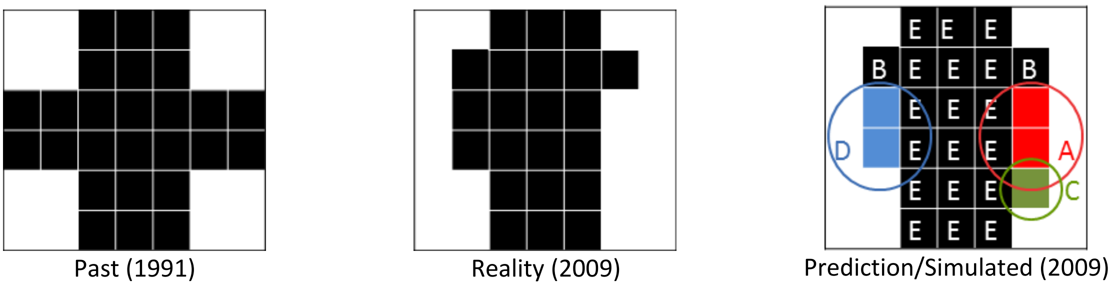

Figure 56: Graphical explanation of the 'Overall Accuracy' factor

The OA factor was calculated using three images, whereby the past image (1991), the reality and the predicted images were taken for 2009. The changes between these images were analysed with GIS by comparing pixels to calculate different areas of error. The OA factor subsequently compares changes that occurred between 1991 and 2009 in reality and in the simulated image by verifying the areas of error (see Equation 8). This factor provides an overall comparison between the reference and the simulated image. If the OA factor is zero, there is no overlap between the reality and the predicted image and if it is 100%, it means accurate prediction due to 100% overlap. In reality, it is quite impossible to have a 100% overlap. The comparison of the simulated and real image for Gauteng results in an overlap of 91%, validating the simulation model at the quantitative level.

4.3.8. Step eight: Project future urban growth

The simulation model for Gauteng evaluates the impacts of future urban growth under various boundary conditions. Figure 57 illustrates the final sub-model, which projects the future urban growth based on the CA principles. As seen in the figure, the model receives four inputs (transition matrix, initial land use, rastercube containing relevant parameters and the weights for each category). This model can be run for any number of years in the future with the preferred time interval. For Gauteng, the simulation was conducted until 2040 with an interval of one year.

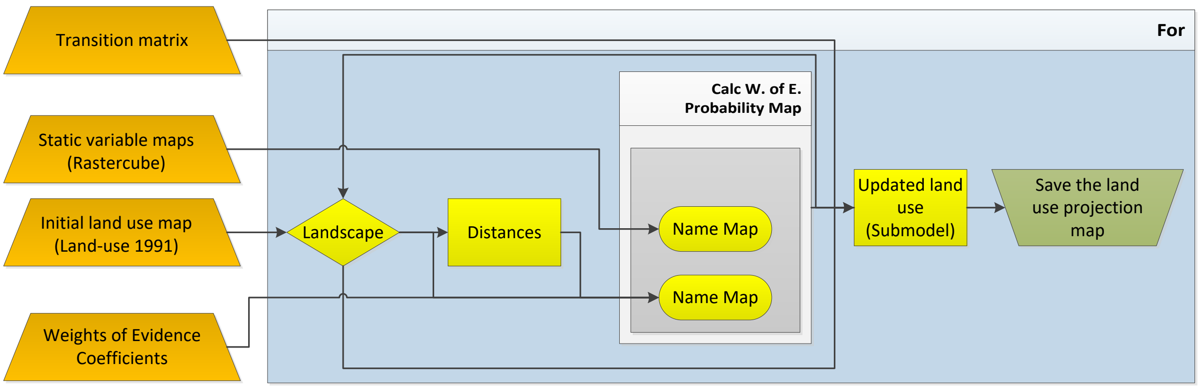

Figure 57: Sub-model 8 for projecting future urban growth

4.4. Micro-geographical model results

The validation results show that the micro-geographical model provided an important basis to analyse the spatial and temporal changes of land use and examine the driving forces behind those changes in Gauteng. In the past decade, the changes in the built-up area in Gauteng have been quite rapid and visible. Table 24 represents the results of the BAU and the PUG scenario. The table shows the area in km² under six different land use categories (1991 and 2009) and the simulation results for each category for BAU and PUG scenario in 2040.

Table 24: Micro-geographical model results for the BAU and the PUG scenario (area in km²)

Category			BAU	PUG
	1991	**2009**	**2040**	**2040**
Open space	360	188	124	188
Water	906	842	599	842
Urban	2,392	3,146	5,871	4,109
Cultivated	6,273	6,179	5,789	6,179
Grass	6,024	6,957	5,061	5,546
Forest	2,550	895	726	1,306
Total	18,170	18,170	18,170	18,170

The open space category is negatively affected in the BAU scenario, i.e. the area under this category will reduce by 34% by 2040. As the urban expansion in the open spaces is prohibited in the PUG scenario, the open space category area remains unchanged in this scenario. In 2040, the urban/built-up area will increase from 3,146 km² in 2009 to 5,871 km², i.e. 87% in BAU scenario and 4,109 km², i.e. 31% in the PUG scenario. As the BAU scenario considers no additional restrictions/policies for conservation areas, the area under water, including wetlands, will reduce from 842 km² to 599 km² (loss of 29%) whereas in the PUG scenario it will remain unchanged. Moreover, the area under cultivated category went down from 6,179 km² to 5,789 km² in BAU scenario. By contrast, the PUG scenario shows no change in the cultivated category. In the PUG scenario, stricter laws and regulations are expected to be enforced to increase the forest area. This can be seen through an increase in the forest area from 895 km² in 2009 to 1,306 km² in 2040. The area under the category grass will reduce in both scenarios.

The results from Table 24 are illustrated graphically in Figure 58. The growth in the urban area between 2009 and 2040 is evident from this figure, for both the BAU and the PUG scenario. Nonetheless, the growth in the latter scenario is slower than in BAU scenario. The land use category of grass experiences a reduction in both scenarios, whereas forest will increase.

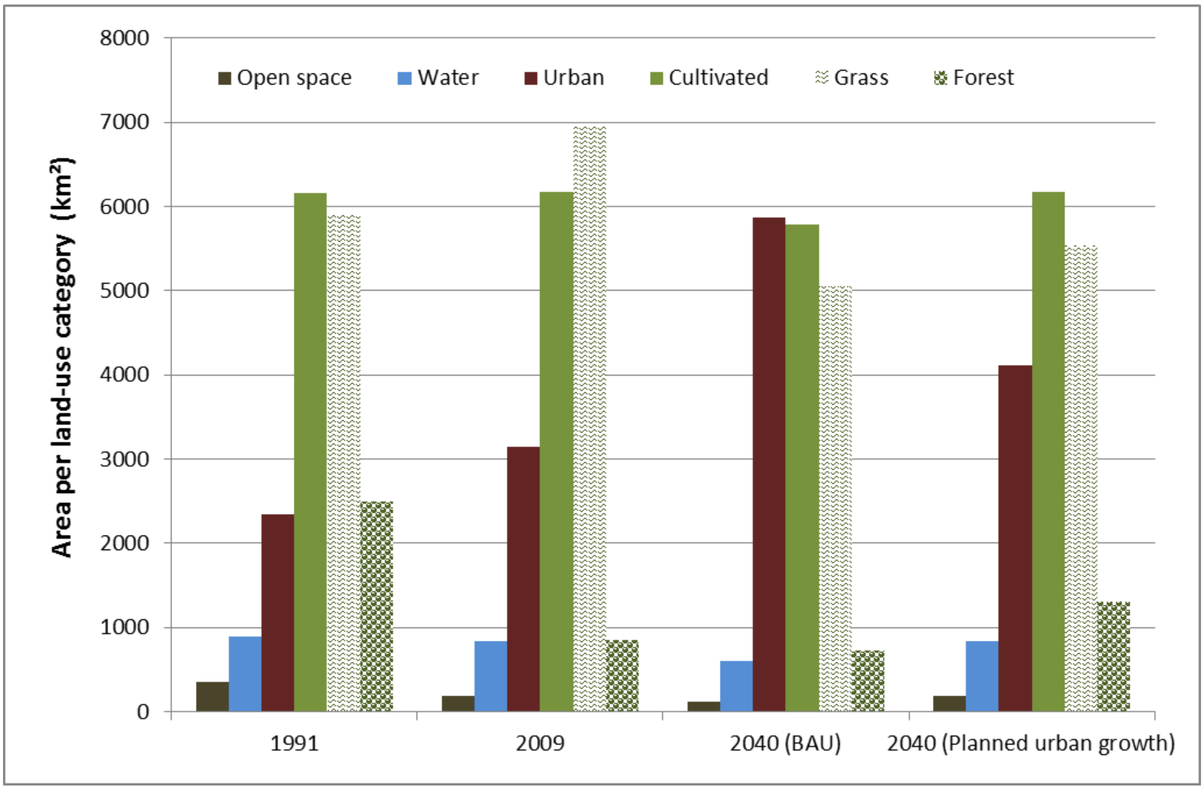

Figure 58: Area under six land use categories in Gauteng in km² (1991-2040)

The scenario results are illustrated in Figure 59 and Figure 60, demonstrating substantial land use transitions during the study period of 49 years (1991-2040). These two figures illustrate the urban area development between 1991 and 2040. To emphasise the urban area expansion that took place between these years, only urban areas are shown in the following figures for 1991, 2001, 2009 and 2040. The simulated urban growth until 2040 is shown in black colour. In the BAU scenario, the urban areas have expanded in the outward direction due to no spatial restriction. Compared to the BAU scenario, in the PUG scenario, there is no visible outward expansion. In the PUG scenario, it is assumed that the vacant plots within the urban boundary (brownfield and infill development) will be used for the future development before extending the city outwards. This results in a compact form of the region as the same population will be spread over a smaller area compared to the BAU scenario.

Changes in the land use category 'Urban' between 1991 and 2040

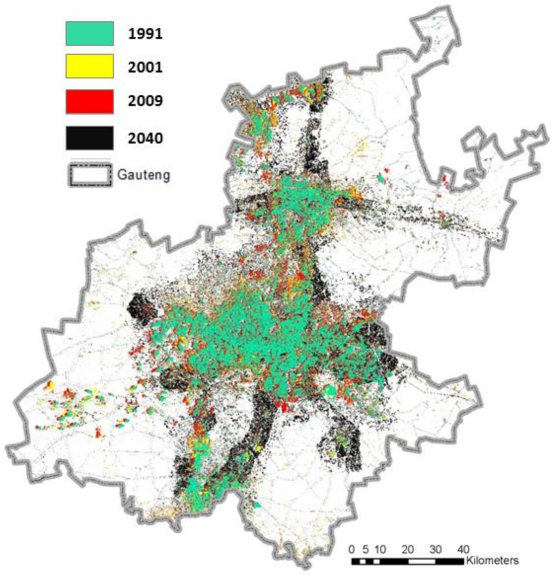

Figure 59: Development of urban areas between 1991 and 2040 (BAU scenario)

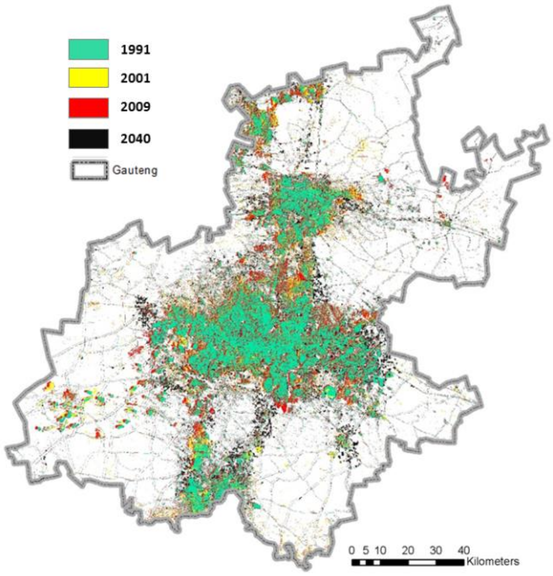

Figure 60: Development of urban areas between 1991 and 2040 (PUG scenario)

The BAU scenario shows an outward expansion in the direction of industrial areas situated on the outskirts of Gauteng, e.g. towards Vereeniging, which is one of the important industrial centres in Gauteng. Moreover, the expansion of the urban areas is mostly near or along the important transport routes, e.g. from Johannesburg towards the South of Gauteng to Orange Farm (youngest informal settlement in South Africa). Similarly, more expansion is seen in the Ekurhuleni metro due to higher job opportunities. By contrast, the outer municipalities remain rather unaffected due to unattractive job prospects.

If the urban expansion continues as seen in BAU scenario, it is practically impossible to establish strong public transportation services due to sparse population density on the outskirts and resulting exorbitant infrastructure costs for a small share of population. Moreover, providing basic infrastructure will also be one of the major problems, i.e. extending water and waste-water lines, electricity network, etc.

4.5. Shannon's entropy factor & urban footprint in 2040

Based on the results of the micro-geographic model, Shannon's entropy Index was calculated for both scenarios for 2040 to ascertain the impact of restricted growth on the entropy factor. The results are illustrated in Table 25, showing that in the 'BAU' scenario the entropy factor for few municipalities has increased compared to 2009. Most of these municipalities are located around the busiest main roads connecting important business and industry centres in Gauteng (see Figure 33). Entropy factors for Ekurhuleni and Johannesburg remained the same as in 2009.

The entropy factors for the PUG scenario remain the same as the city is not allowed to extend beyond the urban boundary in 2009. As brownfield and infill areas were already considered under built-up area and entropy calculations in 2009, the entropy factor does not change in 2040.

Table 25: Development of entropy factor in Gauteng between 2009 and 2040

Entropy factor			Category
2009	**2040 BAU**	**2040 Planned urban growth**	
0.97	0.98	0.97	Gauteng
0.86	0.88	0.86	Merafong city
0.78	0.80	0.78	Nokeng
0.98	0.99	0.98	Emfuleni
0.89	0.89	0.89	Midvaal
0.87	0.87	0.87	Lesedi
0.82	0.84	0.82	Kungwini
0.94	0.94	0.94	Mogale city
0.93	0.93	0.93	Randfontein
0.85	0.88	0.85	Westonaria
0.99	0.99	0.99	Ekurhuleni
0.99	0.99	0.99	Johannesburg
0.98	0.99	0.98	Tshwane
0.97	0.98	0.97	Roads

Urban footprint in 2040

In the BAU scenario, Gauteng's urban footprint increases slightly from 299 m² per capita (2009) to 307 m² per capita (2040). In comparison, in the PUG scenario, it is reduced to 215 m² per capita. Due restricted outward growth, the built-up area is used more efficiently in the PUG scenario. The small urban footprint is an indicator of compact urban form. The results show, compared to the BAU scenario, the PUG scenario would help in achieving a compact urban form in Gauteng by 2040.

Urban footprint is a better measure than population density as the urban footprint is calculated based upon built-up area and not the total area of a region, which usually remains the same, whereas the built-up area changes over time (especially in fast-growing cities).

4.6. Macro-geographical model results

The results of macro-geographical scenario analysis for both scenarios are presented in the following section. The results of the final energy demand are based on building types, income group, type of fuel used, appliances and their efficiencies. These parameters are presented in detail in Appendix L (see Table 61 to Table 80). The final energy demand in the residential sector in Gauteng influences the increase of GHG emissions. An increased share of renewable energy and efficient appliances are few of the factors that influence the reduced GHG emissions in the PUG scenario. There are no power plants within Gauteng's boundary. Hence, the amount of electricity shown in the BAU and the PUG scenario is imported electricity.

4.6.1. BAU scenario results

In 2007, the residential sector was responsible for 10% of the final energy consumption in Gauteng. Energy demand in the residential sector in Gauteng is strongly influenced by the standard of living, access to fuel, household size and income of the household. The standard of living and household income are interdependent and influence the choice of appliances and the type of fuel used by the households. Hence, affordability is the most important issue while choosing the energy carrier. The dwelling type, its size, the position (e.g. north-facing) and the condition of the dwelling (e.g. if it needs retrofitting) where the household lives also influence the energy demand. In the high-income group, the location of the dwelling also plays a major role. Households in gated communities use less outdoor lighting than those living outside, mainly due to security reasons.

In 2007, the final energy demand in Gauteng was 76.0 PJ, steadily increasing over the years until 2040 due to increasing population in the region. The energy carriers used to fulfil this demand are electricity (79.7%), paraffin (10.9%), LPG (3.4%), coal (2%), wood and natural gas (each at 1.7%) and solar (0.8%) in the decreasing order of their share in total energy demand, with electricity being the most dominant energy carrier in all income groups. The total final energy demand is expected to increase up to 194.46 PJ in 2040. Table 26 shows the final energy demand in the residential sector in Gauteng between 2007 and 2040 in PJ.

Table 26: Final energy demand in the residential sector in Gauteng in PJ (2007 - 2040)

Year	2007	2010	2015	2020	2025	2030	2035	2040
Energy demand	76.0	79.74	98.32	116.96	133.75	152.68	172.51	194.46

The average final energy demand per household by energy carrier is represented in Figure 61. The figure shows average final energy demand for all income groups in GJ. Electricity demand per household would increase from 18 GJ in 2007 to 18.9 GJ in 2040. Paraffin was the second highest used energy carrier (2.37 GJ/HH) in the residential sector in 2007. In 2040, solar will be the second most (2.67 GJ/HH) used energy carrier. Wood consumption will also increase from 0.39 GJ/HH in 2007 to 1.96 GJ/HH. Both, LPG and natural gas consumption show a steady increase until 2040.

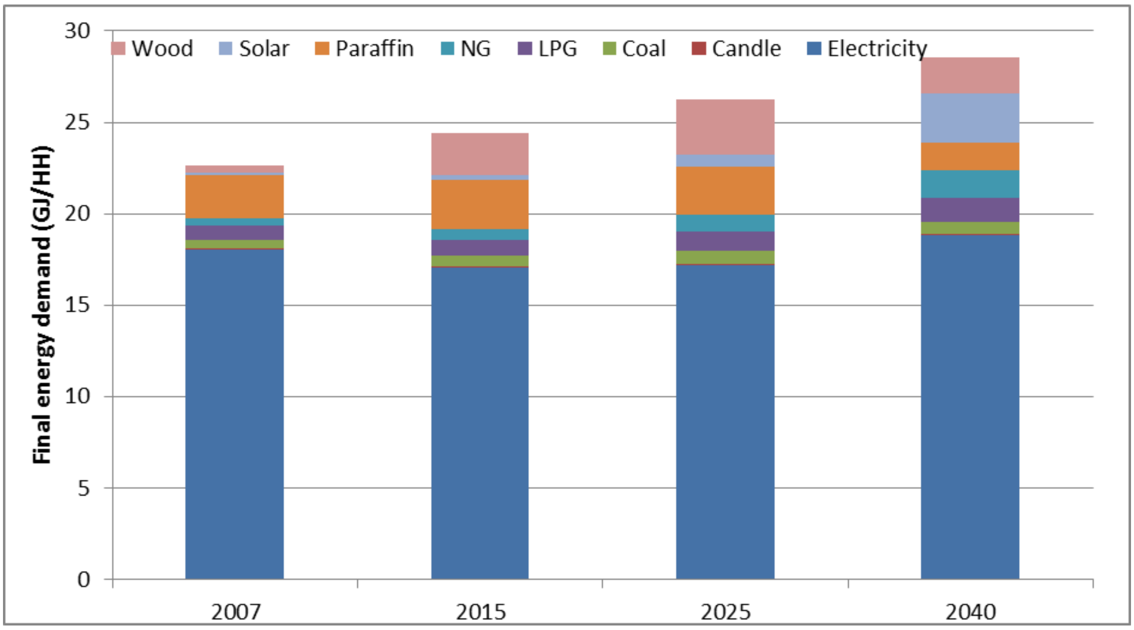

Figure 61: Average final energy demand per household by energy carrier in the BAU scenario (GJ) (2007 - 2040)

Although electricity remains the important energy carrier until 2040, the share of the other fuels – such as solar energy and natural gas – will substantially increase whereas the use of wood and paraffin will decrease by 2040. The energy demand in Gauteng and its spatial distribution (2007 and 2040) is discussed in detail later in section 5.2.

The number of households will increase from 3.18 M. in 2007 to 6.82 M. in 2040. The total number of households will double in size whereas the energy demand will increase almost threefold compared to 2007 (194.46 PJ in 2040). The reason for this is the increased average household energy demand, which will rise from 22.65 GJ in 2007 to 28.52 GJ in 2040.

4.6.2. Planned urban growth (PUG) scenario results

In the 'planned urban growth' scenario, it is assumed that new efficient technologies for cooking, water heating, space heating and lighting will be available. In addition, it is assumed that the newly dwellings are built according to the South African National Standard (SANS) norm resulting in reduced space heating demand. Based upon the aforementioned assumptions, the final energy demand for both scenarios is shown in Table 27. Through various energy saving measures, the PUG scenario will have 10 PJ less energy demand in 2040.

Table 27: Final energy demand in the residential sector in the BAU and the PUG scenario (PJ) (2007 - 2040)

Scenario	2007	2010	2015	2020	2025	2030	2035	2040
BAU	76.0	79.74	98.32	116.96	133.75	152.68	172.51	194.46
Planned urban growth	76.0	79.74	98.23	118.24	135.61	152.95	168.20	184.58

The final energy demand by energy carriers per households is illustrated in Figure 62. The average final energy demand per household is shown in GJ per annum. When both scenarios are compared, the influence of different technologies used in both scenarios is visible through varying shares of different energy carriers. In 2007, the average annual household energy consumption was 22.7 GJ, which constantly grew to 28.5 GJ in 2040 in the BAU scenario and 27.1 GJ in the PUG scenario. Electricity remains the important energy carrier in both scenarios in 2040, although the share of electricity in decreased from 80% to 66% and 63% in BAU and 'planned urban growth', respectively. The share of solar energy increases considerably in both scenarios. LPG, natural gas and paraffin still remain important energy carriers in both scenarios. A remarkable difference is observed in the usage of wood between the BAU and the PUG scenario. In the BAU scenario, wood usage increases from 1.7% (2007) to 6.9% (2040) compared to only 1.9 % in the PUG scenario. Candle and coal remain the least used energy carriers in both scenarios.

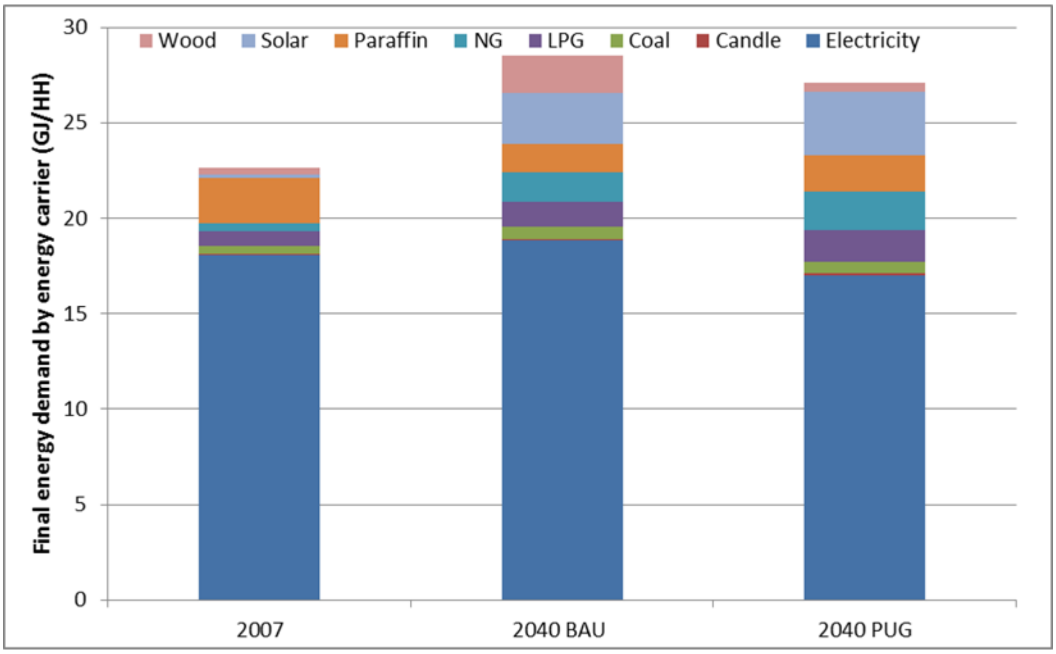

Figure 62: Average final energy demand per household by energy carrier in the residential sector for the BAU and the PUG scenario (GJ) (2007 - 2040)

The final energy demand subdivided in end-use type is presented in Figure 63. The end-use is differentiated in six categories: appliances, cooking, lighting in (inside the dwelling), lighting out (outside the dwelling), space heating and water heating. The total final energy demand in the residential sector in Gauteng is illustrated for the base year 2007 and for 2015, 2025 and 2040 for the BAU and the PUG scenario.

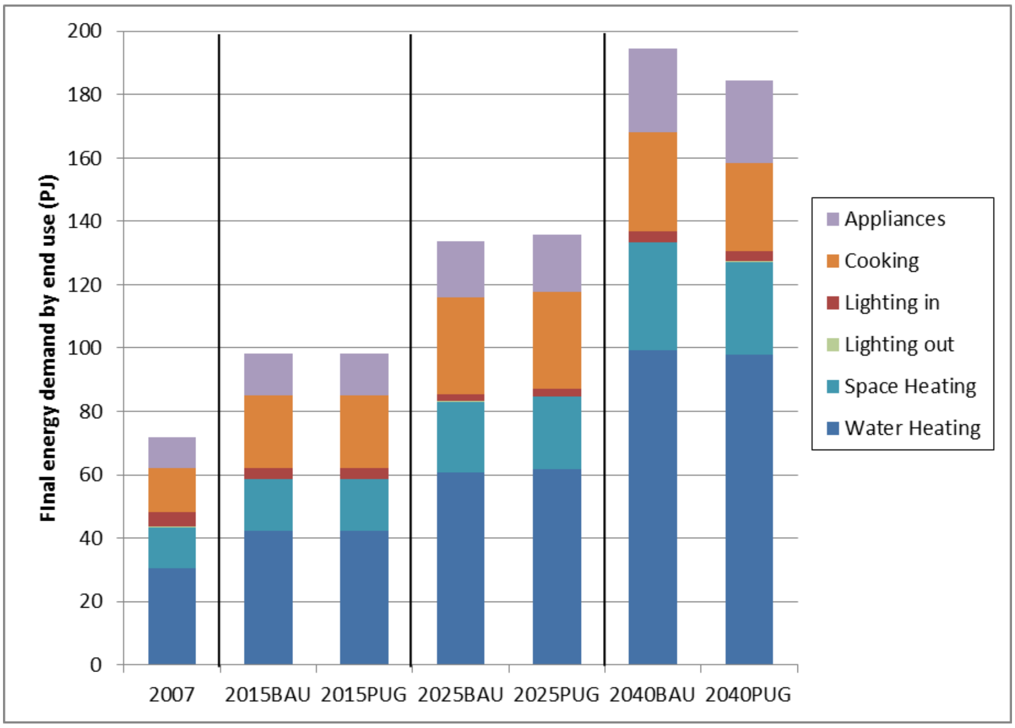

Figure 63: Final energy demand in the residential sector in Gauteng by end-use type (PJ) (2007 - 2040)

Water heating had the highest share in the base year 2007 with 30.57 GJ and it remains the dominant category in both scenarios until 2040. The share of water heating in total energy demand increases from 42% to 51% and 53% in the BAU and the PUG scenario respectively. By 2040, cooking will have the third highest share in total final energy demand with a share of 16% and 15% in the BAU and the PUG scenario, respectively. In 2040, space heating takes over cooking as the second highest category with a 17 % and 15.8% share in the final energy demand in the BAU and the PUG scenario, respectively.

Although the final energy demand for appliances increases from 9.89 GJ in 2007 to 26.36 GJ in both scenarios, the share of appliances remains constant at around 13 to 14 % in both scenarios. The share of lighting (both inside and outside lighting) remains negligible, i.e. less than 5% in both scenarios, which is presumably due to the introduction of more efficient CFL and LED technology.

In Figure 64, the final energy demand in the BAU scenario in Gauteng for all sectors is compared with the final energy demand in the residential sector. The share of the residential energy will increase constantly between 2007 and 2040. In 2007, the residential final energy had a share of 10% in the total final energy demand in Gauteng which will increase to 13.5% in 2040. In 2040 in Gauteng, the final residential energy demand will be 194 PJ whereas the total final energy demand will sum up to 1,441 PJ.

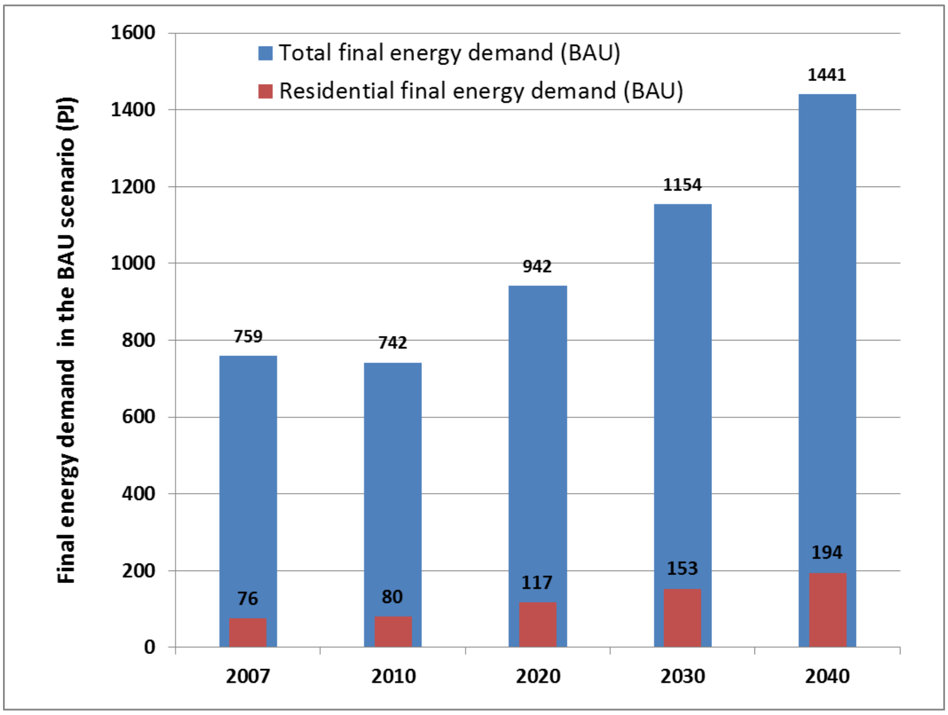

Figure 64: Final energy demand - total and in the residential sector in Gauteng, BAU scenario (2007 - 2040) (own calculations based upon EnerKey, 2010)

Figure 65 compares the total final energy demand and the final energy demand in the residential sector in Gauteng based upon the PUG scenario. In 2007, with 76 PJ final energy demand, the residential sector had only 10% share in the total final energy demand in Gauteng. Alike BAU scenario, the share of the final energy demand in the residential sector grows constantly over the years. In 2040, in the PUG scenario, the residential sector will have a substantial share of almost 15% in the final energy demand in Gauteng. The total final energy in Gauteng in this scenario is lesser compared to the BAU scenario due to energy saving measures considered in the residential, industry and transport sector (Tomaschek et al, 2012, EnerKey, 2013, EnerKey 2014).

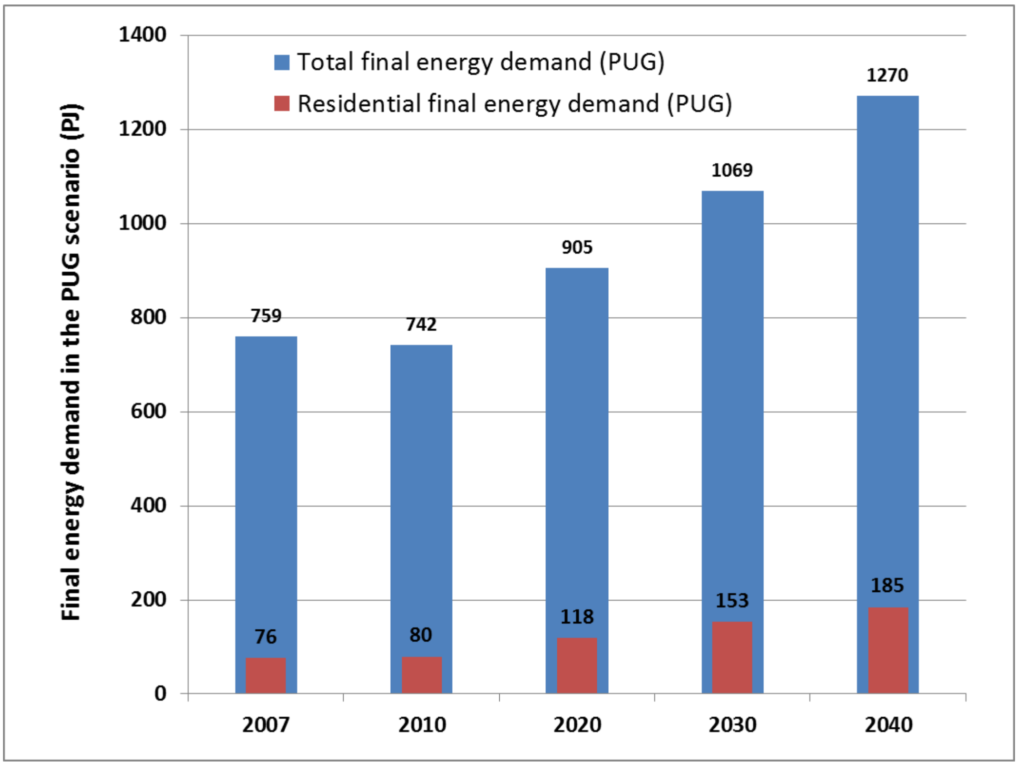

Figure 65: Final energy demand – total and in the residential sector in Gauteng, PUG scenario, (2007 – 2040), (own calculations based upon EnerKey, 2010)

4.6.3. Comparison of greenhouse gas (GHG) emissions in the BAU and the PUG scenario

Total emissions (direct and indirect)

In this study, only greenhouse gas emissions are taken into consideration. The emissions factors for various technologies and energy carriers are presented in Table 58, Table 59 and Table 60 for CO_2, CH_4 and N_2O respectively (Tomaschek et al, 2012). All the emissions (CH_4 and N_2O) are converted to CO_2-equivalent using IPCC factors (see Table 57). Total emissions for each scenario are presented in this section. The emissions resulting from each scenario depend on the different technologies considered in that scenario, their efficiency, the energy carriers used and their share in the final energy demand in the residential sector.

Figure 66 compares the GHG resulting from both scenarios between 2007 and 2040. Total CO_2-equivalent emissions increase continuously between 2007 and 2040 in both scenarios. The total CO_2-equivalent emissions in 2007 amount to 0.90 Mt of CO_2-equivalent and increase by 164% in 2040, resulting in a total emission of 2.37 Mt in 2040 for the BAU scenario. The PUG scenario shows a slightly lower increase in the total emissions, resulting in 2.27 Mt CO_2-equivalent in 2040, i.e. an increase of 152% over 33 years. Despite restricting the urban growth and increasing the share of renewable energy carriers such as solar, the total CO_2-equivalent emissions in 2040 do not show a substantial reduction compared to the

BAU scenario. An increased number of high-income households, a higher share of fossil fuels such as LPG, NG and paraffin are few reasons for high CO_2-equivalent emissions. Furthermore, use of paraffin in the poor and low-income households also contributes to higher emissions.

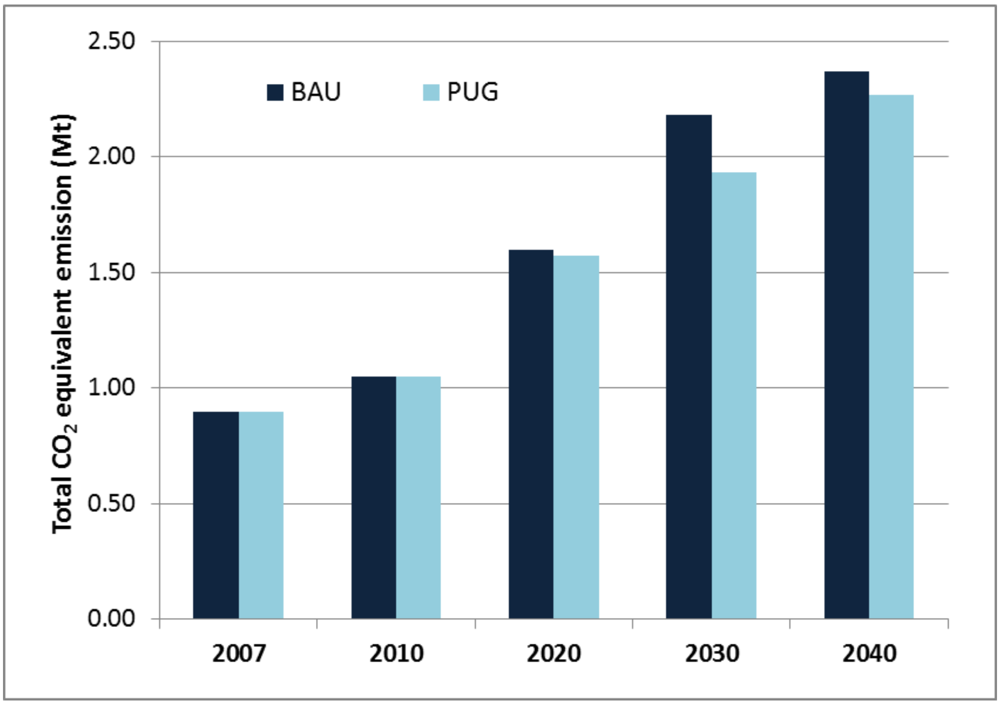

Figure 66: Total CO_2-equivalent emissions in the residential sector in Gauteng (2007 - 2040)

Direct emissions

By definition, direct emissions are those emissions occurred at the source, e.g. combustion of fossil fuels for space heating, cooking or water heating purposes. In Gauteng, use of fossil fuels, such as coal, LPG, NG or paraffin, in the residential sector is still very high and this trend will change slowly till 2040. Economical capabilities along with cultural acceptance play a huge role in accepting new technologies, e.g. electric stove, in the residential sector. Figure 67 compares the total CO_2-equivalent emissions (direct + indirect) with the direct CO_2-equivalent emissions in Gauteng resulting from the final energy demand in the residential sector. The direct emissions for these two scenarios were calculated using TIMES-GEECO model which was used for scenario modelling in the EnerKey project (EnerKey, 2013). The emissions are shown for the BAU and the PUG scenario for the years 2007, 2010, 2020, 2030 and 2040. In the base year 2007, the direct CO_2-equivalent emissions amounted to be 0.2 Mt in the residential sector, which means a share of 23% in the total CO_2-equivalent emissions. As the energy demand grows, the direct and indirect emissions will also increase. In the year

2040, in the BAU scenario, the total CO_2-equivalent emissions would add up to 2.37 Mt. The direct CO_2-equivalent emissions sum up to 1.45 Mt, i.e. 61.15% of the total emissions would result from direct combustion. The share of direct CO_2-equivalent emissions in the PUG scenario is slightly lower than in the BAU scenario, namely, 54.47%. In 2040, in the PUG scenario, 1.23 CO_2-equivalent would be emitted directly in Gauteng's residential sector. With the increasing share of high- and mid-income households and higher living standards, the energy demand will increase constantly. Moreover, a higher share of direct emissions in Gauteng results from increased share of comfort energy carriers, such as CNG, LPG or NG used for cooking, space heating and water heating purposes in both scenarios.

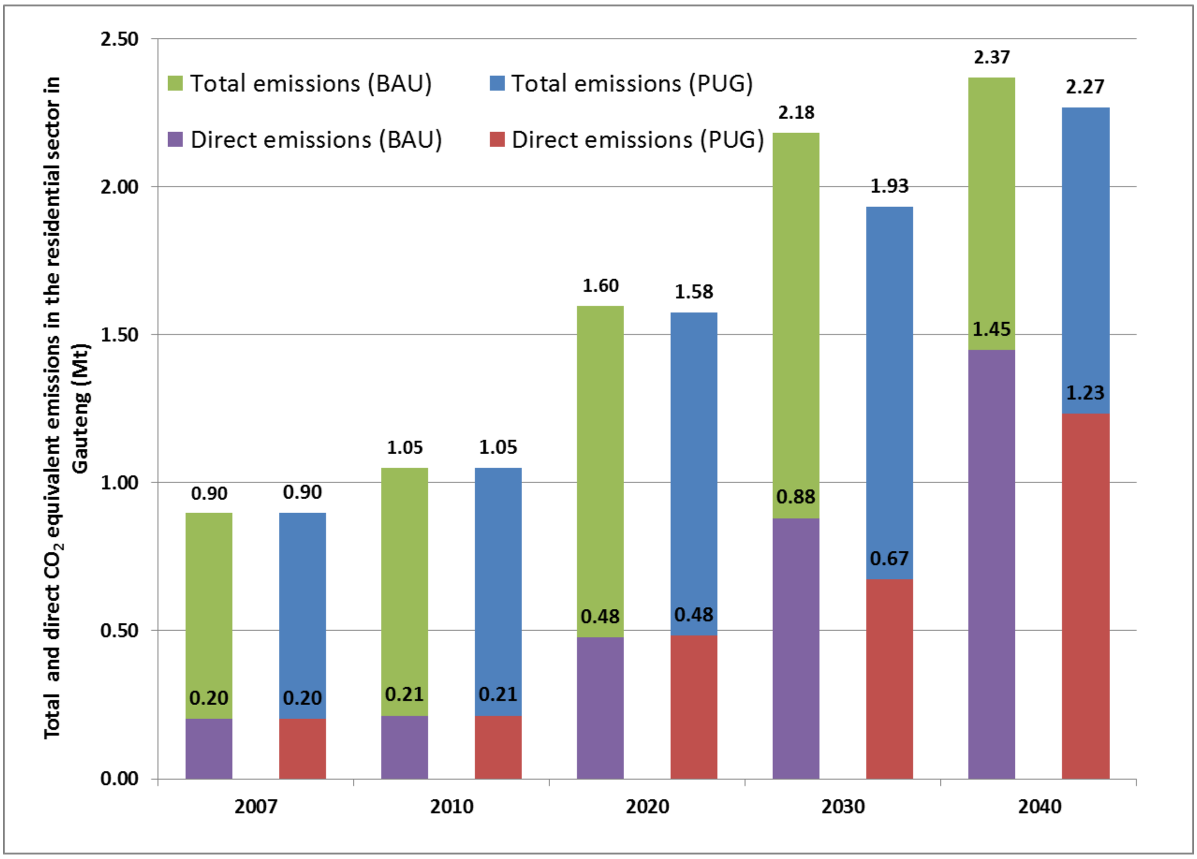

Figure 67: Total and direct CO_2-equivalent emissions in the residential sector in Gauteng for the BAU and the PUG scenario (Mt) (2007 – 2040)

5. Spatial distribution of residential energy demand and renewable energy potential

In the first section, this chapter addresses the need to illustrate energy demand on a spatial level and its approach using the GIS tool. The second section of the chapter deals with the renewable energy potential in Gauteng and its illustration using GIS.

5.1. Need for illustrating energy demand in Gauteng

Gauteng is a highly urbanised region, with 97% of its population living in urban areas (Stats SA, 2008). Along with its population increase, the energy demand in the region is constantly growing. Being highly urbanised region, most of the urban population in Gauteng uses electricity to fulfil their energy needs and more than 90% of the electricity generation in Gauteng is coal-based, resulting in high carbon emissions. To lower these emissions, it is essential to minimise the energy consumption in the urban areas. Accordingly, adequate and suitable technologies must be developed and established under a regulatory framework. These technologies should be based upon the easily available (renewable) energy resources in the near vicinity.

Illustrating the spatial distribution of the energy demand will help in terms of locating the energy hotspots in Gauteng. The location of energy demand in space also reveals about energy efficiency in different regions. Although the energy saving potential lies on the demand side, localised energy supply offers possibilities to establish new sources and new potentials. Rather than looking at the entire region, energy efficiency measures should be implemented on a community or settlement level as they can be implemented quickly.

The urban form also influences energy demand to an extent. There is no information available on the localised energy demand in Gauteng. In addition, there have been inconsistencies on the available data on energy and its dynamic of change. This study overcomes these issues by illustrating the energy demand distribution on the spatial level and providing localised renewable solutions based on available potential in the region. The time and spatial dynamics of the urban space will become an important factor to understand and assess the distribution of energy demand within urban space (Markus et al, 2009). Hence, understanding Gauteng’s present energy and spatial pattern will help in creating sustainable solutions for an energy efficient Gauteng.

5.2. Spatial distribution of energy demand

One of the main aims of this study is to ascertain the relationship between the spatial distribution of the households and localised use of energy. The energy demand at the provincial level needed to be disaggregated onto the ward level[37] (smallest administrative boundary in South Africa, similar to 'Bezirksebene' in Germany) to obtain a finer spatial distribution. The approach taken to distribute the energy demand data at the household level is demonstrated in the following Figure 68.

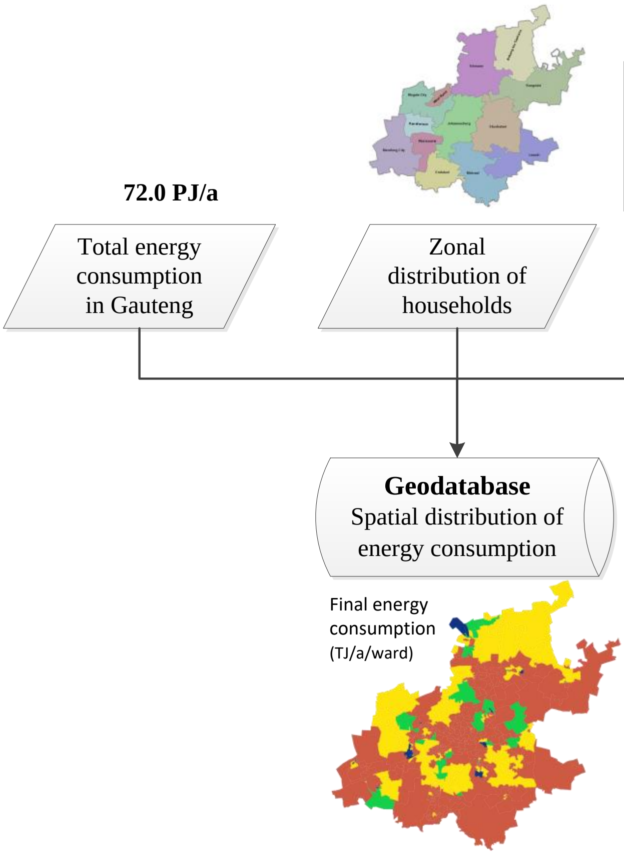

Figure 68: Model approach for distributing energy demand on a spatial level

The point data such as total energy demand in Gauteng, the number of households in Gauteng, the number of buildings in different categories and households belonging to four income groups was gathered. The average annual energy demand based on the dwelling type and the income group was calculated for each household, resulting in 36 types of different households (9 dwelling types x 4 income groups). Data from census and community surveys (Stats SA, 2002 and Stats SA, 2008) were used to calculate the number of households living in each ward. Based on the number of households and built-up area in each ward, the spatial distribution of energy demand could be illustrated with the help of

[37] There are 508 wards in the province Gauteng, varying in size.

GIS integrated tool. The last step of integrating database and geographic information with GIS is represented in detail in Figure 69.

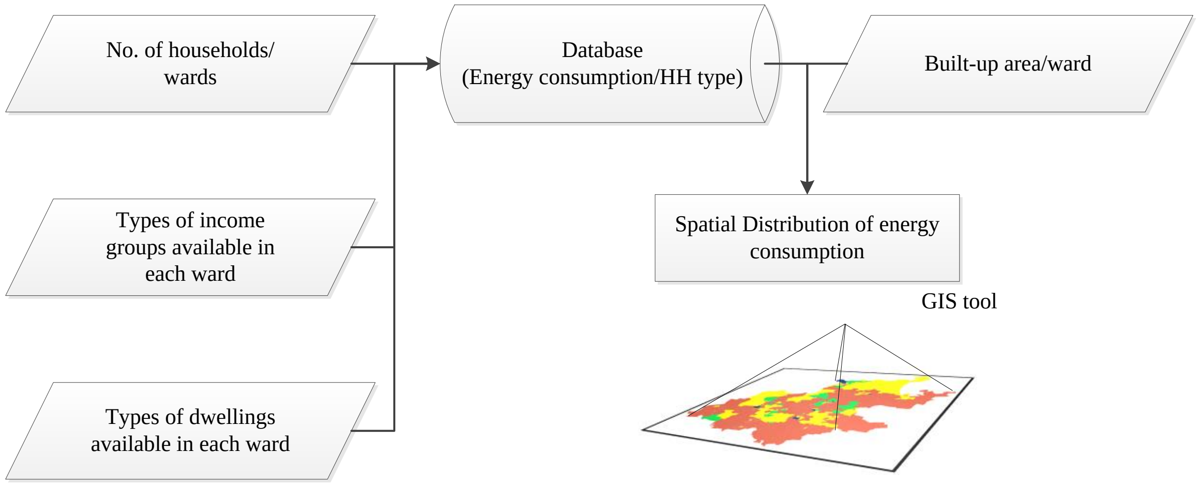

Figure 69: Flowchart illustrating integration of energy demand database and GIS

The model illustrated in Figure 68 is fed with data such as a number of households and dwellings (building type) per ward, the share of households belonging to different income groups and built-up area in each ward. Based upon the model approach shown in Figure 68 and Figure 69, energy demand at the ward level was obtained. The model also enables visualisation of other information such as the number of households using a particular energy carrier for specific needs, e.g. the number of households using candles for lighting or LPG for cooking (see Figure 74 and Figure 75). Given the available information on income groups, the correlation between income groups and energy carriers used can be visualised, e.g. many poor households living near Central Business District, with access to electricity still use candles for lighting.

Figure 70 and Figure 71 show the spatial distribution of the poor and low-income groups in Gauteng. Most of the poor population lives away from both Central Business Districts (Johannesburg and Tshwane) or rather on the outskirts of the metros, with no easy access to public transport, and especially the poor income group. There are a few places like Alexandra and Soweto in the middle of the city where densely populated poor and low-income households exist, although these two are the only examples.

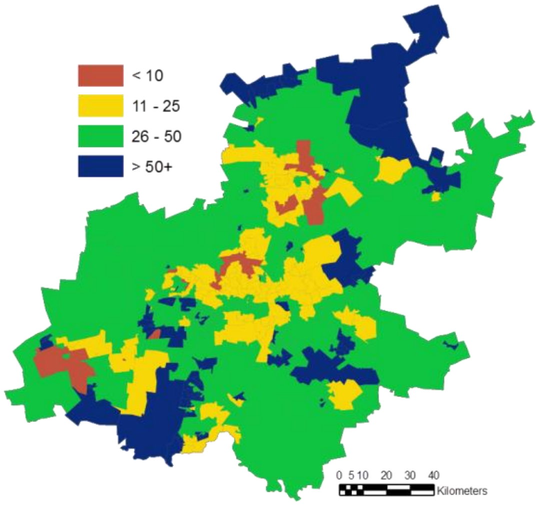

Figure 70: Spatial distribution of the poor population (share of population in % per ward), 2007

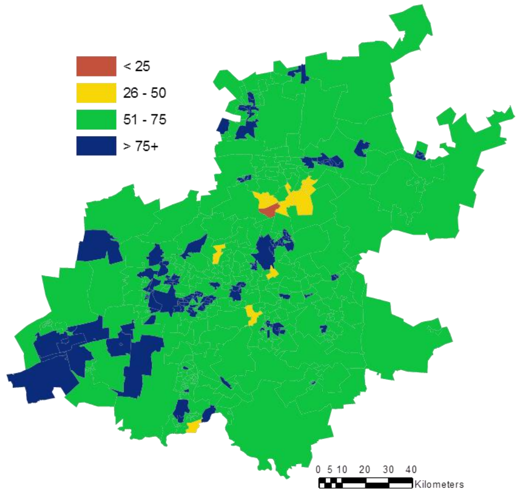

Figure 71: Spatial distribution of the low-income population (share of population in % per ward), 2007

The spatial distribution of mid and high-income groups is shown in Figure 72 and Figure 73. The mid and high-income group population is concentrated around both Central Business Districts. The distribution of the mid-income group is quite heterogeneous compared to that of the high-income group. In Gauteng, only 20.5% of households belong to the mid-income group and 12.2% to the high-income group (2007).

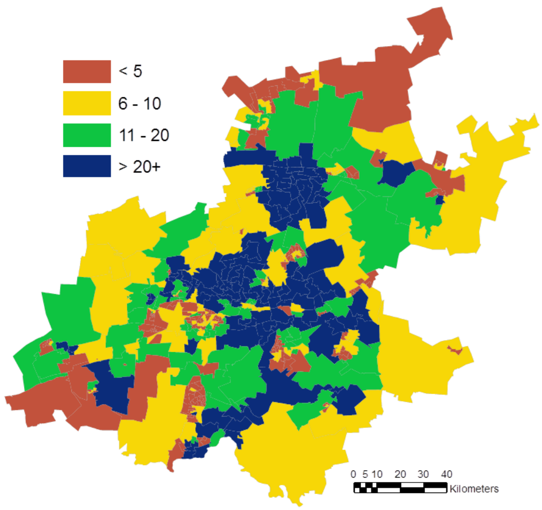

Figure 72: Spatial distribution of the mid-income population (share of population in % per ward), 2007

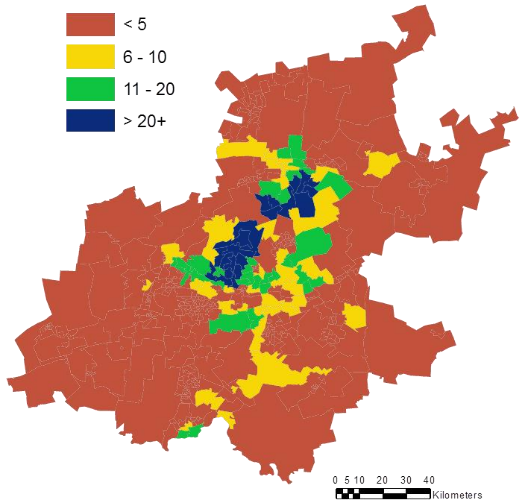

Figure 73: Spatial distribution of the high-income population (share of population in % per ward), 2007

Furthermore, these four figures are compared with the following two figures (Figure 74 and Figure 75), which show the type of energy carriers used for lighting. The use of electricity is prominent in the areas where mid and high-income communities are dominant. However, it is interesting to observe that candles remain an important source of lighting in many households. This concludes the vast income disparity and energy poverty in Gauteng. Very few households used other fuels such as paraffin, gas or solar (passive) for lighting. The spatial distribution of various fuels for cooking and heating purpose is depicted in Appendix K.

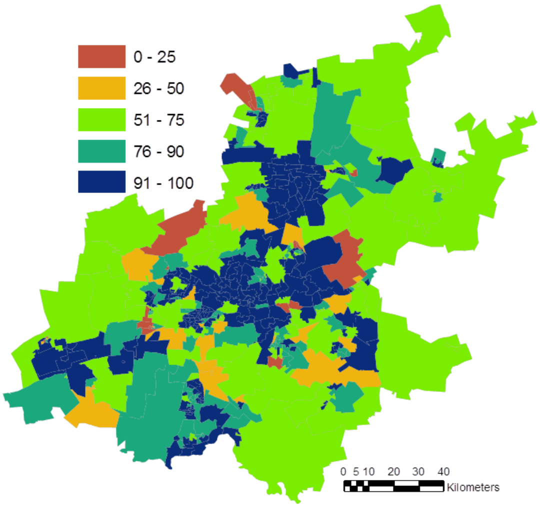

Figure 74: Share of households using electricity as the main source of lighting (%), 2007

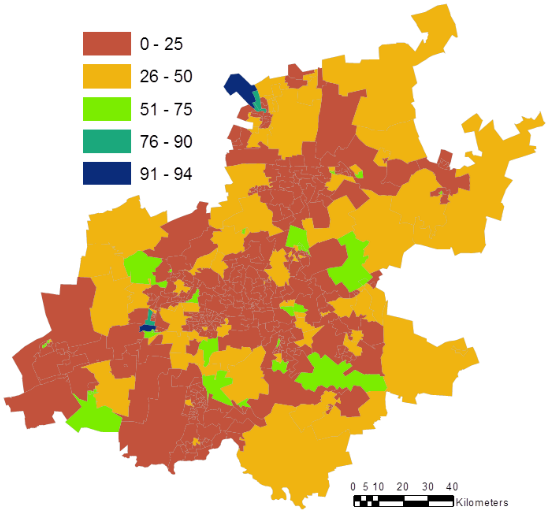

Figure 75: Share of households using candles as the main source of lighting (%), 2007

Energy demand & Gross-geographic Value Added (GVA) correlation

A spatial mapping comparison of the spatial relationship between energy demand and gross-geographic value added (GVA) was conducted to understand the impacts of economic parameters on the spatial distribution of energy demand of Gauteng. Based upon the available data, the concept of GVA is used as a basis for estimating the regional economic activity. GVA denotes regional output and GDP.

Figure 76 shows total GVA in Gauteng billion ZAR per km² for 2007. The highest intensity areas - with a GVA more than 500 billion per km² - are indicated by blue colour. The light green and dark green areas depict GAV 51-250 and 251 -500 million GVA per km², respectively. These comprise major towns or metropolitan nodes (e.g. Johannesburg or Pretoria).

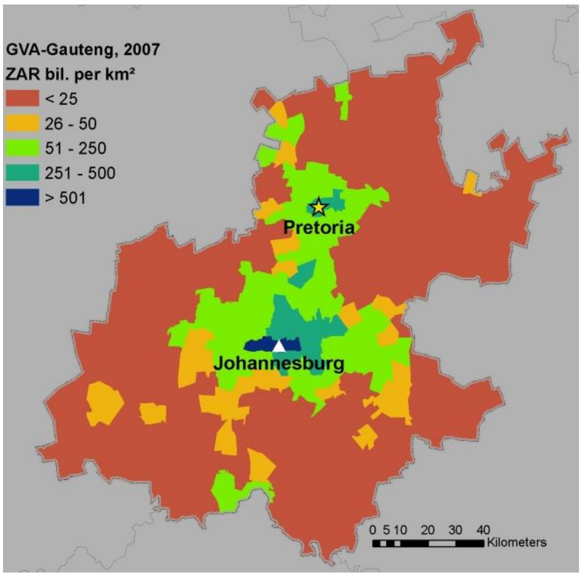

Figure 76: Total Gross-geographic Value Added (GVA) in Gauteng, 2007

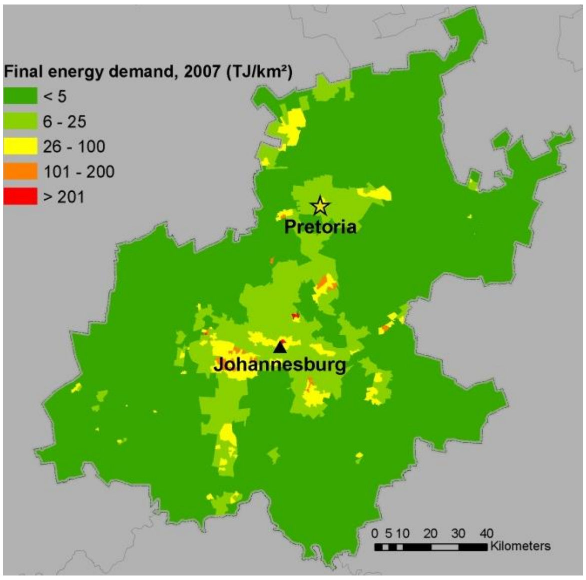

Figure 77: Final energy demand in the residential sector in Gauteng, 2007

Most of the GVA production is from the three metros (shown in blue and green). The southern industrial region also contributes to higher GVA, as seen in Figure 76. The energy demand, shown in Figure 77 has a similar pattern seen in the GVA distribution. The major energy demand is in the three metros with high GVA production. Moreover, when the income distribution (shown in Figure 72 and Figure 73) is compared with the GVA distribution, it shows a positive correlation between the high-income groups, final energy demand and GVA.

The outer municipalities with fewer job opportunities are mostly inhabited by poor and low-income groups and hence have comparatively low energy demand. As stated earlier, the spatial distribution of energy demand helps in locating households with high energy demand. The potential analysis of main renewable energy sources conducted in the next chapter will help in finding local solutions for such areas, which is described in the next section.

Comparison of final energy demands in the residential sector (2007 and 2040)

The final energy demand in the residential sector between 2007 and 2040 can be compared using following figures. The legend used for all three options, namely 2007, BAU and PUG is presented next to Figure 78. The energy demand per ward is divided into five categories, less than 50, 50 – 100, 101 – 250, 251 – 500 and more than 500 TJ per ward. Figure 78 presents the final energy demand for 2007. The final energy demand for 2040 using the BAU scenario is presented in Figure 79 and in Figure 80 for the PUG scenario. In 2007, most of the wards in the outer municipalities had a final energy demand of less than 100 TJ. Moreover, there were only two wards had a final energy demand of more than 500 TJ. On the contrary in 2040, three metros, Ekurhuleni, Johannesburg and Tshwane have many wards with final energy demand higher than 500 TJ. Similarly, the final energy demand in most of the wards in the outer municipalities has grown comparatively between 2007 and 2040. The final energy demand in the BAU scenario in 2040 will be 194 PJ and 185 PJ in the PUG scenario. As the difference of 10 PJ is spread over 450 wards in Gauteng, there is no visible difference between the spatial representation of these two scenarios (see Figure 79 and Figure 80).

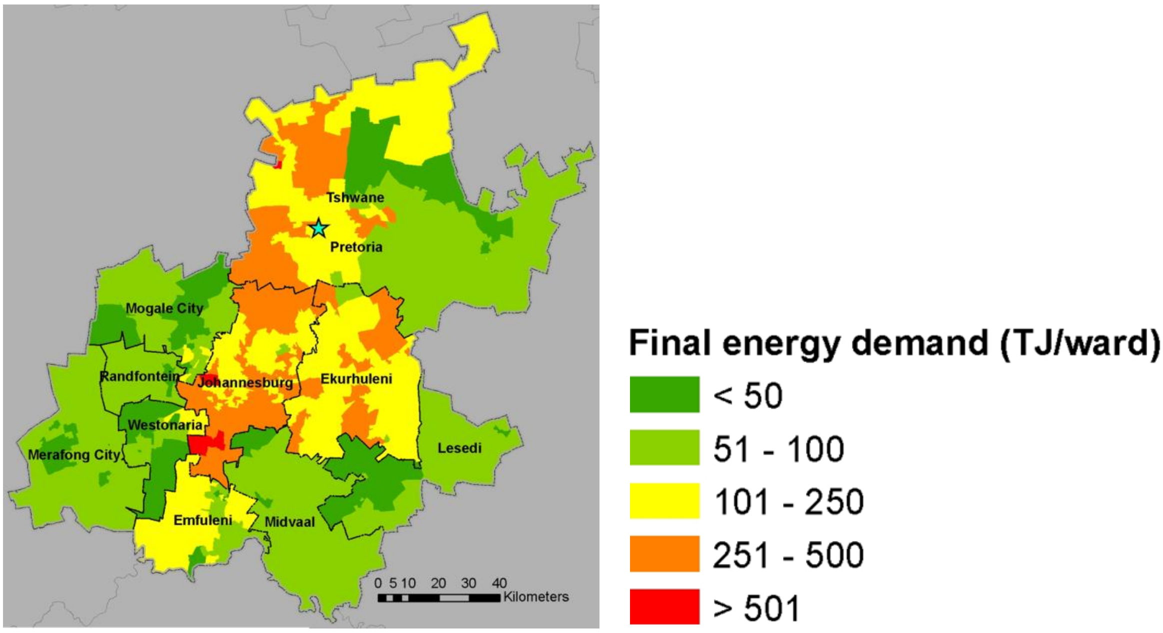

Figure 78: Spatial distribution of the final energy demand in the residential sector, 2007 (TJ/ward)

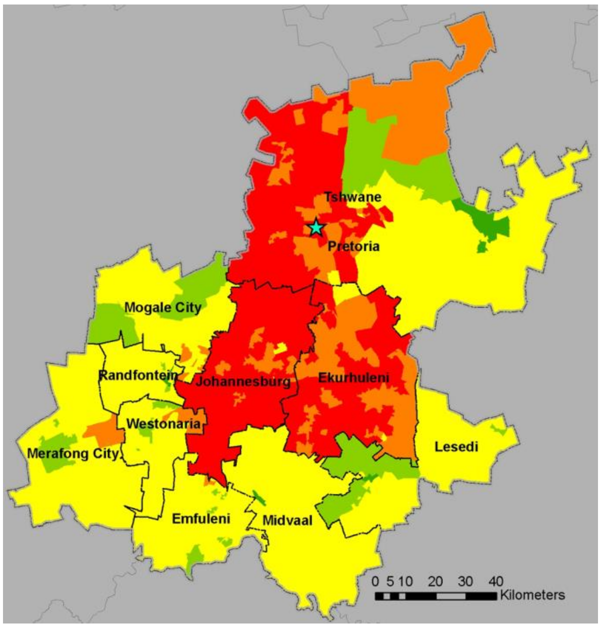

Figure 79: Spatial distribution of the final energy demand in the residential sector, BAU 2040 (TJ/ward)

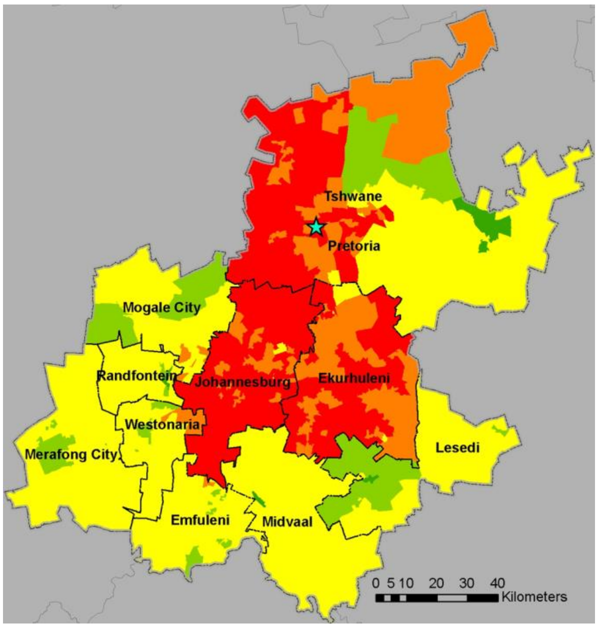

Figure 80: Spatial distribution of the final energy demand in the residential sector, PUG 2040 (TJ/ward)

Additionally, the results for the final energy demand in the residential sector at the municipality level are presented in Table 28. The final energy demand in the metro municipalities (Ekurhuleni, Johannesburg and Pretoria) is very high compared to the other municipalities. Economic and industrial development in these municipalities has resulted in high population density in these municipalities. Moreover, many mid- and high-income households live in these municipalities, resulting in high energy consumption.

Table 28: Final energy demand in the residential sector in Gauteng in the BAU and in the PUG scenario (2007 - 2040)

Municipality	Final energy demand in the residential sector (TJ)		
	2007	BAU 2040	PUG 2040
Emfuleni	2,866	6,022	5,590
Midvaal	628	1,583	1,506
Lesedi	59	1,038	979
Mogale City	2,341	6,290	6,027
Randfontein	967	1,879	1,786
Westonaria	592	1,826	1,758
Merafong City	114	3,682	3,488
Ekurhuleni	18,204	47,670	45,244
Johannesburg	30,120	75,941	72,757
Tshwane	20,110	48,073	45,931

The final energy demand in the residential sector in TJ per km² in 2007 and 2040 (BAU) is illustrated in Figure 81 and Figure 82 respectively. The increasing population, high share of mid- and high-income groups will result in increased energy demand in 2040. The areas of final energy demand more than 25 TJ per km², shown in yellow and orange will also increase by 2040.

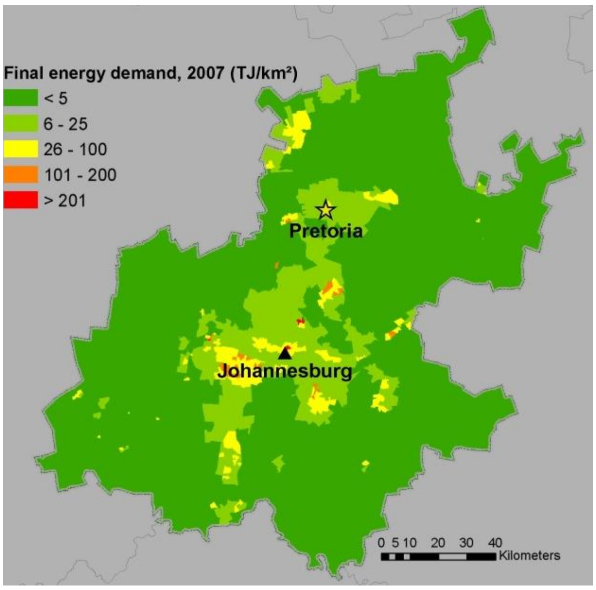

Figure 81: Final energy demand in the residential sector, 2007

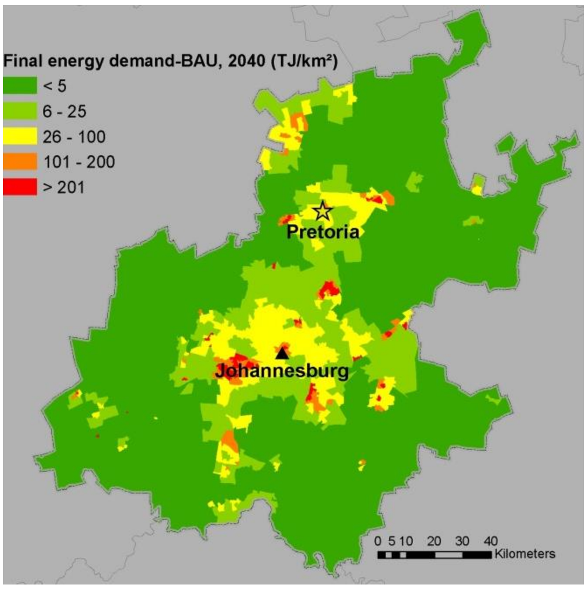

Figure 82: Final energy demand in the residential sector –BAU 2040

5.3. Potential of renewable energies in Gauteng

South Africa's electricity generation is mostly coal-based, which results in high greenhouse gas emissions. Very few attempts have been made in the past to estimate the available potential of renewable energy in the Gauteng region or in South Africa. Various spatial planning regulations have mentioned the use of renewable energy in the future, although none of these documents mentions concrete plans to implement it. To support the use of renewable energy in Gauteng and raise awareness in the region, it is important to analyse the available renewable energy potential in Gauteng. The policy-makers can use this analysis to create region-based policies for renewable energies in Gauteng. Furthermore, it can also be used by developers, planners to integrate renewable energy solutions in the new settlements and especially the communities can use the data at the local level to obtain specific solutions.

The main emphasis of the potential analysis is to manifest the geographic (location based) availability of various renewable energy sources in the region. This section presents the results of a GIS-based analysis at the provincial level, which was conducted to calculate the potential of renewable energy for: the wind, biomass (wood and energy crops) and solar. The solar energy is further divided into two categories according to the technology used: photovoltaic (PV) and solar water heaters. Land use constraints used for each technology are not exclusive, i.e. the same land area is used to estimate the potential of multiple technologies. Furthermore, as the technologies evolve, this technical potential may also change.

5.4. Analysis of wind potential

Wind data for coastal areas in South Africa can be found in the 'South African Wind Atlas', but detailed information on the inland wind speed in South Africa is still missing. Wind speed data used for the wind energy analysis is taken from NASA website. The available meteorological data is on a 1-degree longitude by 1-degree latitude equal angle grid covering the entire globe (64,800 regions) at a height of 50 m above ground. With the logarithmic elevation profile Equation 9 (Hau, 2006), the data is then converted to a height of 120 m above ground (Usual tubular steel towers of multi megawatt turbines have a height of 70 m to 120 m and in extremes up to 160 m).

$$v(z2) = v(z1)0.5 * \frac{[\ln z2/z0]}{[\ln z1/z0]}$$ **Equation 9**

Where,

v = wind speed, z0 = roughness length (0.03), z1 = 50m, z2 = 120m

Evaluation of suitable areas

At present, there are no regulations available for exclusion criteria for wind energy in South Africa. Hence, the exclusion criteria regulations available from the state of Baden-Württemberg, Germany are used here as a substitute which is shown in Table 29. Further information on GIS data used for the calculations can be found in Appendix I.

Table 29: Buffer zones used for calculating suitable area for wind turbines in Gauteng

Category	Buffer (m)
Urban area/Built up area	700
Roads and railways	200
Transmission lines	200
Industrial area	300
Protected areas	200
Water bodies	100

Areas excluded from the potential sites include:

- Topographic*:* Water bodies, wetlands (protected areas) and conservation areas
- Anthropogenic: Industrial areas (including oil and gas fields, mines, quarries), transportation (roads, railway lines), supply sector (transmission lines, substations), urban areas.
- Areas with a gradient of 8 % or higher (due to technical difficulties)

After the exclusion areas were discarded from the total area, the remaining available area was evaluated based on their proximity to the existing infrastructure (roads and transmission lines), as well as the wind speed. Multiple buffer zones around the roads and transmission lines were generated and then intersected with the wind speed zones. Data (shape files) used for wind potential are shown in Figure 83. The resulting map of wind suitability is illustrated in Figure 84. The total suitable area - after deducting exclusion areas- in Gauteng sums up to 2,182 km².

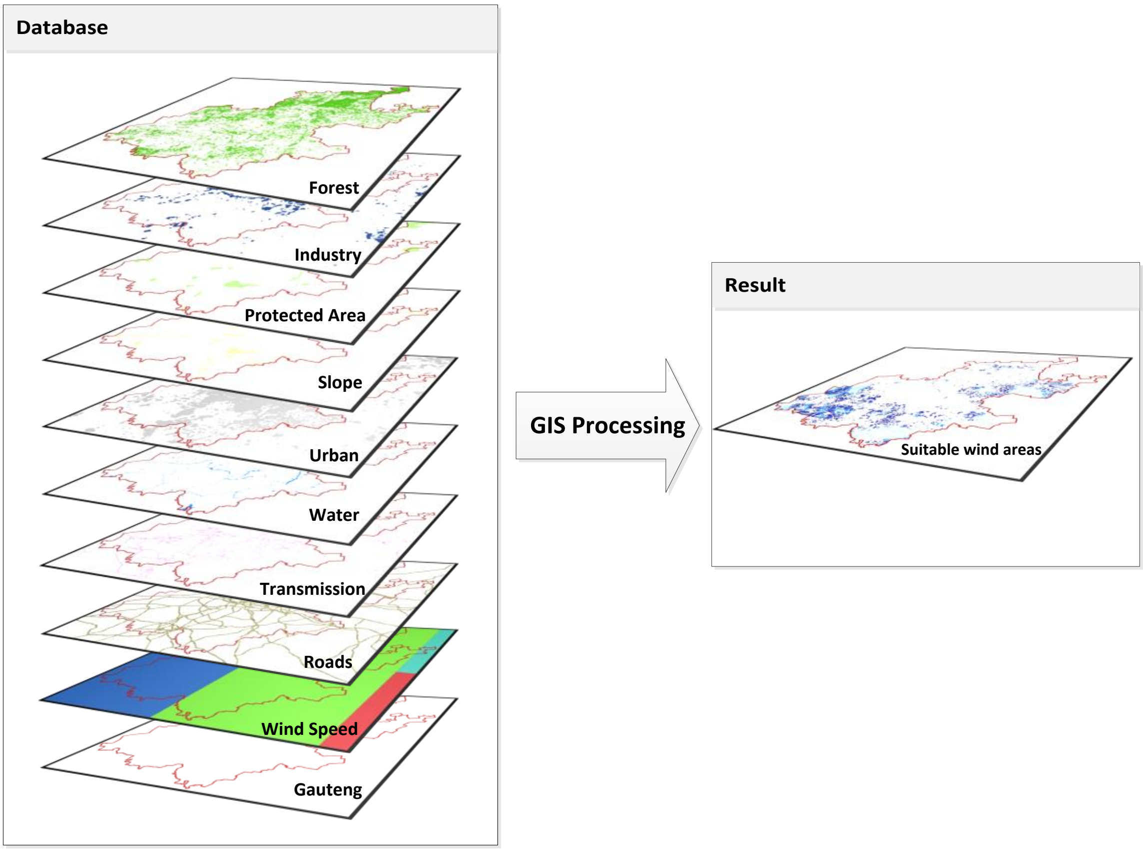

Figure 83: Database used for wind energy analysis and the resulting layer

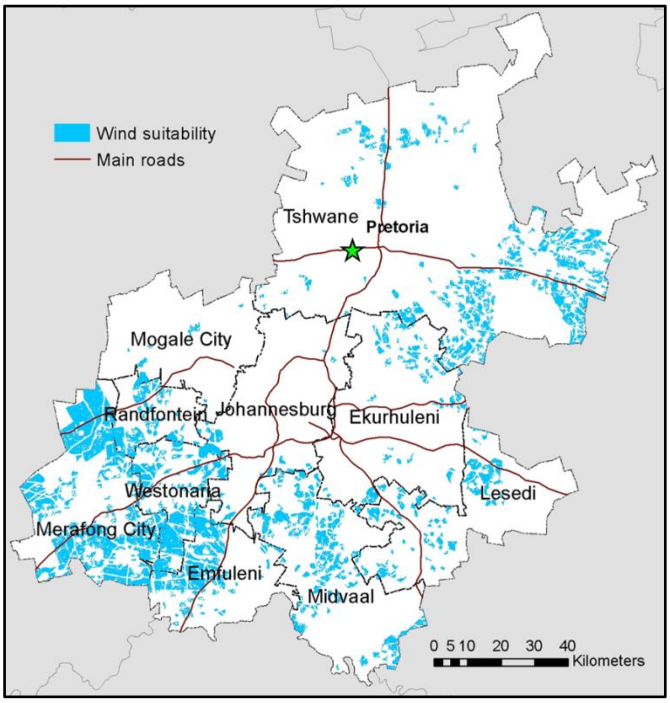

Figure 84: Map showing suitable areas for wind energy in Gauteng

The average wind speed in the aforementioned suitable area is 4.57 m/s. Hence, to calculate the possible wind potential, a representative 'Vestas V-80, 2MW' turbine was considered. The technical data used for the estimates are listed in Table 30. The availability factor for different wind speeds can be found in Schwarz (2011). In this study, the availability factor used for class 3 (4.5 to 6 m/s) was 16.5%, which is applicable to the average wind speed in Gauteng.

Table 30: Technical data used for wind potential analysis

Technical parameter	Unit	
Rotor diameter	m	80
Area swept	m^2	5,027
Cut-in wind speed	m/s	4
Nominal wind speed	m/s	15
Cut-out wind speed	m/s	25
Nominal output	MW	2
Availability factor	%	16.5
Annual electricity generation	MWh	2,891

Based on the technical data and the area required per wind turbine generator (WTG), the number of WTGs per municipality were calculated, which is depicted in Table 31. The table also shows annual electricity generation potential per municipality in comparison with the residential electricity demand. In 2007, in total, 3969 WTGs could be installed in Gauteng with an annual electricity generation potential of 11.47 TWh. With 100% potential utilisation, wind energy would cover about 54% of the total annual electricity demand in the residential sector in Gauteng. Although most of the Gauteng lies on the Highveld plateau, the wind potential in Gauteng is not very promising as the average wind speed in Gauteng is below 5 m/s.

Table 31: Wind energy potential in Gauteng, 2007

Municipality	Res. Demand (TWh)	Area (km^2)	No. of WTG	Elect. generation potential (TWh)
Emfuleni	0.80	203.05	369	1.07
Midvaal	0.17	262.27	477	1.38
Lesedi	0.02	142.66	259	0.75
Mogale City	0.65	19.91	36	0.10
Randfontein	0.27	101.52	185	0.53
Westonaria	0.16	221.62	403	1.16
Merafong City	0.03	592.16	1077	3.11
Ekurhuleni	5.06	104.85	191	0.55
Johannesburg	8.37	46.55	85	0.24
Tshwane	5.59	488.22	888	2.57
Total	**21.13**	**2182.81**	**3969**	**11.47**

Technical wind potential in 2040

For the year 2040, a detailed wind power analysis could not be carried out as the important data needed for exclusion criteria, such as infrastructure data is not available. Hence, due to lack of essential data, the wind energy potential in 2040 could not be evaluated. Additionally, though the land use model predicts simulated urban areas for the year 2040, it does not contain further disaggregation of urban areas into residential, infrastructure, industry, etc., hence important buffer zone calculation would be impossible. Moreover, based on the available open area in 2040, it can be concluded that lesser wind energy potential will be available in the 'BAU scenario', but for the 'PUG scenario', the potential is expected to remain the same.

5.5. Analysis of biomass potential

This analysis gives a spatial overview of biomass potential taking into account the availability from different sources such as woody biomass from forests and plantation, and energy crops.

Woody biomass potential: This analysis is based on the method developed by the Food and Agriculture Organisation of the United States (FAO). In 2010, FAO published a country-specific report on South African forest resource assessment (FAO, 2010). This report is based upon the thematic elements of sustainable forest management.

In this analysis, only woody biomass available from forests and plantations is considered. The 'forest' category is subdivided into woodlands, dense trees and wooded grasslands. Table 32 shows different types of land cover categories used in the analysis, along with their ownership share and the available area in km². Land under 'private ownership' is excluded from the analysis as acquiring such land or biomass from these lands may require legal efforts. On the other hand, land under 'public ownership' falls under community or local government ownership and can be easily administered by the local authorities. Land use category 'Plantation' has a low share of publically owned land, namely only 25%. Forests, on the other hand, have 70% of publically owned and 30% privately owned land.

Table 32: Land use categories and their share in Gauteng, 2007

Land cover category	Subtype	Area* (km²)	Share of public land (%)	Available land (km²)
Plantation	-	129.47	25	32.37
Forest	Woodlands	484.11	70	388.88
	Dense trees	114.58	70	80.21
	Wooded grasslands	233.27	70	163.29

*: area calculated from Geo-terra land use images

Table 33 shows additional parameters, such as stem volume, density, stem wood and biomass expansion factor (BEF[38]) used for the potential analysis. In South Africa, trees found in plantation areas have more than three times as much stem volume than the trees in the forest areas, which results in higher stem volume per hectare for plantation. On the contrary, the biomass expansion factor for the forest is more than twice compared to plantations. The calorific value used in the analysis for both categories is 15.6 MJ/kg (FAO, 2010). Country specific values for all these parameters are taken from FAO country report, South Africa (2010). Equation 10 shown below determines the amount of available biomass in tonnes. Based on these parameters and Equation 10, woody biomass potential for each municipality was determined.

Table 33: Parameters used for woody biomass potential, FAO 2010

Land cover category	Stem volume (m³/ha)	Density (t/m³)	Stem wood (t/ha)	BEF	Calorific value (MJ/kg)
Plantation	140	0.58	81.2	2.35	15.6
Forest	38	0.58	182.7	5.00	15.6

$$Available\ biomass = Area_{available} * stem\ wood * BEF$$ **Equation 10**

The total amount of electricity produced from available woody biomass can be estimated using a share of sustainable biomass available, calorific value and conversion efficiency (30%). To practice sustainable forest management, based on the literature data, two possible scenarios were determined (Duryea and Dougherty, 1991; IPCC, 2000). Based on the sustainable forest regeneration rates, in the realistic scenario, 5% of the total available woody biomass will be used for electricity generation and 10% woody biomass will be used in the optimistic scenario. Total woody biomass potential (tonnes) per municipality; final

[38] BEF: Biomass Expansion Factor is defined as the ratio of total aboveground oven-dry biomass density of trees with a minimum diameter at breast height (dbh) of 10 cm or more to the oven-dry biomass density of the inventoried volume. FAO country report South Africa gives a detailed overview of various BEF factors for plantation and different forest types in South Africa (FAO 2010).

energy demand in the residential sector and electricity generation potential from woody biomass are presented in Table 34. In Total, when the demand and the electricity generation potential are compared, it can be concluded that woody biomass can cover only a small share of electricity demand in the residential sector, merely 2.3% in the realistic scenario and 4.33% in the optimistic scenario.

Table 34: Technical woody biomass potential from forests and plantation in Gauteng, 2007

Municipality	Res. demand (GWh)	Available woody biomass	Technical woody biomass potential (GWh/a)	
		tonnes	Realistic (5%)	Optimistic (10%)
Emfuleni	797	232,063	17.55	35.11
Midvaal	175	229,196	19.20	38.40
Lesedi	16	135,728	11.14	22.28
Mogale City	651	374,699	29.68	59.36
Randfontein	269	128,855	8.95	17.90
Westonaria	165	81,076	5.61	11.22
Merafong City	32	218,234	19.44	38.89
Ekurhuleni	5,061	192,261	14.85	29.69
Johannesburg	8,373	111,318	10.51	21.03
Tshwane	5,590	4,716,657	320.79	641.57
Total	**21,128**	**6,420,086**	**472.72**	**915.45**

<u>Technical woody biomass potential in Gauteng, 2040</u>

Based on the micro-geographical model results (see 4.4), land use categories and available area under each category (km²) in 2040 in Gauteng for BAU and PUG scenario are illustrated in Table 35. The BAU scenario shows a total decrease of ca. 16% in the year 2040. The total increase in the total available area in the PUG scenario is 338.83 km² (51%). The vast difference between these two scenarios is due to the restricted urban growth and the assumption of stricter law and regulations (sustainable forest management) in the PUG scenario.

Table 35: Available area under various land use categories in Gauteng, 2040

Land cover category	Subtype	Available area (km²)		
		2007	BAU	PUG
Plantation	-	32.37	53.71	91.93
Forest	Woodlands	388.88	300.24	575.01
	Dense trees	80.21	70.14	136.10
	Wooded grasslands	163.29	135.78	200.54

The technical potential for BAU and PUG scenario in 2040 in Gauteng is presented in Table 36. The final energy demand in the residential sector disaggregated at the municipality level is compared with realistic (5%) and optimistic (10%) woody biomass potential for both scenarios. In 2040, the final energy demand in the residential sector is 53,933 GWh, compared to the realistic technical potential of 430.73 GWh (BAU) or 572.26 GWh (PUG). The optimistic technical potential is twice as much in both scenarios. Though there has been an increase in the total technical potential in Gauteng in the PUG scenario, the potential from the woody biomass is not enough to fulfil the final energy demand in the residential sector.

Table 36: Technical woody biomass potential from forests and plantation in Gauteng, 2040

Municipality	Res. demand (GWh)	Technical woody biomass potential (GWh)			
		BAU		PUG	
		Realistic (5%)	Optimistic (10%)	Realistic (5%)	Optimistic (10%)
Emfuleni	1,674	16.52	33.04	21.95	43.89
Midvaal	440	18.07	36.14	24.00	48.01
Lesedi	288	10.48	20.96	13.93	27.85
Mogale City	1,749	27.93	55.86	37.11	74.21
Randfontein	522	8.42	16.85	11.19	22.38
Westonaria	508	5.28	10.56	7.02	14.03
Merafong City	1,024	18.30	36.59	24.31	48.62
Ekurhuleni	13,252	13.97	27.94	18.56	37.12
Johannesburg	21,112	9.89	19.79	13.15	26.29
Tshwane	13,364	301.86	603.73	401.05	802.10
Total	**53,933**	**430.73**	**861.45**	**572.26**	**1144.51**

Technical energy crops potential in Gauteng, 2007

In Gauteng, several energy crops such as maize, rapeseed, sunflower, sugar cane and sugar beet are planted, although due to a lack of data availability on the other crops, this study only concentrates on maize and sunflower. First, from the land use data, the cultivation areas were recognised and analysed (see Appendix I). Figure 85 depicts the crop suitability areas in each municipality in Gauteng. Available areas in each municipality are indicated in Table 38.

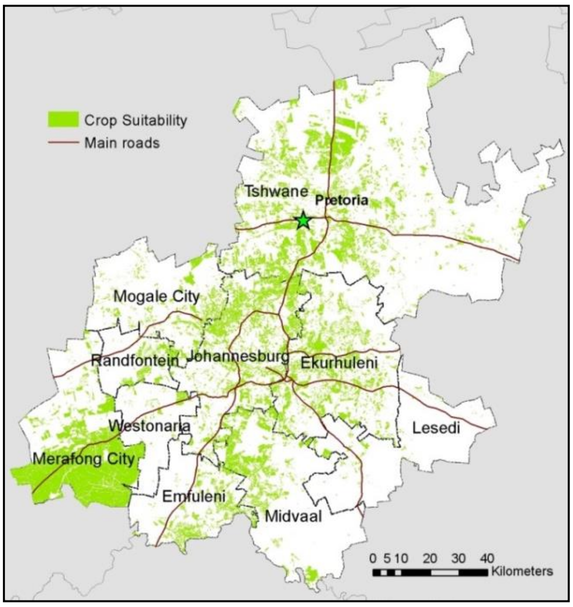

Figure 85: Crop (maize and sunflower) suitability areas at municipality level in Gauteng

Subsequently, the total potential from these areas was calculated and eventually, the number of power plants for each municipality was estimated. Technical data used to estimate biomass potential are described in Table 37. From one hectare cultivated area of maize, 8,500 m³ of biogas can be produced, with an assumption that maize has 30% dry matter (SGC, 2012; FNR, 2009). Sunflower has a comparatively low biogas generation rate of 5100 m³/ha. According to literature, one m³ of biogas corresponds to 6 KWh (FNR, 2009).

Table 37: Technical data used for energy crops potential in Gauteng

Parameter	Unit	Maize	Sunflower
Biogas from crop	m³/ha	8,500	5,100
Calorific value of biogas	kWh/m³	6	6
Plant efficiency	%	30	30

Table 38 demonstrates area under each crop in ten municipalities, along with the amount of electricity that can be generated. Based on the agricultural study conducted by Brent in 2014, only 10% of the available area under maize will be used for energy generation (Brent, 2014). The potential shown in this table is based on the assumption that for maize, 10% of the available area will be used for energy generation and 100% for sunflower. The total energy generation potential from energy crops in Gauteng is 443 GWh per annum, covering only 2% of Gauteng's final energy demand from the residential sector.

Table 38: Electricity generation potential from energy crops in Gauteng, 2007

Municipality	Demand	Area under Sunflower	Elect. generation	Area under Maize	Elect. generation	Total generation potential
Unit	**GWh**	**ha**	**GWh**	**ha**	**GWh**	**GWh**
Emfuleni	797	4,466	41.00	1,447.55	221.48	63.14
Midvaal	175	1,919	17.61	3,053.89	467.24	64.34
Lesedi	16	1,800	16.52	4,689.34	717.47	88.27
Mogale City	651	516	4.74	381.41	58.36	10.58
Randfontein	269	986	9.06	1,171.88	179.30	26.99
Westonaria	165	2,239	20.55	1,097.03	167.85	37.34
Merafong City	32	492	4.51	766.41	117.26	16.24
Ekurhuleni	5,061	805	7.39	2,662.74	407.40	48.13
Johannesburg	8,373	31	0.28	70.56	10.80	1.36
Tshwane	5,590	1657	15.21	4,675.27	715.32	86.74
Total	**21,128**	**14,911**	**136.87**	**20,016.08**	**3062.46**	**443.12**

Technical energy crop potential in Gauteng, 2040

The micro-geographical model analysis (see Table 24) carried out in this study shows 6.3% decrease in the agriculture area in the BAU scenario. In the PUG scenario, the area under agriculture remains unchanged. Furthermore, based on the historic data (Stas SA, 2008, 2010) and agriculture data provided by AGIS[39] and EnviroGIS[40], it was determined that the area under Maize and Sunflower will not change in the future. Hence, the same potential from the energy crops is estimated for 2040.

5.6. Analysis of solar energy potential

South Africa is endowed with very high solar radiation. Though solar power still does not play a major role in South Africa's energy mix, it may be an upcoming energy source for the country. This section analyses potential of various solar energy based technologies, such as solar water heaters (SWH) and photovoltaic (roof-top and open space) which are suitable for the residential sector.

[39] AGIS: Agricultural Geo-Referenced Information System. This institute is part of the National Department of Agriculture, South Africa.

[40] EnviroGIS: EnviroGIS is a South African multi-disciplinary professional company with expertise in both natural sciences and geographic information systems technology.

Technical potential of solar water heater in Gauteng, 2007

When the end-use energy demand is examined carefully, one can see that hot water demand is responsible for almost 40% of the end-use energy demand in Gauteng. Against the background of high hot water demand, the analysis of rooftop solar water heaters (SWH) was carried out. This analysis includes only suitable roofs, e.g. shacks in the informal settlements, small rooms in backyards, caravans, etc. are excluded due to the inability to support the weight of solar water heaters.

Hot water demand calculations

The households are divided into income groups as they have different hot water demand. A detailed analysis of hot water demand in Gauteng was carried out in 2012 (Oezdemir at al, 2012). Hot water demand data used is taken from Oezdemir at al, 2012, which is presented in Table 39. Based on economic status, average annual household hot water demand varies from 24,104 litres to 113,427 litres. To calculate the energy required to heat the specific amount of water, it is important to know the temperature of water at the inlet and to which degree it is heated. According to Meyer and Tshimankinda, who measured inlet temperature in numerous households Johannesburg, the average temperature was 17.3°C (Meyer and Tshimankinda 1997a, b). Typical thermostat temperature of an electric geyser in Gauteng is 65°C and is taken as the outlet temperature for specific heat calculations. To calculate the energy demand for heating water, Equation 11 was used.

$$Q = m * c_p * \Delta T \qquad \textbf{Equation 11}$$

Where,

Q = required amount of energy,
m = mass of heated water,
Cp = specific heat of water (4183 J/kg.K),
ΔT = temperature difference.

Using Equation 11, the temperature of water at inlet and amount of water used per year, hot water demand in Gauteng was calculated which is demonstrated in Table 39. The specific hot water demand of a poor household is 4.8 GJ per annum, low-income household lies at 10.5 GJ per annum, mid-income household consumes 16.4 GJ per annum, and high-income household has the highest energy demand for hot water, 22.6 GJ per annum.

Table 39: Hot water demand based upon income groups in Gauteng (Oezdemir et al, 2012)

	Unit	Poor	Low-income	Mid-income	High-income
Average hot water demand	l/HH.a	24,104	52,556	82,249	113,427
Tin	°C	17.3	17.3	17.3	17.3
Tout	°C	65	65	65	65
ΔT	°C	47.7	47.7	47.7	47.7
Specific hot water demand	GJ/HH/a	4.8	10.5	16.4	22.6

Analysis of available rooftop area

The available roof area was calculated for each income group and building type. Only three building types separate house, apartment buildings (flat) and semi-detached house were included in the analysis due to their stability and capacity to carry the weight of solar water heater. Area of each building type and roof type, the slope of the roof and available roof area for each income group and building type are presented in Table 40. The total roof area in Gauteng in 2007 amounted to be 215.41 km². To calculate the rooftop area, available for solar water heaters, two scenarios – a realistic and an optimistic- (based on the literature data) were developed. The realistic scenario assumes that 15.5% of roof area can be used for solar water heaters (Kaltschmitt, 1990) and the optimistic scenario assumes a share of 50% (Telsnig et al, 2014).

Table 40: Calculations of residential roof area in Gauteng, 2007 (Oezdemir et al, 2012)

	Building type	Roof type	Floor area (m²/HH)	Roof area (m²/HH)	Roof slope	% of HH	No. of HH	Roof area
High income	Separate House	Hipped	240	276	30	8.76	278,129	76.74
	Flat	Flat	82	27	0	0.81	25,880	0.92
	Semi-detached	Hipped	200	230	30	1.43	45,258	1.25
	Other*	-	-	-	-	1.23	38,924	0.00
Mid income	Separate House	Pitched	140	161	30	13.63	432,750	66.28
	Flat	Flat	82	21	0	2.34	74,335	1.00
	Semi-detached	Hipped	110	110	30	1.98	62,821	0.88
	Other*	-	-	-	-	2.56	81,386	0.00
Low income	Separate House	Pitched	50	58	30	22.02	699,119	47.96
	Flat	Flat	82	10	0	2.73	86,655	0.88
	Semi-detached	Pitched	45	52	30	0.88	27,853	0.59
	Other*	-	-	-	-	19.44	617,245	0.00
Poor	Separate House	Pitched	28	30.89	25	10.22	324,533	18.07
	Flat	Flat	82	8.2	0	1.08	34,441	0.53
	Semi-detached	Pitched	28	30.89	25	0.44	14,064	0.31
	Other*	-	-	-	-	10.46	332,186	0.00
	Total	-	-	-	-	**100**	**3,175,579**	**215.41**

Other*: Dwellings with roofs that are not suitable for solar water heaters.

For the technical potential of solar water heaters, it is assumed that the roofs are exclusively used for solar water heaters.

The potential is calculated using Equation 12. All required variables (Gauteng-specific) which were used to calculate the available potential in Gauteng are presented in Table 41.

$$P_{SWH} = A_R^{total} * F_a^{roof} * I_S * \eta_{SWH}$$ **Equation 12**

Where,

P_{SWH} = Potential of hot water obtained from solar energy (PJ/a),

A_R^{total} = Total available residential roof area (m²),

F_a^{roof} = Availability factor

I_S = Solar irradiation for the Gauteng region (7,837 MJ/m².a),

η_{SWH} = Efficiency of a solar water heater system.

Solar radiation data was taken from Winkler et al (2012) who analysed solar radiation data from 11 different sources at two sites in South Africa, namely, Pretoria (Gauteng) and Upington. The availability factor (F_a^{roof}) depends on slope, orientation, shading and obstacles (e.g. chimney) on the roof. For German conditions, on an average, a very conservative share of only 15.5% of the total roof would be available for solar water heaters (Kaltschmitt, 1990). Telsnig et al, on the other hand, assumed that 50% of the total rooftop will be available (2014). Hence, two scenarios were developed with realistic (15.5%) and optimistic (50%) share of the roof area. Based on literature data, a solar water system efficiency of 60% was assumed for the calculations (Oezdemir et al, 2012).

Table 41: Technical data used for SWH potential in Gauteng

Technical data	Unit	
Solar radiation	MJ/m².a	7,837
Availability factor (realistic)	%	15.50
Availability factor (optimistic)	%	50
SWH System efficiency [41]	-	0.60

The solar water heater potential for Gauteng was carried out at the municipality level. Based upon the available roof area (Table 40), the number of households[42], Equation 12 and the parameters shown in Table 41, the solar water heater potential in Gauteng was estimated, which is presented in Table 42. The number of households, their hot water demand and the potential for a realistic and optimistic scenario for each municipality can be

[41] SWH system efficiency factor is adopted from the solar water heater study conducted by Oezdemir et al. for the Gauteng region (Oezdemir et al, 2012). According to this study, this factor was calculated by estimating the demand side management potential of a SWH. To supply hot water throughout the day, electrical heating is necessary as a backup power. Solar water heaters have significant potential to reduce the electricity consumption in households, especially during peak periods, which is represented in form of system efficiency.

[42] Based on the South African statistical data, it is estimated that each household owns only one dwelling (Stats SA 2008 and Stats SA 2012). Hence, number of households and dwelling is equal, i.e. 3,127,293.

seen in this table. In all ten municipalities, in both scenarios, the amount of hot water that can be produced using solar water heaters is more than the demand. GIS-based visual representation of these results can be seen in Figure 86.

Ekurhuleni, Johannesburg und Tshwane have a higher share of the population compared to other municipalities, resulting in higher number of buildings and high SWH potential from the rooftop. In 2007, Gauteng had a total demand of 37.07 PJ. The realistic potential of 157.01 PJ is more than three times of the total demand or the optimistic potential of 506.47 PJ is almost 14 times the demand. This suggests that with the conservative roof availability factor of 15.5%, enough hot water for the residential water can be produced with solar energy.

Table 42: Technical SWH potential in 2007 in Gauteng at the municipality level (PJ)

Municipality	Households	HW* demand in the res. Sector (PJ)	Technical SWH potential	
			Realistic (15.5%)	Optimistic (50%)
Emfuleni	161,742	1.58	8.64	27.87
Midvaal	25,505	0.31	1.39	4.48
Lesedi	2,693	0.03	1.24	4.01
Mogale City	94,540	1.12	4.67	15.05
Randfontein	39,762	0.47	1.70	5.49
Westonaria	27,748	0.28	0.96	3.10
Merafong City	5,298	0.06	2.07	6.67
Ekurhuleni	845,280	9.31	34.09	109.98
Johannesburg	1,145,870	14.14	60.49	195.14
Tshwane	778,857	9.76	41.75	134.68
Total	**3,127,293**	**37.07**	**157.01**	**506.47**

HW*: hot water

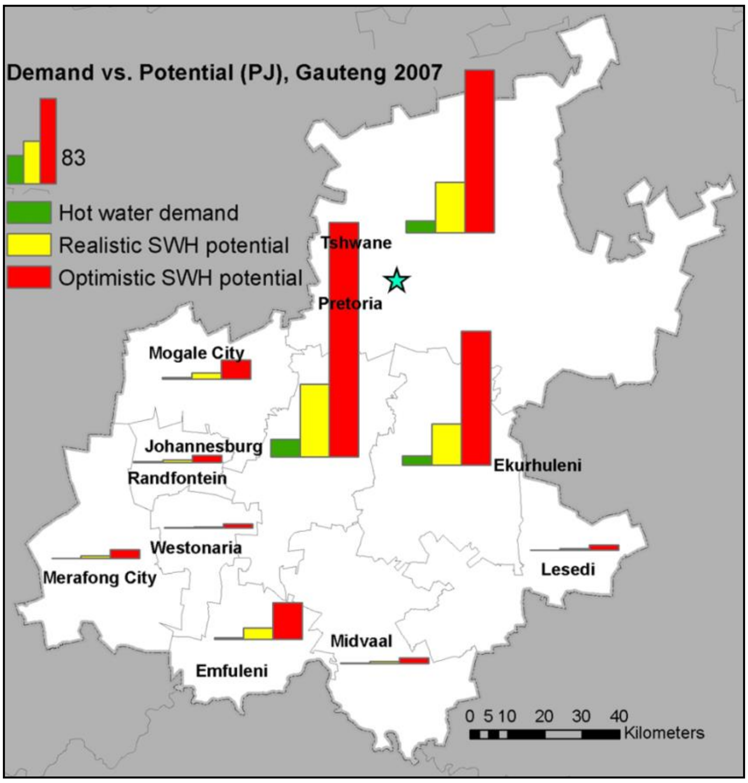

Figure 86: Comparison of the residential hot water demand and SWH potential (PJ) in Gauteng, 2007

Technical potential of solar water heater in Gauteng, 2040

Table 43 shows the estimates of the technical potential of solar water heater in 2040 for the 'BAU' and the 'planned urban growth (PUG)' scenario. In 2040, the hot water demand in the residential sector in Gauteng will rise up to almost 98 PJ. The technical potential from solar water heater for both scenarios was calculated based on the methodology described in the previous section. In 2007, in the residential sector in Gauteng, 215.41 km² of total roof area was available (see Table 40). Due to increased population and a high share of mid- and high-income group households in 2040 (see Figure 39); the total roof area will increase to 625.74 km². The realistic (i.e. 15.5% roof area) potential sums up to 456.08 PJ for BAU & PUG scenario. The optimistic (i.e. 50% roof area) potential amounts to 1471.24 PJ for both scenarios. The analysis shows there is enough rooftop potential for solar water heaters in Gauteng to cover the hot water demand of the residential sector in 2040.

Table 43: Technical SWH potential in 2040 in Gauteng at the municipality level (PJ)

Municipality	Households	HW demand (PJ)	BAU & PUG	
			Realistic (15.5%)	Optimistic (50%)
Emfuleni	307,996	3.24	23.46	75.68
Midvaal	54,263	0.81	4.07	13.13
Lesedi	42,926	0.54	3.30	10.63
Mogale City	211,368	3.13	14.07	45.39
Randfontein	76,211	0.95	3.94	12.71
Westonaria	64,601	0.89	3.56	11.49
Merafong City	139,912	1.90	6.43	20.76
Ekurhuleni	1,764,378	24.45	107.02	345.23
Johannesburg	2,535,322	37.85	171.79	554.17
Tshwane	1,621,936	24.23	118.44	382.05
Total	**6,818,913**	**97.98**	**456.08**	**1471.24**

Analysis of photovoltaic potential

For PV potential calculations, suitable rooftops and open spaces in Gauteng were considered. The detailed analysis is described in the following sections.

Technical potential of PV-rooftop in Gauteng, 2007

The rooftop analysis, which was carried out for solar water heaters was also used for the photovoltaic (PV) analysis (Table 40). The amount of electricity produced by each PV module is calculated using Equation 13.

$$E_{PV} = I_s * A_{available} * (100\% + f_{inclination}) * \eta * PR \quad \textbf{Equation 13}$$

Where,
E_{pv} = Amount of electricity produced by PV module (kWh/a),
I_S = Solar Irradiation (2,178.8 kWh/m²/a),
$A_{available}$ = Required roof area for one PV system (m²)
$f_{inclinatio}$ = Inclination factor (0.125),
η = module efficiency (0.15),
PR = Performance ratio (0.75).

Solar irradiation data mentioned above is taken from Winkler et al (2012). Area required for different PV modules can be calculated using Equation 14.

$$A_{available} = P_{el}/(STC * \eta) \quad \textbf{Equation 14}$$

Where,
$A_{available}$ = Required roof area for one PV system (m²)

P_{el} = Installed capacity (kWp),
STC = Standard test conditions (1 kW/m²),
η = module efficiency (0.15).

As the electricity demand of each household depends on their income, four different PV module sizes were chosen for this analysis. Furthermore, high-income households usually have bigger houses, providing more space on the roof for bigger PV installations compared to low or poor income groups. Hence, PV modules with an installed capacity of 5 or 10 kWp were chosen for mid and high-income households. Depending on the building type, low and poor households were provided with a 2 or 1.5 kWp panel system. An overview of the installed capacity, the area required and the amount of electricity produced by each system (based on Equation 13) are shown in Table 44.

Table 44: Different sizes of PV systems used for the PV-rooftop analysis in Gauteng, 2007

Income group	Building type	Installed capacity (kWp)	Area of each PV system (m²)	Electricity generation (MWh/a)
High and Mid	House on separate stand, Semi-detached	10	66.67	18.38
High and Mid	Flat	5	33.33	9.19
Low and Poor	House on separate stand	2	13.33	3.68
Low	Flat, Semi-detached	2	13.33	3.68
Poor	Flat, Semi-detached	1.5	10.00	2.76

The technical PV-rooftop potential for Gauteng was estimated using different PV systems (Table 44), available roof area pertaining to each dwelling type (Table 40) and no. of households in each income category; which are presented in Table 45. In this table, the technical potential is compared with the final energy demand in the residential sector at the municipality level, along with two possible penetration rates for household PVs. Comparing the penetration rates for various countries around the world[43], a realistic rate of 10% and an optimistic rate of 15% were chosen. Table 45 also shows the share of roof used for each option. When the total technical potential is utilised, i.e. all households with PV-rooftop, ca. 38% of available rooftop areas will be covered with PV panels. The realistic and optimistic penetration options will cover only 3.79% and 5.68% rooftops respectively.

[43] Penetration rate of household PV around the world varies a lot. Australia leads with a penetration rate of 16.5%, followed by Hawaii (12.39%) and Belgium (7.45%) (ESAA, 2013).

Table 45: Technical potential from PV-rooftop in 2007 in Gauteng (TWh)

Municipality	Res. demand (TWh)	Technical PV-rooftop potential (TWh)		
		Total (100%)	Realistic (10%)	Optimistic (15%)
Emfuleni	0.80	99.07	9.91	14.86
Midvaal	0.17	14.16	1.42	2.12
Lesedi	0.02	13.45	1.35	2.02
Mogale City	0.65	51.10	5.11	7.66
Randfontein	0.27	21.19	2.12	3.18
Westonaria	0.16	12.18	1.22	1.83
Merafong City	0.03	25.03	2.50	3.75
Ekurhuleni	5.06	255.46	25.55	38.32
Johannesburg	8.37	617.09	61.71	92.56
Tshwane	5.59	422.20	42.22	63.33
Total	**21.13**	**1,513.92**	**153.09**	**229.64**
Share of roof area	**-**	**37.87%**	**3.79%**	**5.68%**

GIS-based visual representation of the technical potential from PV-rooftop in Gauteng is demonstrated in Figure 87. Municipalities with the highest population have more dwellings/buildings and hence have more roofs which result in higher potential than in the other non-urbanised municipalities such as Lesedi or Midvaal. In spite of low or high share of the population, each municipality has enough PV-rooftop potential to cover the demand in the residential sector.

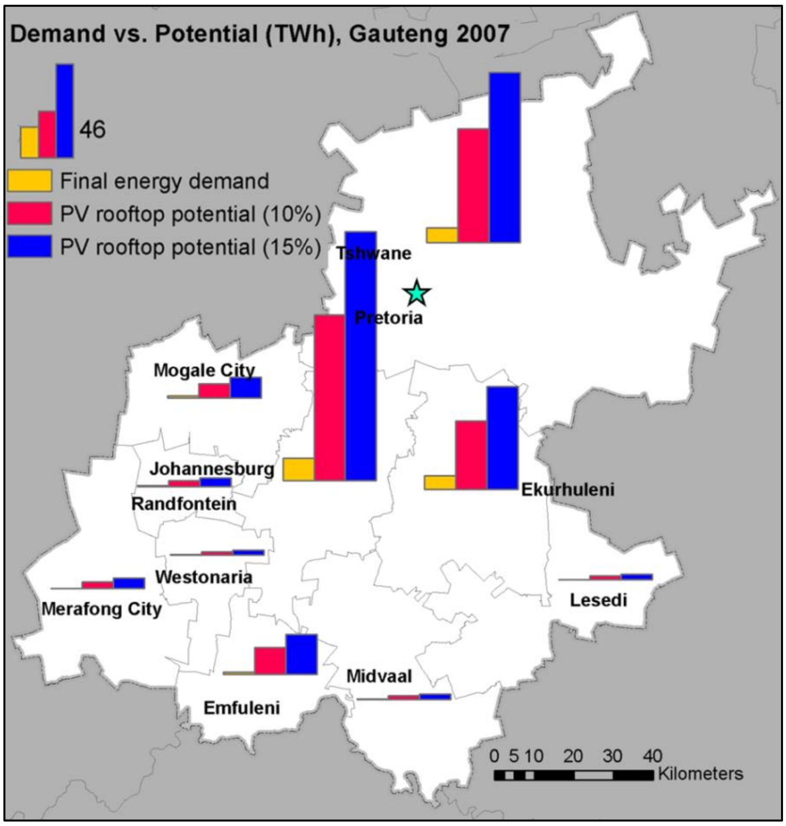

Figure 87: Comparison of the final energy demand in the residential sector and PV-rooftop potential (TWh) in Gauteng, 2007

<u>Technical potential of PV- rooftop in Gauteng, 2040</u>

The technical potential from PV-rooftop for both scenarios was calculated based on the approach described in the previous section. Compared to the analysis in 2007, an enhanced module efficiency of 0.25 was considered for the PV modules in 2040, resulting in smaller PV system area for the same installed capacity as shown in Table 46. If detailed data, such as, actual demand (2040) and detailed information on PV-technology development by 2040 is available, the PV-potential could be estimated more precisely.

Table 46: Different sizes of PV systems used for the PV-rooftop analysis in Gauteng (2040)

Income group	Building type	Installed capacity (kWp)	Area of each PV system (m²)	Electricity generation (MWh/a)
High and Mid	House on separate stand, Semi-detached	10	40.00	18.38
High and Mid	Flat	5	20.00	9.19
Low and Poor	House on separate stand	2	8.00	3.68
Low	Flat, Semi-detached	2	8.00	3.68
Poor	Flat, Semi-detached	1.5	6.00	2.76

The estimates of the technical potential of PV-rooftop in 2040 for the BAU and the PUG scenario, and the final energy demand in the residential sector are shown in Table 47. Total demand in the residential sector in 2040 would be ca. 54 TWh. The realistic (10% households) potential sums up to 251.74 TWh and the optimistic (15% households) adds up to 377.61 TWh in 2040 This analysis shows that enough potential would be available to cover the final energy demand of residential sector in 2040 in Gauteng.

Table 47: Technical potential from PV-rooftop in 2040 in Gauteng (TWh)

Municipality	Res. demand (TWh)	Technical PV-rooftop potential (BAU & PUG) (TWh)	
		Realistic (10%)	Optimistic (15%)
Emfuleni	1.67	15.72	23.58
Midvaal	0.44	2.40	3.60
Lesedi	0.29	1.84	2.75
Mogale City	1.75	11.21	16.82
Randfontein	0.52	3.28	4.93
Westonaria	0.51	1.99	2.99
Merafong City	1.02	3.95	5.92
Ekurhuleni	13.25	55.81	83.72
Johannesburg	21.11	103.98	155.97
Tshwane	13.36	51.56	77.34
Total	**53.93**	**251.74**	**377.61**

Technical potential of PV on open spaces in Gauteng, 2007

Open spaces used for PV analysis include abandoned sites (e.g. mining), bare land, bare rock, grasslands and open spaces. Two different sizes of power plants – 5 MW and 50 MW – were assumed for this analysis. To calculate the area required for the plant and the amount of electricity produced per plant, Equation 13 and Equation 14 were used. Under standard test conditions of 1 kWh/m², a performance ratio of 0.75 and a module efficiency of 0.15

were considered. Based on Equation 14, the total module surface area required amounts to be 3.33 ha for one 5 MW power plant and 33.33 ha for a 50 MW power plant. Total area required for the power plant is assumed to be 50% more than the required module surface area. The amount of electricity generated by 5 MW and 50 MW power plants is 9.19 GWh per annum and 91.92 GWh per annum respectively.

Availability of open spaces for PV

To calculate the available open space area, a GIS-based analysis was carried out. The exclusion criteria used for this investigation are similar to those used in the wind potential analysis. The excluded areas were conservation areas, natural reserve areas and wetland areas. After deducting these areas, the remaining plots were proofed for minimum available size. For the 5 MW plant, plots smaller than 5 ha and for 50 MW power plants, plots smaller than 50 ha were discarded from the available areas.

PV potential: 5 MW power plant

Similar to the rooftop analysis in the previous two sections, PV potential from open spaces was also carried out at the municipality level. Figure 88 shows areas with PV suitability in Gauteng. Merafong City has the largest area available for PV, in contrast to Lesedi, which has the least available area. The main reason for Lesedi's less potential is that most of the area in this municipality comes under conservation area and hence excluded from the analysis. The total available open space amounts to ca. 1,519 km².

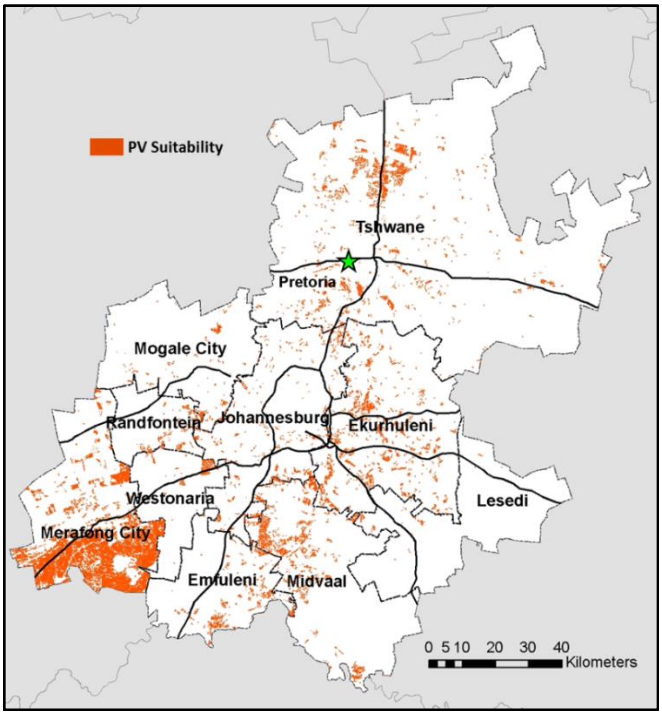

Figure 88: Map showing suitable areas for PV installation (5 MW) in Gauteng

The technical potential in each municipality is illustrated in Table 48. The total technical potential with 5 MW PV power plants sums up to 279.40 TWh in 2007. The table also compares technical potential with the residential demand in each municipality and demonstrates two possible options, a realistic option with 15% utilisation of the available area and an optimistic option with 25% utilisation. Even with the realistic option which uses only 15% of the available area, the demand for most of the municipalities, with the exception of Johannesburg, can be fulfilled. To satisfy the final residential energy demand in Johannesburg, ca. 58% of the available open space (in Johannesburg) must be utilised for PV power plant.

Table 48: Technical potential from 5 MW PV power plants in Gauteng, 2007 (TWh)

Municipality	Res. demand (TWh)	Area available (km²)	Technical PV potential (TWh)		
			Total (100%)	Realistic (15%)	Optimistic (25%)
Emfuleni	0.80	63.78	11.73	1.76	2.93
Midvaal	0.17	159.33	29.29	4.39	7.32
Lesedi	0.02	9.91	1.82	0.27	0.46
Mogale City	0.65	30.95	5.69	0.85	1.42
Randfontein	0.27	28.00	5.15	0.77	1.29
Westonaria	0.16	24.64	4.53	0.68	1.13
Merafong City	0.03	675.19	124.12	18.62	31.03
Ekurhuleni	5.06	187.47	34.46	5.17	8.62
Johannesburg	8.37	77.98	14.34	2.15	3.58
Tshwane	5.59	262.57	48.27	7.24	12.07
Total	**21.13**	**1,519.82**	**279.40**	**41.91**	**69.85**

PV potential: 50 MW power plant

The GIS analysis results for 50 MW PV power plants are illustrated in Figure 89. Total area requirement for a 50 MW power plant is 50 ha. The total available open spaces available in Gauteng were 721 km². Due to large plot size requirements, the area available for 50 MW is distinctively lower, reduced to less than 50% of the area available for 5 MW power plants.

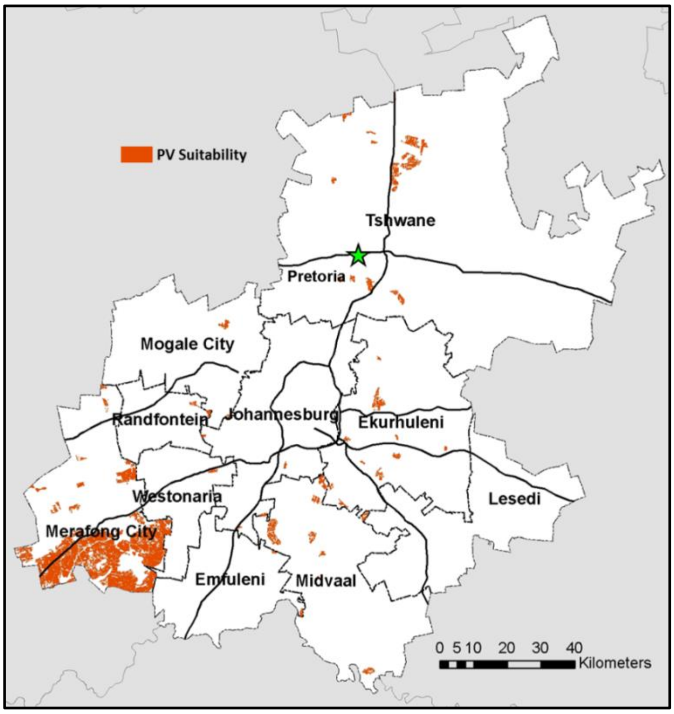

Figure 89: Map showing suitable areas for PV installation (50 MW) in Gauteng

The technical potential in each municipality is illustrated in Table 49. The total technical potential using 50 MW PV power plants lies at 132.54 TWh in 2007. Furthermore, the table compares technical potential with the residential electricity demand in each municipality. Similar to the analysis carried out for 5 MW power plants, two possible options, a realistic option with 15% utilisation of the available area and an optimistic option with 25% utilisation, are also presented in Table 49. The realistic option would generate 19.88 TWh, i.e. with the realistic utilisation option, 94% of the total residential demand can be satisfied. It must be noted that, the above-mentioned potential can only be fully exploited if appropriate storage technologies and infrastructure are available.

Table 49: Technical potential from 50 MW PV power plants in Gauteng, 2007 (TWh)

Municipality	Demand (TWh)	Area available (km^2)	Technical PV potential (TWh)		
			Total (100%)	Realistic (15%)	Optimistic (25%)
Emfuleni	0.80	3.20	0.59	0.09	0.15
Midvaal	0.17	46.40	8.53	1.28	2.13
Lesedi	0.02	0.00	0.00	0.00	0.00
Mogale City	0.65	6.44	1.18	0.18	0.30
Randfontein	0.27	5.02	0.92	0.14	0.23
Westonaria	0.16	3.27	0.60	0.09	0.15
Merafong City	0.03	544.25	100.05	15.01	25.01
Ekurhuleni	5.06	31.30	5.75	0.86	1.44
Johannesburg	8.37	4.03	0.74	0.11	0.19
Tshwane	5.59	77.08	14.17	2.13	3.54
Total	**21.13**	**720.99**	**132.54**	**19.88**	**33.14**

<u>Technical potential of PV on open spaces in Gauteng, 2040</u>

Table 50 shows the technical potential in TWh for 5MW PV power plants in Gauteng in 2040. Compared to the technical potential in 2007, there will a reduction of almost 20%, resulting in 225.03 TWh in 2040 in the BAU scenario. As the urban areas expand, lesser open space will be available for PV. On the contrary in the PUG scenario, there is only 6.5% reduction in the technical potential. In this scenario, the outward expansion of urban areas is restricted within the urban boundary, which results in more availability of open spaces compared to BAU scenario. Though it would not be feasible to utilise 100% technical potential shown below, it can be stated that enough PV-potential is available to cover the residential demand in 2040.

Table 50: Technical potential from 5 MW PV power plant in Gauteng, 2040 (TWh)

Municipality	Demand (TWh)	Technical PV potential (TWh)		
		2007	BAU (100%)	PUG (100%)
Emfuleni	1.67	11.73	8.79	11.73
Midvaal	0.44	29.29	21.97	29.29
Lesedi	0.29	1.82	1.28	1.82
Mogale City	1.75	5.69	4.27	5.69
Randfontein	0.52	5.15	4.38	5.15
Westonaria	0.51	4.53	4.08	4.08
Merafong City	1.02	124.12	117.92	124.12
Ekurhuleni	13.25	34.46	20.68	27.57
Johannesburg	21.11	14.34	7.88	10.75
Tshwane	13.36	48.27	33.79	41.03
Total	**53.93**	**279.40**	**225.03**	**261.23**

Table 51 presents the technical potential (TWh) from 50MW PV power plants in Gauteng in 2040. Similar trends, observed in technical potential from 5 MW PV (Table 50) are also seen here. Compared to 2007, the technical potential in the BAU scenario reduces to 102.85 TWh with a reduction of 22% and to 114.22 TWh in the PUG scenario with a reduction of 14%. Furthermore, the technical potential in both scenarios is still more than the residential demand in 2040.

Table 51: Technical potential from 50 MW PV power plant in Gauteng, 2040 (TWh)

Municipality	Demand (TWh)	Technical PV potential (TWh)		
		2007	BAU (100%)	PUG (100%)
Emfuleni	1.67	0.59	0.00	0.59
Midvaal	0.44	8.53	4.27	7.68
Lesedi	0.29	0.00	0.00	0.00
Mogale City	1.75	1.18	0.89	1.18
Randfontein	0.52	0.92	0.74	0.92
Westonaria	0.51	0.60	0.00	0.60
Merafong City	1.02	100.05	80.04	85.05
Ekurhuleni	13.25	5.75	4.32	4.89
Johannesburg	21.11	0.74	0.56	0.56
Tshwane	13.36	14.17	12.04	12.75
Total	**53.93**	**132.54**	**102.85**	**114.22**

5.7. Integration of energy demand and energy potential

5.7.1. Supply and demand comparison at the municipality level

The potential was compared at the municipality level in order to have an overview of the spatial distribution of the available resources in the region in order to provide suitable local solutions. Furthermore, the analysis shows that at the municipality level, depending on the type of renewable energy carrier chosen, there is more than enough potential available. Due to the abundance of high solar irradiation in the region, solar energy options, except 50 MW PV-plant, are suitable for almost all municipalities. Wind and biomass are best suited for the municipalities which are not yet highly urbanised, e.g. Lesedi or Midvaal. The municipality Merafong city, with less population and plentiful availability of land, is best suited for all renewable energy options examined in this study.

5.7.2. Supply and demand comparison at the provincial level

Though various renewable energy potentials cannot be added together, an attempt has been made to compare the supply and demand in Gauteng. Table 52 compares the potential (electricity and heat) from various renewable energy carriers with the residential demand in Gauteng for the year 2007. The potential is divided into three categories, namely, total, realistic and optimistic potential. Various assumptions made for the optimistic and realistic potential estimates are described in the previous section in detail and vary for each energy carrier or technology. The abundance of solar energy in Gauteng can be verified through the high technical potential estimates for solar water heaters and photovoltaic. Potential from the wind, woody biomass and energy crops are minimal and should be verified at the local community level.

Table 52: Technical potential of various renewable energy carriers in Gauteng, 2007 (TWh)

Energy carrier	Potential			Generation type
	Total	Realistic	Optimistic	
Wind	11.47	11.47	-	Electricity
Biomass-Wood	9.15	0.46	0.92	
Biomass-Energy crops	0.44	0.44	-	
Solar PV Rooftop	1,530.92	153.09	229.64	
Solar- PV (5 MW)	279.40	41.91	69.85	
Solar PV (50 MW)	132.54	19.88	33.14	
Residential demand	21.13			
Solar-SWH	140.69	43.61	140.69	Heat
Residential demand	10.30			

Summary of the total technical potential for various renewable energy carriers in Gauteng for 2040 is presented in Table 53. Due to lack of infrastructure data, the wind energy potential for 2040 could not be estimated. The energy crop potential remains same as in 2007. Woody biomass potential is reduced (0.54 TWh) in the BAU scenario and increased by 2.3 TWh in the PUG scenario. Due to increase in the roof area, an increase in SWH and rooftop-PV can be seen in both scenarios. On the contrary, reduction in open space PV (5 MW & 50 MW) potential is expected in both scenarios. To conclude, in 2040, enough technical potential (electricity and heat) will be available in Gauteng to cover the final energy demand in the residential sector.

Table 53: Technical potential of various renewable energy carriers in Gauteng, 2040 (TWh)

Energy carrier	Potential (BAU)			Potential (PUG)			Generation type
	Total	Real.	Opti.	Total	Real.	Opti.	
Wind	-	-	-	-	-	-	Electricity
Biomass-Wood	8.61	0.43	0.86	11.45	0.57	1.14	
Biomass-Energy crops	0.44	0.44	-	0.44	0.44	-	
Solar PV Rooftop	2,157.42	251.74	377.61	2,157.42	251.74	377.61	
Solar- PV (5 MW)	225.03	33.75	56.26	261.23	39.18	65.31	
Solar PV (50 MW)	102.85	15.43	25.71	114.22	17.13	28.55	
Residential demand	53.93						
Solar-SWH	408.68	126.69	408.68	408.68	126.69	408.68	Heat
Residential demand	27.24			27.24			

6. Conclusion and recommendations

One of the main objectives of this study was to evaluate the land use change in Gauteng and simulate the future land use patterns in the region. The land use patterns, their transition and simulated future urban dynamics in Gauteng were analysed with the help of a cellular automata and GIS-based simulation model.

Further objectives include the analysis of the final energy demand in the residential sector and its relation to the changing land use patterns. A GIS-based tool was developed, that distributes the energy demand on a spatial level/larger geographical area. Moreover, with the help of ArcGIS, the potential of various renewable energy carriers (biomass, solar and wind) was also investigated.

6.1. Conclusions

6.1.1. Land use change and spatial form of Gauteng

The land use change in Gauteng indicates a high rate of the encroachment of urban areas into other land use categories due to rapid urban growth between 1991 and 2009. The forest areas and open spaces were the most vulnerable land use categories. Between 1991 and 2009, Gauteng lost more than 1600 km² of forest. Furthermore, open space, areas under water and wetlands were also affected. Despite the government’s effort to stop the encroachment into these vulnerable areas, a lot of land was lost to urban/built-up areas. Stricter law enforcements must be practised to stop further deforestation and loss of biodiversity while preserving the natural environment.

To identify Gauteng’s spatial form, a commonly used factor - Shannon’s entropy - was employed. As this factor is used by many researchers around the world it is a good comparative indicator to measure Gauteng’s spatial form. Especially, GIS data coupled with Shannon’s entropy approach helped in recognising and measuring the spatial extents of land development at both the municipal and the regional level. The entropy factor calculations confirm Gauteng’s dispersed urban form.

As Shannon’s entropy factor is highly sensitive to the area of each zone, the calculations of the entropy factor were made at three different levels: regional, municipal and along the road network. The three sets of calculations were conducted to ascertain whether the entropy factor in Gauteng varies at different levels. The calculation showed that urban sprawl in Gauteng does exist at various levels.

The use of Shannon’s entropy factor has its advantages and disadvantages. As it is a universally used factor, it is easier to compare the study area with other cities around the world. Additionally, it does not require a lot of data to calculate the spatial form of a region; hence, the calculations are simpler and quicker and can be applied to cities/regions like Gauteng that lack detailed data. The factor measures the share of built-up area compared to the total area in a zone. The distribution of this built-up area (in the considered zone) is not considered in the entropy factor. This might be misleading as parts of the city can be densely populated whereas other remaining parts could be vacant. Furthermore, the ward size in Gauteng depends on administrative boundaries and varies a lot. This also has a negative impact on the entropy factor.

Despite its advantages and disadvantages, the method can be used to quickly measure, monitor and identify the spatial form of a city/region and provide policy-makers and planners with a quick scientific method to monitor the urban growth, especially for large regions like Gauteng.

The urban sprawl was also verified through visual examination by overlapping the urban areas of three images (1991, 2001 and 2009) using GIS. The analysis confirmed that the urban areas in Gauteng have become more dispersed in the last two decades.

This study has demonstrated the usefulness of GIS and CA-based urban growth modelling in providing useful land use change information, which plays an important role in planning and policy-making. The approach and the models used in this study can be further used for the analysis of urban growth and land use changes in other developing countries, where the amount of data available and the quality of geographic information is very limited.

6.1.2. Consequences of urban sprawl

Poorly managed urban structure and rapid urban growth have resulted in the sprawling structure of Gauteng which has resulted in the following consequences:

Reduction in the open spaces: Open space is usually one of the first victims of increasing urbanisation. Between 1991 and 2009, a decrease of around 48% took place, i.e. a total of 172 km² area was converted from open space to another category.

Reduction in the fertile land: Land under plantation has reduced from 325 km² in 1991 to only 133 km² in 2009, i.e. more than half of the land under plantation is lost.

Reduction in the forest area: Forest areas include woodlands, areas under dense trees and wooded grasslands. There has been a constant decrease in all these three categories over the years. A total decrease of 1,644 km^2 (approximately 66%) occurred between 1991 and 2009.

Reduction in wetlands: Wetlands are one of the most important parts of biodiversity. Losing wetlands can result in an imbalanced ecological environment. Gauteng lost almost 4% (21 km^2.) of its wetland area during last two decades.

Moreover, simulation results show that if the uncontrolled urban growth continues (BAU scenario), there will be a noticeable reduction in all land use categories, except the category 'urban'. Moreover, the land under 'urban' will grow by 86 %. On the contrary, PUG scenario results show planned growth will not only result in urban densification of Gauteng but will also help in conserving land under open space, forest and cultivation. This scenario shows an increase of 30% in the category 'urban'.

6.1.3. Energy demand and GHG emissions

In 2007, the residential sector in Gauteng was responsible for 10% of the final energy demand. The energy demand in the residential sector is driven by various factors such as the economic background of the household, the price of fuels and appliances used, the availability of fuels and appliances and the cultural preferences. The financial status of the household determines the type and quantity of fuel used. In 2007, on average, poor households consumed 12.39 PJ, low-income households 16.91 PJ, mid-income households 37.95 PJ and high-income households consumed 52 PJ of energy. This confirms that the income disparity is also mirrored in the energy demand patterns.

When total final energy consumption in 2007 is further divided by end-use type, water heating has the highest share in the final energy, followed by cooking, space heating, appliances and lighting. As the technologies used for space heating, lighting and appliances are more efficient that those used for water heating and cooking, they have a smaller share in the total final energy consumption. Although the high demand for water heating is seen in all income groups, the appliances and fuel used vary between different income groups. An average high-income household has a water heating demand of about 27 GJ and mainly uses electricity to fulfil their need. A small share of high-income households also uses natural gas and LPG for water heating. The use of natural gas is, to an extent, dependent on the location of the household as the natural gas pipeline network is yet to be extended to all parts of Gauteng. An average mid-income household uses 19 GJ of energy for water heating and uses the same share of fuel as high-income households. An average low income and poor household use around 4 GJ and 3 GJ, respectively. These households mainly use electricity and paraffin to fulfil their needs.

In most of the end-use needs, high-income households on an average consume more energy in comparison with the other income groups. The only exception is the energy demand for cooking, where low and poor income households consume ca. 5.5 GJ per household more energy than mid (2.4 GJ per household) or high-income households (1.9 GJ per household). The higher energy consumption results from usage of technologies with lesser efficiency than an electric stove, such as paraffin stoves or wood and coal stoves. Many poor and low-income households can neither afford efficient technologies nor have access to electricity. Hence, they usually fulfil their energy needs with a mix of fuels, such as LPG, coal and wood. Based upon technologies used by various income groups and their energy demand patterns, it is evident that the lower income groups (poor and low income) have different concerns than higher income groups (mid and high income). Hence, the former income groups need better and more efficient appliances, cleaner fuel and access to electricity, whereas for the latter group the integration and higher share of renewable energy, and energy savings should be the main focus.

In 2007, the energy carriers used in the residential sector in Gauteng were electricity, paraffin, LPG, coal, wood, natural gas and solar energy in the decreasing order of magnitude. Electricity will remain the dominant energy carrier in all income groups until 2040. The final energy demand in the residential sector will increase from 76.0 PJ in 2007 to 194.46PJ (BAU) or 184.58 PJ (PUG) in 2040, i.e. an increase of 170 % or 156 %. Both scenarios consider different shares of energy carriers and penetration rates for various technologies. The GHG emissions are strongly influenced by the energy carriers used, their share in the final energy mix, appliances used and their efficiency. The GHG emissions in 2007 amount to 0.9 Mt CO_2-equivalent. The BAU scenario shows an increase of 163% with 2.37 Mt CO_2-equivalent in 2040. The PUG scenario results in slightly lower emissions than the BAU scenario due to a higher share of renewable energy. The PUG scenario emission sums to 2.27 Mt CO_2-equivalent in 2040, reflecting a total increase of 152%.

6.1.4. Importance of mapping energy distribution & calculating potential

Data on the spatial distribution of energy demand and renewable energy potential for Gauteng are non-existential. In this study, based on various data and assumptions, maps for energy demand and technical potential of biomass, solar and wind were created. The methodology developed and the results presented could provide guidance to the government and the policy makers in evaluating the potential and in setting energy strategies for the region.

Energy consumption distribution

This study has identified and mapped the locations of energy demand throughout the region. With the help of these maps, the city planners will be able to identify priority locations for energy efficiency and sustainable energy solutions. Additionally, the representation of the future energy demand will help city planners in integrating city development with energy planning. With the help of these results, a strategic evidence-based energy plan for the city can be created, especially with the help of renewable energy sources available in the region.

The spatial allocation of energy helps in understanding the energy problems in the region, particularly concerning where the areas of high energy demand are situated. Residential areas with high energy demand should be targeted for implementing energy efficiency technologies and renewable energy solutions as mentioned above. Furthermore, this analysis also assists in locating the areas affected by high as well as low energy demand. Low-cost and clean energy solutions for such communities should also be integrated into energy policy.

Renewable energy potential

To quantify and locate the technical potential of local sustainable resources, the renewable energy potential at the municipality level was calculated. The technical potential (biomass, solar and wind) estimate matched with the energy demand reveals that enough potential (electricity and heat generation) is available to cover the residential energy demand in Gauteng. The mapping also helps in recognising decentralised solutions for far-off communities.

It should not be forgotten that this analysis considers overlapping areas (same area for more than one energy carrier) in the calculations. Hence, the potential from different energy carriers should not be added together as it will result in the parallel use of the same area for various energy carriers. Furthermore, a detailed wind speed map at 80 m, 100 m and 140 m height (same as the height of rotor) along with the wind direction will help in terms of better understanding the wind potential in the region. The biomass potential was conducted for woody biomass from forest and two energy crops: maize and sunflower. Lack of spatial data on other crops hindered the possibility of conducting detailed potential for other crops. Also, more accurate solar irradiation data will help in achieving more precise results.

Although Gauteng has a high renewable energy potential, it should be dealt with caution owing to above-mentioned limitations. For local solutions, each area should be examined carefully. The 'Spatial Development Framework' and other planning regulations talk about renewable energy options but do not mention any strict rules and regulations for implementation. The local and provincial government should consider enforcing the increased use of renewable energy at the municipality level based on the available potential illustrated in this study.

6.2. Recommendations

The simulation model results show that emphasis should be placed upon restricting future urban growth within today's urban boundary to stop future sprawl. Encouraging the brownfield and infill development within the city will help in terms of the more effective and efficient use of such areas. A polycentric city structure - where plenty of housing and job opportunities are available nearby - would be a suitable option for Gauteng. The following recommendations/policy implications can be deduced from the conclusions drawn in the previous section.

6.2.1. Policy implications for efficient spatial development

The compact urban form must be one of the main focuses of the spatial planning guidelines in future. Preferring inner city development, promoting mixed-income and mixed-use settlements, envisaging higher densities, strengthening the transport-oriented corridor development[44], as well as the polycentric development in Gauteng, are few of the measures that need to be included in the framework guidelines. These measures should not only be

[44] The article 'Historical spatial change in the Gauteng City-Region' (Mubiwa and Annegarn, 2013) throws light on benefits of transport-corridor development in Gauteng.

included in the framework but also enforced and implemented soon in Gauteng. The spatial structures that warrant focus are further described below:

Achieving **mixed development** through the creation of neighbourhood units comprising different housing categories with a variety of housing typologies and densities, suitable for various income groups. High-income households agglomerated in one region results in high energy demand in that area. Mixed development will help in reducing high-intensity energy demand areas in Gauteng.

Intensification and in-filling: The micro-geographical model results show that uncontrolled urban growth will lead to low density and dispersed urban growth which will result in loss of important land, e.g. forest, open spaces or wetlands. Using abandoned settlements or land available within Gauteng’s urban boundary will assist in urban densification and stop urban sprawl. Also, it will lead to the resourceful use of available land. Expansion of urban areas outside this urban boundary should only be permitted once the land resources within the urban boundary are fully exhausted.

Polycentric development: Industrial and economic development shall be encouraged in the non-metro municipalities creating small economic centres all over the region. This will result in polycentric development in Gauteng. Increased job opportunities in these areas would also induce population influx from metro municipalities which will help in reducing energy demand in the metro municipalities.

6.2.2. Policy implications for sustainable energy use and climate mitigation

Besides enforcing above-mentioned spatial planning policies, more opportunities should be created for the generation of **renewable energy** from various sources.

In poor and low-income groups, climate mitigation can only take place when poverty is eradicated. For those income groups, poverty alleviation should be the first priority. Providing north-facing passive houses equipped with solar water heaters will not only increase the standard of living of these households but will also help in reducing final energy demand and emissions. Moreover, water heating has the highest share in the final energy consumption in the residential sector. Encouraging the households to use solar water heaters, providing subsidised blankets for electric geyser and promoting in-line geysers rather than old-fashioned boiler geysers that use more energy would save a lot of energy, especially during the peak demand hours.

Furthermore, the energy demand in poor and low-income households is not very high, although the appliances used by these households are highly inefficient and cause direct emissions resulting in indoor pollution. Providing more efficient and cheaper appliances at subsidised rates will reduce the energy demand and the air pollution caused by these income groups.

In the mid and high-income communities, more emphasis should be placed upon spreading awareness regarding energy savings and energy efficiency. Policies like an increased share of green energy in households along with new regulations such as small-scale or community-based REIPPP[45] programme for households and communities should be developed to encourage the use of green energy.

Stricter by-laws shall be developed and enforced for all new buildings. ***Passive houses*** can play a huge role in reducing the future energy demand for space heating. Moreover, upgrading the existing structures, i.e. rehabilitation measure, to match the new regulations should be made mandatory for older buildings which tend to use more energy.

The government should also invest in research and further investigations such as new energy options like waste to heat and biofuels, as well as their applicability in the region. The final energy demand and the carbon emissions in Gauteng can only be reduced if the aforementioned recommendations are implemented through various policy measures.

6.2.3. Outlook on future research

The simulation undertaken in this study was conducted at two different levels, namely the macro- and micro-geographical level. The data used for the macro-geographical level was mainly the province level data (i.e. one value for the entire region), which could not be disaggregated to the metro/municipality level. Explicit data on population growth, GDP and economic activities disaggregated at the metro/municipality will enhance the results.

[45] REIPPP Programme: Renewable Energy Independent Power Producer Procurement Programme. This programme has been designed so as to contribute towards the target of 3 725 megawatts and towards socio-economic and environmentally sustainable growth, and to start and stimulate the renewable industry in South Africa.

The thesis concentrated on the residential sector in Gauteng which has a share of 10% in the final energy demand. The industry sector has the largest share in the final energy demand in Gauteng with significant impact on climate. Further research is needed to identify mitigation options in the industry sector. Furthermore, research on possibilities of energy reduction in the public buildings would assist the Gauteng government in identifying and implementing these solutions which would give the government an opportunity to lead by example for other sectors.

This study focused only on GHG emissions. Other non-GHG pollutants like NO_x, SO_x, and particulate matter (PM) have a negative impact on human health, especially in poor and low-income sectors. These non-GHG emissions were not investigated in this study. Research on this topic can help in understanding their impact on the environment and human health. Moreover, the external costs of emissions should also be investigated in detail.

The potential of energy crops was carried out for maize and sunflower. Lack of data on other crops, such as sugarcane, sugar beet was the main obstacle in conducting a detailed potential analysis. The provincial and municipal government should make such data available for further research. Moreover, the economic aspect of energy generation from various renewable energy sources was not included in this study. Future research could include cost analysis which would help in recognising best suited cost-optimal technology solutions suitable for different municipalities.

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Appendices

Appendix A Land use categories

Table 54: Land use categories defined by GDARD (2011)

No.	Category name	Description
1	Unknown/open space	Area that cannot be categorised into any of the other 13 categories or an open area.
2	Water	All areas of open water that is either man-made or natural in origin. Based on the maximum extent of water identified in all seasonal image acquisition dates.
3	Urban (built-up)	All built-up areas, including all aspects of residential, commercial, industrial, mining and transportation infrastructure, in both urban and rural environments. Represents primarily a non-vegetated, artificially sealed surface, except for vegetated gardens not otherwise identified as urban-trees or urban-grasslands. Also includes all major road and rail networks, recently cleared, non-vegetated areas being prepared for urban development, and rural farm infrastructure (including greenhouses, propagation tunnels and chicken / pig batteries).
4	Mining	Combination of extraction pits, waste and storage dumps, tailings, and other non-vegetated surfaces associated with mining activities. Includes both large-scale subsurface and open cast mines as well as smaller scale roadside borrow pits, rock and sand quarries. Significant areas on vegetation regrowth on previously mined lands or tailings (etc.) will be classified in the appropriate vegetation category.
5	Cultivated	Large-scale, commercially cultivated fields used for the production of both annual and permanent crops (i.e. maize, sugarcane, orchards etc.). The category includes both rain-fed and artificially irrigated fields. The category does not include small-scale subsistence type cultivation.
6	Grasslands	Grass and low shrub-dominated areas, typically with no or only scattered trees and bushes. Mainly natural or semi-natural vegetation communities in both urban and rural environments. May also include some subsistence cropping fields.
7	Woodlands	Tree and bush dominated areas containing natural/semi-natural tree and/or tall bush communities, with typically 40 - 70 % canopy closure, and canopy heights in excess of 3 m. Includes both indigenous and invasive plant species. Examples include dense savannah woodland and open bushveld.
8	Wetlands	Areas under wetland pans and non-pan.

9	Plantation	Planted exotic tree species, typically eucalyptus or poplar species, in the form of linear windbreaks and / or small woodlots, often associated with farm and kraal settlements. Excludes planted trees and bushes in urban areas and self-seeded “wattle jungles”.
10	Dense tree	Tree and bush dominated areas containing natural/semi-natural tree and/or tall bush communities, with typically 70 - 100 % canopy closure, and canopy heights in excess of 3 m. Includes both indigenous and invasive plant species. Examples include riparian forest, tall dense bushveld, tall thicket and bush encroached areas.
11	Wooded grass	Natural/semi-natural grass dominated areas containing only a scattered tree and/or tall bush cover, with typically 10 - 40 % tree canopy closure, and canopy heights in excess of 2 - 3 metres. Includes both indigenous and invasive plant species. Examples include protea woodland and open savannah woodland bushveld.
12	Bare rock	Naturally occurring, non-vegetated rock exposures. Typically associated with ridges and cliffs.
13	Rocky grass	Areas containing a mix of natural/semi-natural grasslands and natural rock exposure, without little or no tree, bush or shrub cover. Typically associated with ridges and escarpment areas.
14	Bare	Bare, non-vegetated areas dominated by loose soil, sand, rock or artificial surfaces. May include some very sparse scattered grass, low shrub and / or tree and bush cover. Can be either natural (i.e. beach) or man-made (i.e. mines or built-up areas).

Appendix B Maps used in rastercube

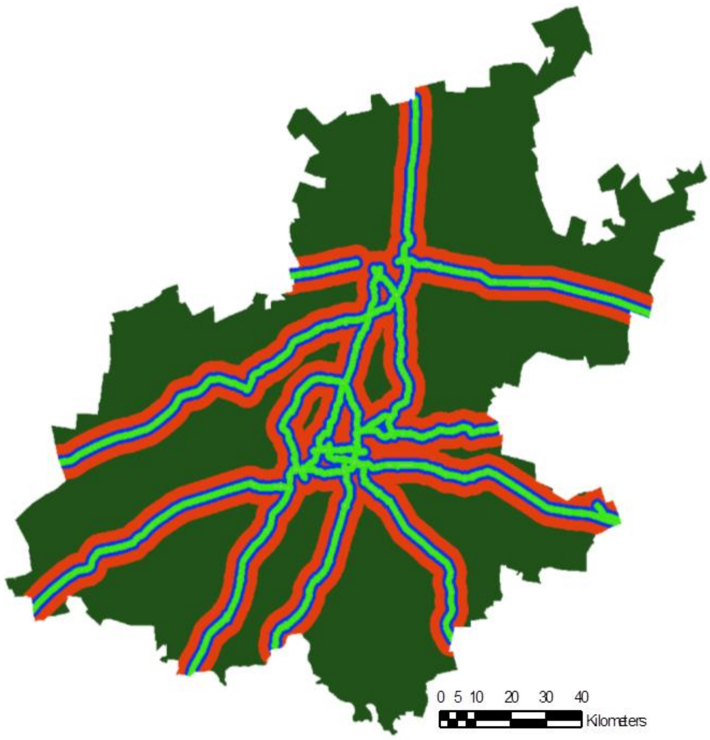

Figure 90: Gauteng's map showing main roads with buffers

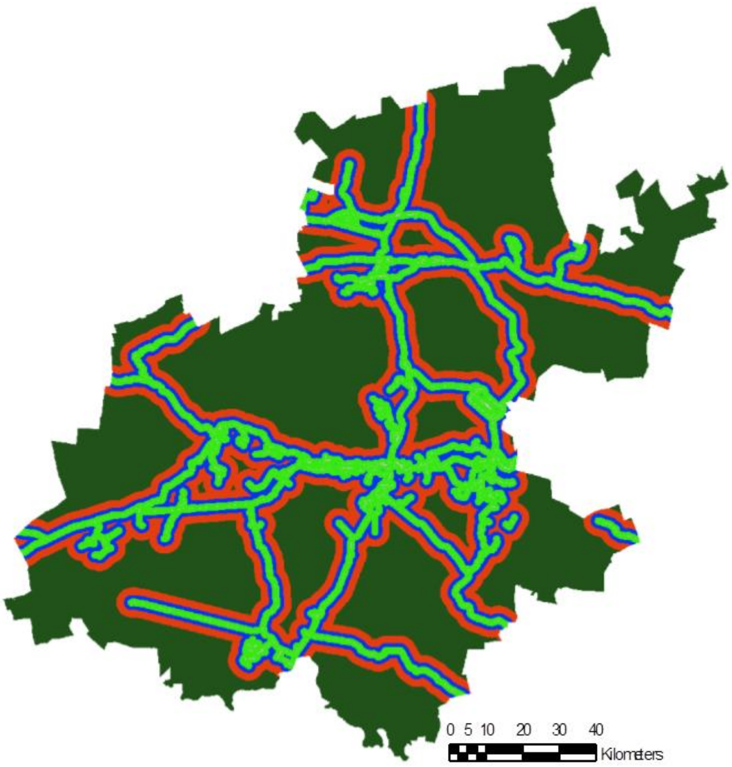

Figure 91: Gauteng's map showing railway network with buffers

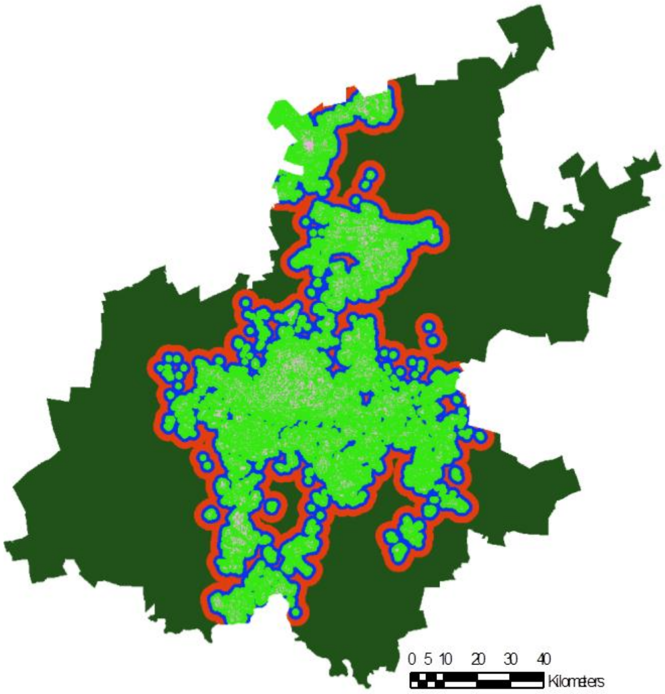

Figure 92: Gauteng's map showing existing settlements with buffers

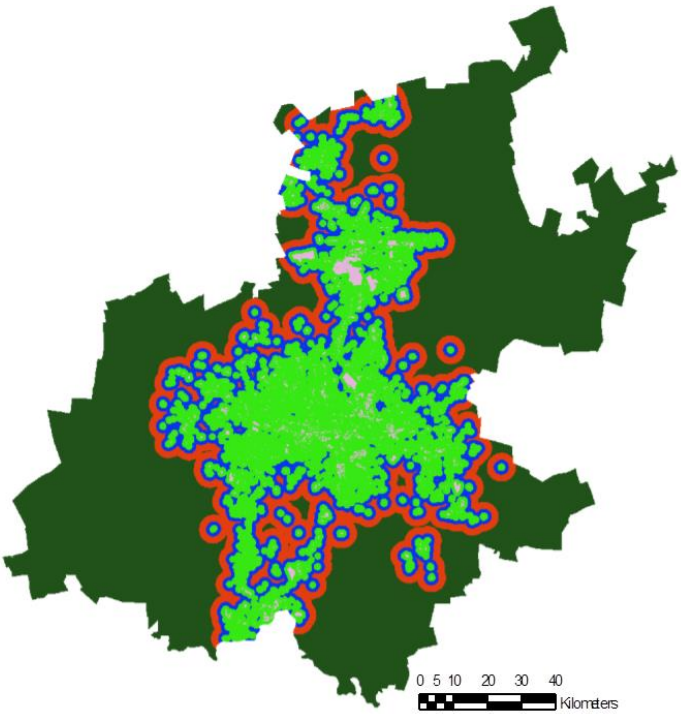

Figure 93: Gauteng's map showing employment opportunities' area with buffers

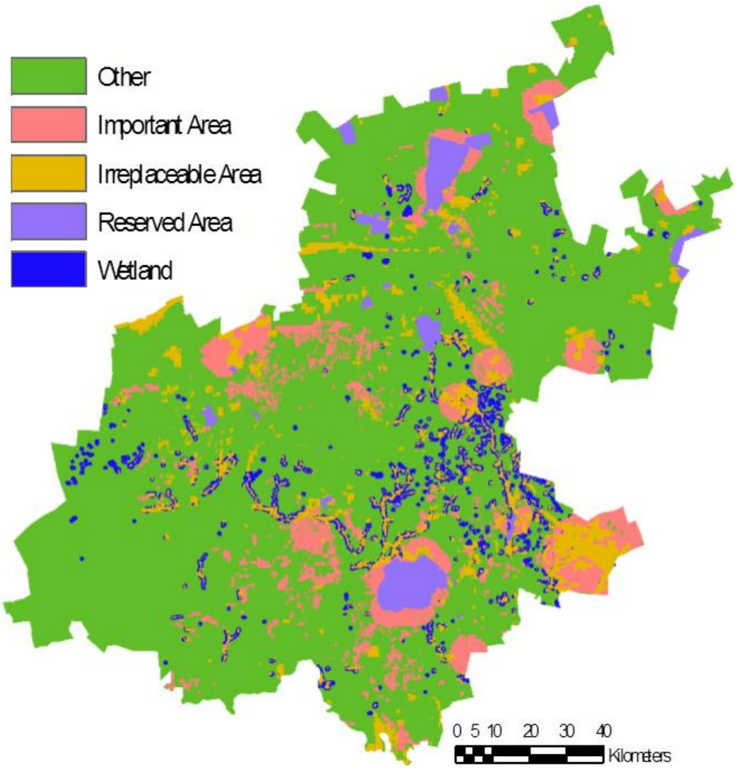

Figure 94: Map showing conservation areas in Gauteng (Based on data from C-Plan 3.3)

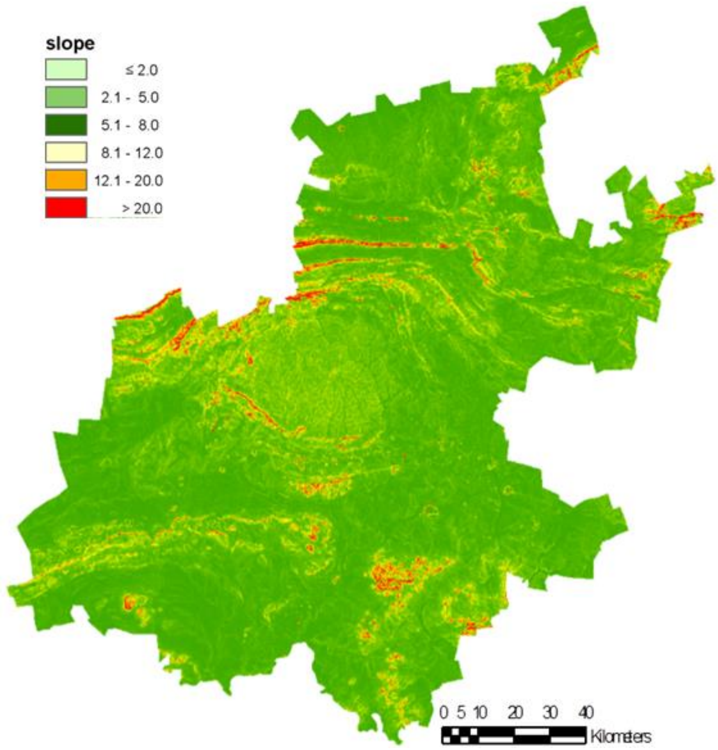

Figure 95: Gauteng's altitude map

Appendix C Map Algebra & Model-Builder

'Map Algebra' is the analysis language for 'ArcGIS Spatial Analyst'. It is a simple syntax similar to any algebra. An output raster dataset will result from manipulation of the input. The input can be as simple as a single raster dataset, raster layer, feature dataset, feature layer, or shape file. Manipulation can be done by calculating the sine of each of the location's values, or you can have a series of input raster datasets or raster layers to which the manipulation is applied, such as when adding raster datasets or raster layers together. Map Algebra allows you to build complex expressions and process them as a single command. For instance, you can calculate the sine of an input raster dataset or raster layer and add that to two other input raster datasets or raster layers.

There are four ways to access Map Algebra. In geoprocessing, Map Algebra is accessed through the Single Output Map Algebra and Multi Output Map Algebra tools. In the ArcGIS Spatial Analyst toolbar, it is accessed through the Raster Calculator. In Arc-Grid Workstation, it is accessed through the command line prompt.

Like all languages, Map Algebra is comprised of a series of rules. By understanding the basic rules, you will be able to use ArcGIS Spatial Analyst in new ways.

The following is a list of tools in the Map Algebra toolset followed by a brief description of each. The 'Multi-Output Map Algebra' tool is designed for processing single or multiline 'Map Algebra' statements and expressions; the 'Single Output Map Algebra' tool processes a 'Map Algebra' expression and provides the capability to link to other data and processes, as well as expose the input and output datasets in Model-Builder. The 'Multi-Output Map Algebra' tool, as its name implies, can create more than one output while the 'Single Output Map Algebra' tool can produce only one.

'ArcGIS Spatial Analyst' includes advanced map algebra functions for combining multiple maps, performing suitability analyses, assigning weights, and identifying relationships.
Map algebra provides an easy-to-use and powerful way to define geographic analyses as algebraic expressions. This allows users to take their real-world data and apply algebraic functions to derive new results.
For example, a single expression can be constructed to find the combined value of two datasets:
>[(Raster1) + (Raster2)]
These algebraic expressions can be simple arithmetic expressions or can consist of complex spatial and algebraic functions.
You can build complex expressions and process them as a single command. For example, you can use a single expression to find all the cells within a specific elevation range, apply a unit conversion such as feet to meters, and calculate the slope at each of those cells. Such an expression might look like the following:
>=Elev_meters = Elev_feet * 3.2808= Rain_total = Rain_April + Rain_May + Rain_June
Outgrid = (Con (elevation > 1000, Slope (elevation * 3.2808))) =

Model-Builder

Model-Builder is an application which is used to create, edit, and manage models. Models are workflows that string together sequences of geoprocessing tools, feeding the output of one tool into another tool as input. Model-Builder can also be seen as a visual programming language for building workflows. Model-Builder is very useful for constructing and executing simple workflows, it also provides advanced methods for extending ArcGIS functionality by allowing creating and sharing models as a tool. Model-Builder can even be used to integrate ArcGIS with other applications

The benefits of Model-Builder can be summarised as follows:

1. Model-Builder is an easy-to-use application for creating and running workflows containing a sequence of tools.
2. You can create your own tools with Model-Builder. Tools you create with Model-Builder can be used in Python scripting and other models.
3. Model-Builder, along with scripting, is a way for you to integrate ArcGIS with other applications.

Appendix D Transition matrix

A transition matrix (also known as stochastic matrix, probability matrix, substitution matrix or Markov matrix) is a matrix used to describe the transitions of a Markov chain. Each of its entries is a nonnegative real number representing a probability. A probability matrix describes a Markov chain X_t over a finite state space *S*. If the probability of moving from *i* to *j* in one step is given by

$$Pr((i|j)) = P_{i,j} \qquad \textbf{Equation 15}$$

The stochastic matrix P is given by using *Pi, j* as the i^{th} row and j^{th} column element.

To analyse a historical context, the initial map should be considered the older map of the time series. Multi-step transition matrix only applies to an ergodic matrix, i.e. a matrix that possesses eigenvalues and vectors. The transition matrix describes a system that changes over discrete time increments, in which the value of any variable in a given time period is the sum of fixed percentages of the value of the variables in the previous time period. The sum of fractions along the column of the transition matrix is equal to one. The diagonal line of the transition matrix needs not to be filled in since it models the percentage of unchangeable cells. The transition rates are passed on to the model as a fixed parameter within a given phase. For Dinamica, time step can comprise any span of time, since the time unit is only a reference parameter externally set.

$$\begin{bmatrix} 1 \\ 2 \\ 3 \\ . \\ . \\ . \\ j \end{bmatrix}_{t=v} = \begin{bmatrix} P_{11} & P_{21} & P_{31} & \cdots & P_{i1} \\ P_{12} & P_{22} & P_{32} & \cdots & P_{i2} \\ P_{31} & P_{23} & P_{33} & \cdots & P_{i3} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ P_{1j} & P_{2j} & P_{3j} & \cdots & P_{ij} \end{bmatrix} x \begin{bmatrix} 1 \\ 2 \\ 3 \\ . \\ . \\ . \\ j \end{bmatrix}_{t=0} \qquad \textbf{Equation 16}$$

An estimation of P_{ij} is given below, where n is the number of state

$$\sum_{i=1}^{n} P_{ij}, j = 1,2,3 \ldots n \qquad \textbf{Equation 17}$$

The transition matrix is calculated for a time period. Dinamica can also be run in multiple time steps. It is necessary for this purpose to derive the multiple-step transition matrix, as this is equivalent to the number of time steps in which the time period is divided.

$$P^t = H * V^t * H^{-1} \qquad \textbf{Equation 18}$$

Where,
H and V are Eigen values and Eigen vector matrices

In the real world, transition rates change constantly through time as a function of economic, political, social and natural causes. The conventional space-Markovian models are unable to simulate such realistic land use changes. To overcome this issue, Dinamica was designed to work in various phases and to vary the transition rates by using the 'Saturation value' parameter (DinamicaEgo, 2013). The Saturation Value is a parameter used for projection purpose. This parameter forces the stopping of the transition ***i–j***, when the number of cells in state ***i*** reaches a minimum quantity. This effect takes into account the asymptotic shape of the diffusion curve and it is calculated by using the following equation:

$$Rate'(ij) = \frac{Rate\ (ij) * (M - v)}{(M + v)}$$ **Equation 19**

Where,

M = A land use category percentage area remaining at a time,
v = Minimum area, in which a land use category will remain

Multiple-step transition matrix: A multiple-step transition matrix is derived from an Ergodic matrix, i.e. a matrix that has real number Eigen values and vectors.

If T is the initial condition matrix, $T = \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix}$ and p_0 is the initial probability distribution, the probability distribution after one year: $p_1 = p_0 * T$. Similarly, the probability distribution after 10 years: $p_{10} = p_9 * T = p_0 * T^{10}$

Transition rates are superimposed again and again over the stock variable. The net transition matrix is passed to the simulation matrix. The model then scans the land use maps to count the number of cells for various categories (and their transitions) to calculate the quantity of cells to be changed, e.g. from T_0 to T_1.

Weights of Evidence

The 'Weights of Evidence' method is introduced to spatially model land use change. 'Weights of Evidence' is a Bayesian method traditionally used by geologists to point out favourable areas for geological phenomena such as mineralisation and seismicity (Agterberg & Bonham-Carter, 1990; Goodacre et al, 1993; Bonham-Carter, 1994). The 'Weights of Evidence' method was adapted from these authors to calculate empirical relationships of spatial variables, represented by either categorical or grey-tone (continuous variable) maps, with respect to land use and cover change.

The favourability for the occurrence of an event (D), such as a land-cover change, given a binary map defining the presence or absence of a geographical pattern (B), such as a type of soil, can be expressed by the conditional or posterior probability (equation 1). This is determined by measuring the number of occurrences of (D) - usually, the number of cells (D) in a raster map -, its overlap with the binary pattern,

$$P\ \{D \cap B\} = \frac{(D \cap B)}{D}$$ **Equation 20**

And the fraction of the area occupied by pattern (B) with respect to the entire study area (A);

$$P\ \{B\} = \frac{B}{A}$$ **Equation 21**

$$P\ \{D|B\} = \frac{\{D \cap B\}}{P\{B\}}$$ **Equation 22**

Algebraic manipulation allows us to represent the conditional probability in terms of its odds ratio

$$P\ \frac{\{D|B\}}{1 - P\{D|B\}}$$ **Equation 23**

Appendix E Correlation coefficients

Correlation coefficient or measure of association designates the association between two variables. Most of the correlation coefficients are scaled so that they reach a maximum numerical value of 1 when the two variables have a perfect relationship with each other. When they reach a value of 0, they have no relationship between them.

The coefficients vary either between 0 and 1 or between -1 and +1. If two variables have a correlation of +1 or -1, they are perfectly correlated. Positively or directly related correlation has values greater than 0, whereas if the values are lesser than 0, the correlation is described as negatively or inversely related.

A. Chi-square (X^2)

Chi-square (X^2) is a simple test that helps in assessing if the relationships between two variables in a sample are due to chance or the relationship is systematic. It can be defined as:

$$X^2 = \sum_i \frac{(O_i - E_i)^2}{E_i} \qquad \textbf{Equation 24}$$

Where,
Oi is the observed number of cases in category i,
Ei is the expected number of cases in category i.
Phi (ϕ) is the measure of association, which adjusts the chi-square statistics by the sample size. It is defined as:

$$V = \sqrt{\frac{X^2}{n}} \qquad \textbf{Equation 25}$$

B. Cramer test (Cramer's V)

Cramer test or Cramer's V is a phi (ϕ) based measure of association. It is defined as:

$$V = \sqrt{\frac{V^2}{t}} = \sqrt{\frac{X^2}{nt}} \qquad \textbf{Equation 26}$$

Where,
t is the smaller of the number of rows minus one or the number of columns minus one.
If,
r is the number of rows
c is the number of columns, then

$$t = Minimum\ (r-1, c-1) \qquad \textbf{Equation 27}$$

If the Cramer's V equals 0, means there is no relationship between the two variables. Cramer's V has a maximum value of 1. This means the two variables have a strong relationship between them if the V values are larger and smaller values of V indicate a weaker relationship.

C. The contingency coefficient

The contingency coefficient is another chi-square based measure of association which can be adjusted for different sample sizes. The coefficient of contingency can be defined as follows:

$$C = \sqrt{\frac{X^2}{n + X^2}} \qquad \textbf{Equation 28}$$

When there is no relationship between two variables, C= 0. The contingency coefficient does not exceed the value C= 1. But the contingency coefficient may be less than 1 even when two variables are perfectly related to each other. This is why; the contingency coefficient is not as desirable a measure of association as those which have the range between 0 and 1.

Appendix F **Expander**

Expander: is a functor used in Dinamica simulation model. This functor expands or contracts previous patches of a certain class or category.

Inputs

Name	Type	Description
Landscape/Land use	Categorical Map	Map of classes or categories.
Probabilities	Map	Map of spatial probabilities. The map layers corresponding to the probabilities of each transition are identified by their layer names. The layers names must be probability_i_to_j where i and j are category values (e.g. probability_11_to_7 for transition 11→7). If the expected layer names are not provided, each layer of the probability map is assigned to a transition based on the transition sorting order.
Changes	Change Matrix	Matrix of number of changes.
Transition Parameters	Transition Function Parameter Matrix	Matrix of transition function parameters consisting of Mean Patch size, Patch size variance, and isometry. By varying these parameters, various spatial patterns can be reproduced. Increase the patch size for a less-fragmented landscape. Increase the patch size variance for a more diverse landscape, and set isometry greater than one for more isometric patches. Typically, the isometry defines the aggregation level of a patch. Assuming that v is the current isometry value, 0<v<1 forces disaggregation, v>1 forces aggregation and v=1 is ignored. The mean patch size and the variance define the size of the patches that will be added to existent ones.

Outputs

Name	Type	Description
Changed Landscape/Land use	Categorical Map	Map of classes or categories.
Corroded Probabilities	Map	Map of depleted spatial probabilities. Where a change occurred, the probability value is set to zero.
Remaining Changes	Change Matrix	Matrix of number of remaining number of changes for each type of transition in case the functor does not succeed in making all the specified changes.

The 'Patcher' function searches for cells around a chosen location for a combined transition. This is done firstly by electing the core cell of the new patch and then selecting a specific number of cells around the core cell, according to their P_{ij} transition probabilities, as depicted below:

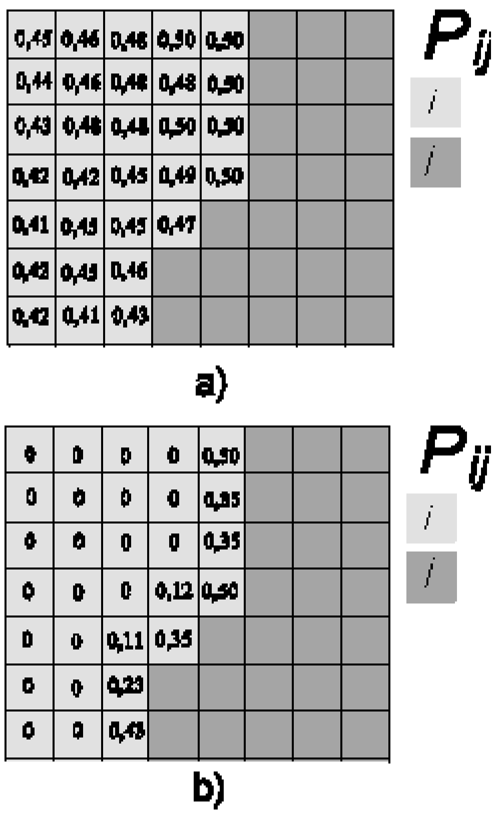

Figure 96: Transition probabilities after convoluting the expander kernel.

Appendix G **Patcher**

Patcher: this functor generates new patches of a certain class or category using a seeding mechanism.

Inputs

Name	Type	Description
Landscape/Land use	Categorical Map	Map of classes or categories.
Probabilities	Map	Map of spatial probabilities. The map layers corresponding to the probabilities of each transition are identified by their layer names. The layers names must be probability_i_to_j where i and j are category values (e.g. probability_11_to_7 for transition 11→7). If the expected layer names are not provided, each layer of the probability map is assigned to a transition based on the transition sorting order.
Changes	Change Matrix	Matrix of number of changes.
Transition Parameters	Transition Function Parameter Matrix	Matrix of transition function parameters consisting of Mean Patch size, Patch size variance, and isometry. By varying these parameters, various spatial patterns can be reproduced. Increase the patch size for a less-fragmented landscape. Increase the patch size variance for a more diverse landscape, and set isometry greater than one for more isometric patches. typically, the isometry defines the aggregation level of a patch. Assuming that v is the current isometry value, 0<v<1 forces disaggregation, v>1 forces aggregation and v=1 is ignored. The mean patch size and the variance define the size of the new patches.

Outputs

Name	Type	Description
Changed Landscape/Land use	Categorical Map	Map of classes or categories.
Corroded Probabilities	Map	Map of depleted spatial probabilities. Where a change occurred, the probability value is set to zero.
Remaining Changes	Change Matrix	Matrix of number of remaining number of changes for each type of transition in case the functor does not succeed in making all the specified changes.

The Patcher function searches for cells around a chosen location for a combined transition. This is done firstly by electing the core cell of the new patch and then selecting a specific number of cells around the core cell, according to their P_{ij} transition probabilities, as depicted below:

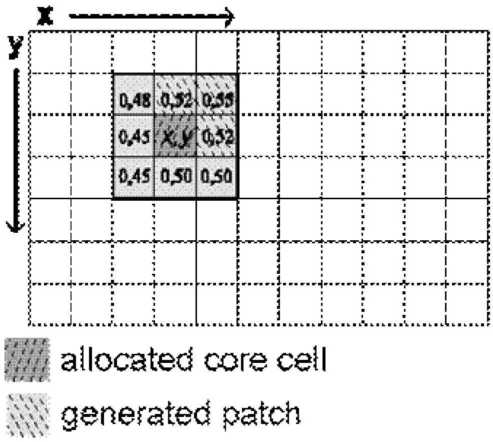

Figure 97: The Patcher algorithm for choosing neighbouring cells

Appendix H **Calc Reciprocal Similarity Map**

Calc Reciprocal Similarity Map: this functor calculated fuzzy similarity indices between maps

Inputs

Name	Type	Description
Initial Map	Categorical Map	A map consisting of classes or categories.
Observed Map	Categorical Map	A map consisting of classes or categories.
Simulated Map	Categorical Map	A map consisting of classes or categories.

Optional Inputs

Name	Type	Description	Default Value
Window Size	Positive Int	Window size with equal number of lines and columns. Only odd numbers are acceptable.	5
Use Exponential Decay	Bool	If true, the similarity is calculated using an exponential decay function truncated by the window size. Otherwise, a constant function is used within the specified window.	True
Cell Type	Cell Type	Data cell type.	Signed 8 Bit Integer
Null Value	Null Value	Null value.	-128
Exponential Decay Divisor	Double	Value used to attenuate the distance in the exponential decay function. This value must be increased when the "Use Exponential Decay" is greater the 11.	2

Output

Name	Type	Description
First Similarity	Map	Map showing the degree of spatial match from the first to the second input map. Similarity varies from zero (no match) to 1 (perfect match) within the specified window size.
Second Similarity	Map	Map showing the degree of spatial match from the second to the first input map. Similarity varies from zero (no match) to 1 (perfect match) within the specified window size.
First Mean	Double	The mean similarity index for the given window size comparing the first map to the second.
Second Mean	Double	The mean similarity index for the given window size comparing the second map to the first.

The fuzzy similarity test is based on the concept of fuzziness of location, in which a representation of a cell is influenced by the cell itself and, to a lesser extent, by the cells in its neighbourhood (Hagen, 2003). Not considering fuzziness of category, the fuzzy neighbourhood vector can represent the fuzziness of location. First a crisp vector is associated to each cell in the map. This vector has as many positions as map categories, assuming 1 for a category = *i* and 0 for categories other than *i*. Thus the fuzzy neighbourhood vector (V_{nbhood}) for each cell is determined as follows:

$$V_{nbhood} = \begin{pmatrix} \mu_{nbhood_1} \\ \mu_{nbhood_2} \\ \vdots \\ \mu_{nbhood_C} \end{pmatrix}$$ **Equation 29**

$$V_{mbhood} = \begin{pmatrix} \mu_{mbhood_1} \\ \mu_{mbhood_2} \\ \vdots \\ \mu_{mbhood_C} \end{pmatrix}$$ **Equation 30**

where *mnbhood*$_i$ represents the membership for category *i* within a neighbourhood of *N* cells (usually $N = n^2$); *mcrisp*$_{i,j}$ is the membership of category *i* for neighbouring cell *j*, assuming, as in a crisp vector, 1 for *i* and 0 for categories other than *i* ($i \in C$) and m_j is the distance based membership of neighbouring cell *j*. *m* represents a distance decay function, for instance, an exponential decay ($m=2^{-d/A}$, where *d* is the distance and *A* is the distance attenuation).

Although spatially continuous, to facilitate computation this decay function most often becomes truncated outside of the neighbourhood window *n x n*. Which function is most appropriate and the size of the window depends on the vagueness of the data and the allowed tolerance for spatial error (Hagen, 2003). As we want to assess the model's spatial fit at various resolutions, in addition to an exponential decay, a constant function equal to 1 inside the neighbourhood window and 0 outside of it is also applied. Equation (14) sets the category membership for the central cell, assuming the highest contribution found within a neighbourhood window *n x n*. Next, a similarity measure for a pair of maps can be obtained through a cell-by-cell fuzzy set intersection between their fuzzy and crisp vectors using the following equations:

$$S\left(V_A, V_B\right) = \left[\left|\mu_{A,1}, \mu_{B,1}\right|_{Min}, \left|\mu_{A,2}, \mu_{B,2}\right|_{Min}, \ldots, \left|\mu_{A,i}, \mu_{B,i}\right|_{Min}\right]_{Max}$$ **Equation 31**

Where, V_A and V_B represent the fuzzy neighbourhood vectors for maps *A* and *B* and $m_{A,j}$ and $m_{B,j}$ are their neighbourhood memberships for categories $i \in C$ in maps *A* and *B*, as in equation (13). According to Hagen (2003), since the similarity measure $S\ (V_A, V_B)$ tends to overestimate the spatial fit, the two-way similarity is instead applied, so that:

$$S_{TwoWay}\left(V_A, V_B\right) = \left|S\left(V_{nbhood_A}, V_{crisp_B}\right), S\left(V_{crisp_A}, V_{nbhood_B}\right)\right|_{Min}$$ **Equation 32**

The overall similarity of a pair of maps can be calculated by averaging the two-way similarity values for all map cells. As random maps tend to score higher, it is recommended picking up the minimum fit value from the two-way comparison.

Exponential Decay Function
The exponential decay function used to calculate similarity can be seen below:

$$S = \frac{1}{2^{\left(\frac{d}{A}\right)}}$$ **Equation 33**

Where, *d* is the distance from the window centre and *A* is the attenuation factor (Exponential Decay Divisor). The attenuation parameter can be used to control how fast the exponential function value decreases. The graphs below illustrate the 'Exponential decay function':

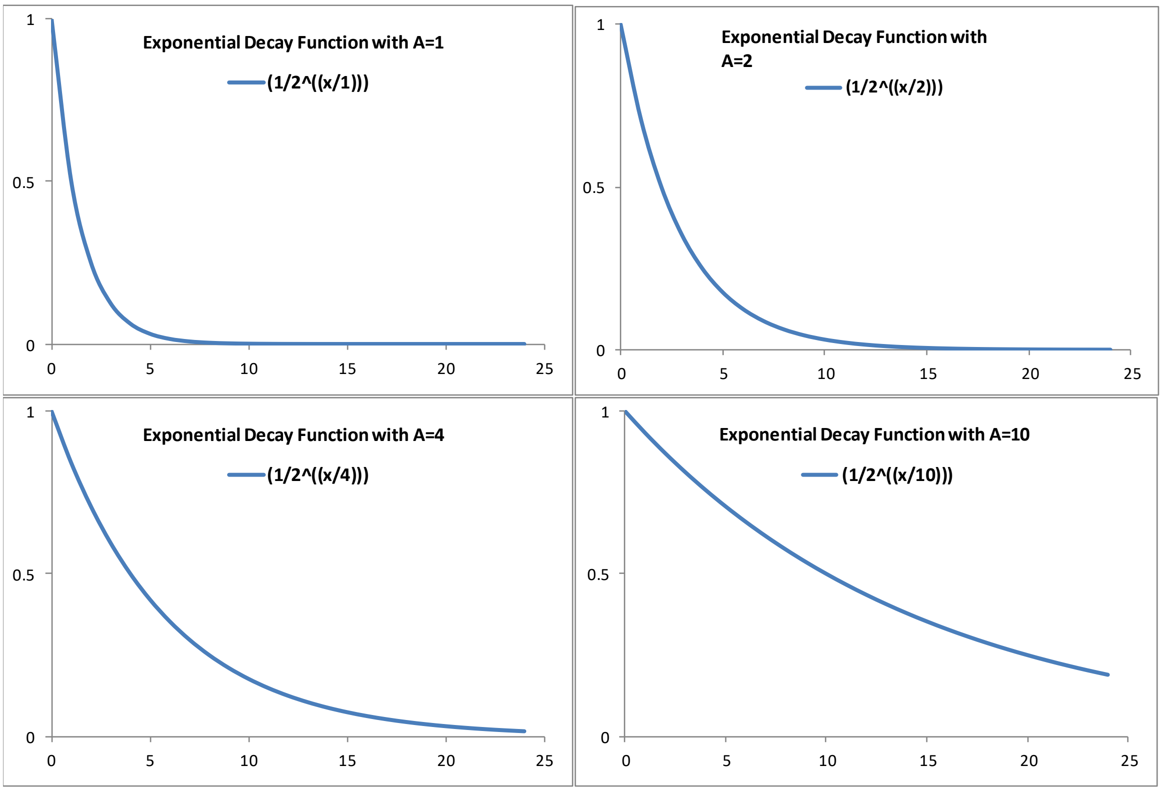

Figure 98: Exponential decay function

Appendix I Datasets used for the calculation of potential of renewable energy

Table 55: Dataset used for calculating the wind potential in Gauteng

Shape File	Remarks
Gauteng Boundary	Boundary of the Gauteng Province
Gauteng Area	Polygon of the province area
Roads	All roads
Transmission Lines	High-voltage transmission lines
Transmission_d200	Buffer zone 200 m around transmission lines
Waters_d100	Buffer zone 100 m around water bodies
Forest_d100	Buffer zone 100 m around forest areas
Traffic_d200	Buffer zone 200 m around traffic infrastructure
UrbanArea_d700	Buffer zone 700 m around urban areas
Industry_d300	Buffer zone 300 m around industrial areas
ProtectedAreas_d200	Buffer zone 200 m around protected areas
Slope	Areas with a gradient of 10 % or higher
Wind Speed	Zones of different wind speeds

Table 56: Dataset used for calculating the biomass potential from crops in Gauteng

Shape File	Remarks
Gauteng Boundary	Boundary of the Gauteng Province
LatLonFifth	Square Array of fifth degrees
Maize	Cultivation areas of maize
Sunflower	Cultivation areas of sunflowers
Yield Capacity	Yield capacities of the cultivation areas
Roads	All roads with multiple buffers
Transmission Lines	Transmission lines with multiple buffers

Appendix J Emission factors

Table 57: Carbon dioxide equivalent factors (IPCC, 2001)

Greenhouse Gas	CO_2-equivalent
Carbon dioxide (CO_2)	1.0
Methane (CH_4)	0.023
Nitrous oxide (N_2O)	0.296

Table 58: CO_2 emission factors (kt/PJ)

Scenario	Period	Electricity	Candle	Coal	LPG	NG	Paraffin	Solar	Wood
	2007	282.36	71.9	94.6	63.1	58.76	71.9	0	0
	2010	243.3334	71.9	94.6	63.1	58.76	71.9	0	0
BAU	2020	237.5551	71.9	94.6	63.1	58.76	71.9	0	0
	2030	222.8052	71.9	94.6	63.1	58.76	71.9	0	0
	2040	208.1641	71.9	94.6	63.1	58.76	71.9	0	0
	2007	282.36	71.9	94.6	63.1	58.76	71.9	0	0
	2010	242.3503	71.9	94.6	63.1	58.76	71.9	0	0
PUG	2020	195.2469	71.9	94.6	63.1	58.76	71.9	0	0
	2030	147.4006	71.9	94.6	63.1	58.76	71.9	0	0
	2040	82.65335	71.9	94.6	63.1	58.76	71.9	0	0

Table 59: CH_4 emission factors (kt/PJ)

Scenario	Period	Electricity	Candle	Coal	LPG	NG	Paraffin	Solar	Wood
	2007	0.29	3	1	1	1	3	0	30
	2010	0.29	3	1	1	1	3	0	30
BAU	2020	0.29	3	1	1	1	3	0	30
	2030	0.29	3	1	1	1	3	0	30
	2040	0.29	3	1	1	1	3	0	30
	2007	0.29	3	1	1	1	3	0	30
	2010	0.29	3	1	1	1	3	0	30
PUG	2020	0.29	3	1	1	1	3	0	30
	2030	0.29	3	1	1	1	3	0	30
	2040	0.29	3	1	1	1	3	0	30

Table 60: N_20 emission factors (kt/PJ)

Scenario	Period	Electricity	Candle	Coal	LPG	NG	Paraffin	Solar	Wood
	2007	3.4	0.6	1.5	0.2	0.1	0.6	0	4
	2010	3.4	0.6	1.5	0.2	0.1	0.6	0	4
BAU	2020	3.4	0.6	1.5	0.2	0.1	0.6	0	4
	2030	3.4	0.6	1.5	0.2	0.1	0.6	0	4
	2040	3.4	0.6	1.5	0.2	0.1	0.6	0	4
	2007	3.4	0.6	1.5	0.2	0.1	0.6	0	4
	2010	3.4	0.6	1.5	0.2	0.1	0.6	0	4
PUG	2020	3.4	0.6	1.5	0.2	0.1	0.6	0	4
	2030	3.4	0.6	1.5	0.2	0.1	0.6	0	4
	2040	3.4	0.6	1.5	0.2	0.1	0.6	0	4

Appendix K Spatial distribution of energy carriers used for cooking and heating

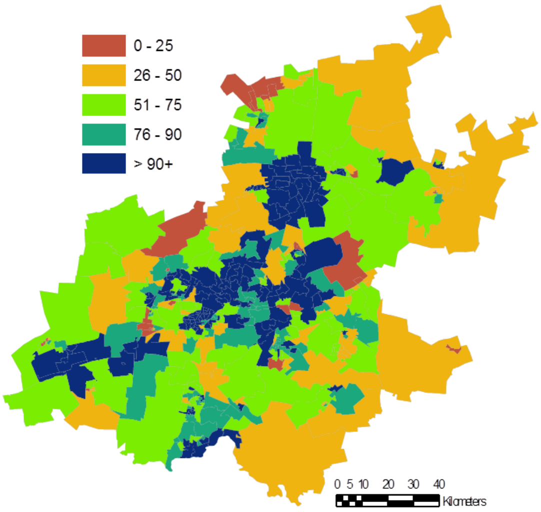

Figure 99: Share of households using electricity as the main source of heating (%)

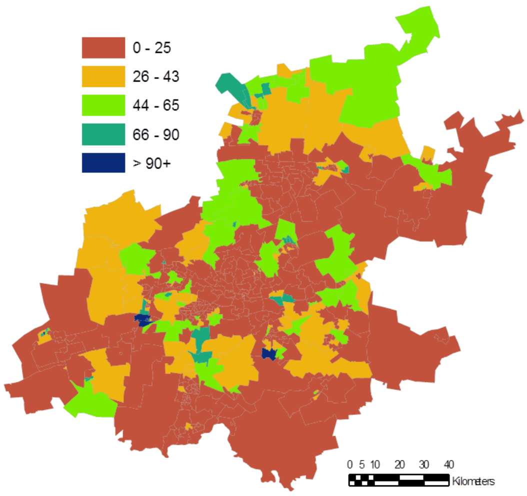

Figure 100: Share of households using paraffin as the main source of heating (%)

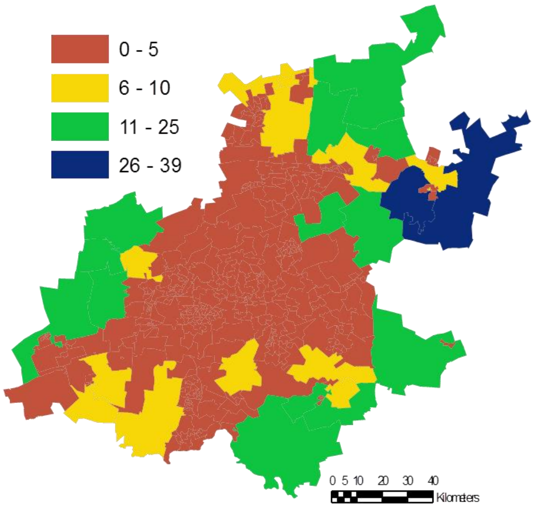

Figure 101: Share of households using wood as the main source of heating (%)

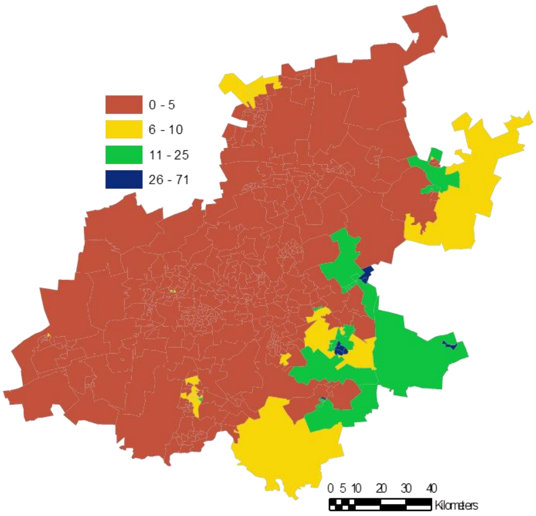

Figure 102: Share of households using coal as the main source of heating (%)

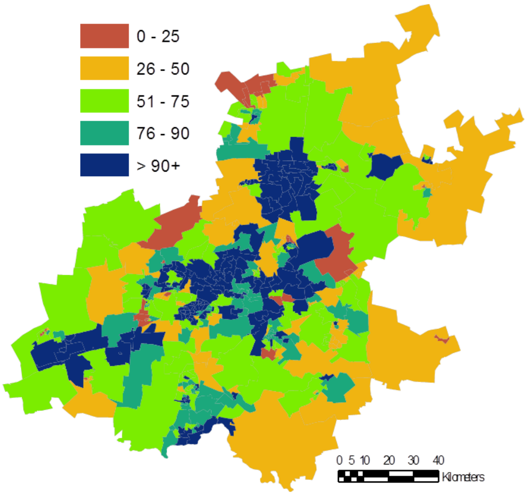

Figure 103: Share of households using electricity as the main source of cooking (%)

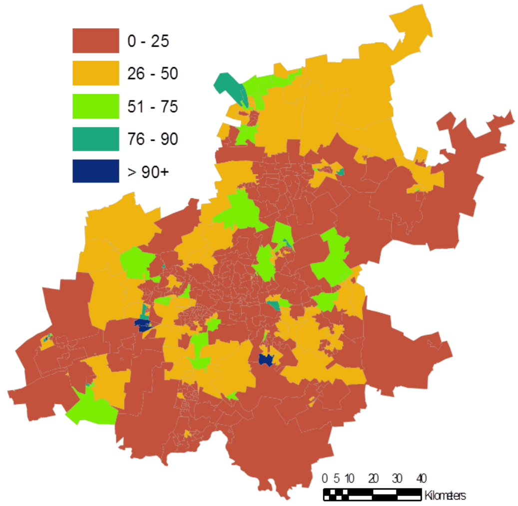

Figure 104: Share of households using paraffin as the main source of cooking (%)

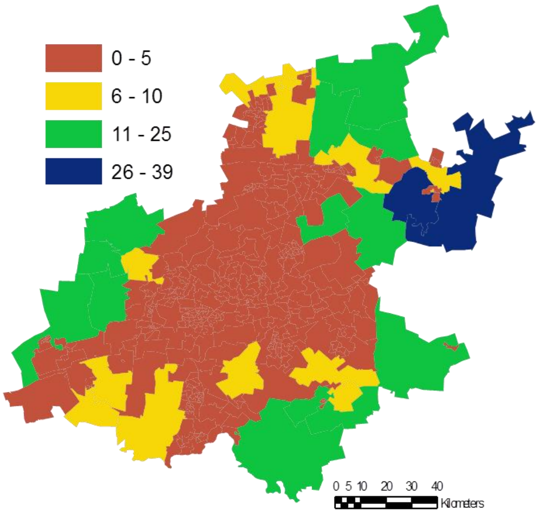

Figure 105: Share of households using wood as the main source of cooking (%)

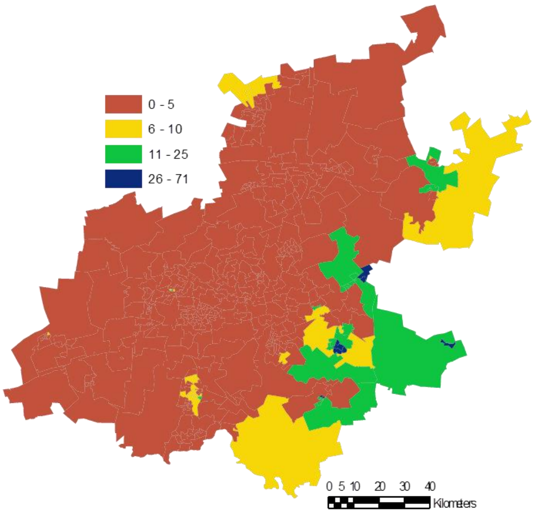

Figure 106: Share of households using coal as the main source of cooking (%)

Appendix L Baseline data for energy demand

Table 61: Final energy demand in 2007 in kWh/a (own calculations based upon EnerKey, 2010)

Group	Name	Heating	DHW*	Lighting		Appliances	Cooking	Total
				In**	Out***			
High-Income	House on separate stand	2,965	6,201	1,891	206	1,646	496	13,404
	Traditional dwelling	902	4,698	236	0	1,648	496	7,980
	Flat	1,308	5,053	650	34	1,648	496	9,189
	Semi-detached houses	5,482	2,985	1,596	206	1,648	496	12,412
	Flat in backyard	1,431	3,870	414	0	1,648	496	7,858
	Dwelling in backyard	10	1,618	177	0	1,055	647	3,508
	Inf. dwelling in backyard	1,298	1,320	1,005	0	1,055	647	5,325
	Dwelling in inf. settlement	1,466	2,060	414	0	1,648	496	6,083
	Hostel	164	1,295	118	34	1,648	496	3,755
Mid-Income	House on separate stand	2,417	4,593	650	137	1,138	647	9,583
	Traditional dwelling	0	3,061	118	0	1,145	647	4,971
	Flat	465	3,147	414	34	1,145	647	5,852
	Semi-detached houses	2,097	2,195	532	137	1,145	647	6,754
	Flat in backyard	1,771	2,312	236	0	1,145	647	6,111
	Dwelling in backyard	0	1,126	118	0	546	811	2,602
	Inf. dwelling in backyard	2,161	815	177	0	546	811	4,511
	Dwelling in inf. settlement	684	1,427	236	0	1,145	647	4,140
	Hostel	0	965	59	34	1,145	647	2,851
Low-Income	House on separate stand	351	1,187	118	0	914	811	3,382
	Traditional dwelling	128	877	59	0	919	811	2,794
	Flat	0	923	236	0	919	811	2,891
	Semi-detached houses	59	530	118	0	919	811	2,438
	Flat in backyard	0	357	59	0	919	811	2,147
	Dwelling in backyard	0	311	59	0	330	780	1,480
	Inf. dwelling in backyard	932	211	118	0	330	780	2,372
	Dwelling in inf. settlement	83	301	118	0	919	811	2,234
	Hostel	0	321	59	0	919	811	2,111
Poor	House on separate stand	596	773	59	0	527	780	2,736
	Traditional dwelling	0	873	59	0	504	780	2,217
	Flat	107	756	177	0	504	780	2,325
	Semi-detached houses	0	932	59	0	504	780	2,276
	Flat in backyard	0	506	59	0	504	780	1,849
	Dwelling in backyard	0	319	59	0	428	780	1,587
	Inf. dwelling in backyard	210	172	59	0	428	780	1,650
	Dwelling in inf. settlement	0	186	59	0	504	780	1,530
	Hostel	0	350	59	0	504	780	1,694

DHW*: Demand for hot water
Lighting In**: Indoor lighting
Lighting Out***: Outdoor (security) lighting
Inf.: Informal

Table 62: Acronyms for various building types

Building type	Acronym
House on separate stand	HSS
Traditional dwelling	TD
Flat	Flat
Semi-detached houses	SDH
Flat in backyard	FB
Dwelling in backyard	DB
Informal dwelling in backyard	IDB
Dwelling in informal settlement	DIS
Hostel	HoS

Table 63: Classification of residential dwelling types and income groups, 2007 (own calculations based upon Stats SA, 2008)

Dwelling type	Poor	Low	Mid	High	Total
House on separate stand	324,533	699,119	432,750	278,129	1,734,531
Traditional dwelling	3,329	5,715	1,630	930	11,603
Flat	34,441	86,655	74,335	25,880	221,311
Semi-detached houses	14,064	27,853	62,821	45,258	149,996
Flat in backyard	42,863	109,133	26,634	11,039	189,669
Dwelling in backyard	89,732	151,813	16,831	8,916	267,292
Informal dwelling in backyard	154,813	256,578	26,588	14,601	452,581
Dwelling in informal settlement	8,591	24,026	4,292	1,459	38,369
Hostel	29,338	62,727	3,664	1,176	96,905
Other* (boat, caravan, etc.)	3,519	7,253	1,747	803	13,322
Total	**705,224**	**1,430,872**	**651,292**	**388,191**	**3,175,578**

* As the category 'Other' has only 13,322 households (0.42%), these households are considered in the category Hostel due to their minor energy consumption.

Table 64: Residential Sector assumptions and modelling input data

		2007	2010	2020	2030	2040
Electrification	**High**	98.8%	99.1%	99.8%	99.9%	100.0%
	Medium	94.9%	95.5%	97.6%	98.6%	99.2%
	Low	80.4%	81.8%	87.7%	90.5%	92.5%
	Poor	72.3%	72.7%	78.0%	84.1%	89.5%
	Average	86.6%	87.3%	90.8%	93.3%	95.3%
Share of households	**High**	12.2%	12.0%	15.5%	19.9%	25.2%
	Medium	20.5%	19.7%	18.5%	21.1%	24.8%
	Low	45.1%	46.5%	47.7%	44.1%	38.6%
	Poor	22.2%	21.9%	18.4%	14.9%	11.4%

The share of a specific technology to fulfil this given demand in the future is flexible and influenced by several factors. Technology bounds are essential to make sure that, on the one hand, the share of (any) technology is limited to avoid a rapid increase (upper bound), but on the other hand, in order to avoid the technology from disappearing or to establish a minimum share, lower bounds are set. Following tables present upper and lower bounds for different technologies until 2040.

The share of water heating technologies used in Gauteng (2007-2040)

Table 65: The share of water heating technologies in high-income households in Gauteng (2007-2040)

Technology	Bound	2007	2010	2012	2015	2020	2025	2030	2035	2040
Electric Geyser	Upper Bound	0.84	0.84	0.84	0.85	0.85	0.85	0.85	0.85	0.85
	Lower Bound	0.84	0.81	0.79	0.75	0.70	0.65	0.58	0.48	0.40
NG Geyser	Upper Bound	0.03	0.03	0.03	0.04	0.05	0.05	0.06	0.07	0.09
	Lower Bound	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
SWH flat plate + evacuated tubes	Upper Bound	0.04	0.05	0.06	0.07	0.09	0.13	0.19	0.20	0.36
	Upper Bound	0.04	0.06	0.07	0.09	0.15	0.25	0.44	0.67	0.91
LPG Stove	Upper Bound	0.09	0.10	0.10	0.10	0.11	0.12	0.13	0.14	0.15
	Lower Bound	0.09	0.08	0.08	0.07	0.06	0.05	0.05	0.05	0.05

Table 66: The share of water heating technologies in mid-income households in Gauteng (2007-2040)

Technology	Bound	2007	2010	2012	2015	2020	2025	2030	2035	2040
Electric Geyser	Upper Bound	0.78	0.78	0.79	0.80	0.80	0.81	0.81	0.81	0.82
	Lower Bound	0.78	0.77	0.76	0.74	0.72	0.68	0.62	0.53	0.45
NG Geyser	Upper Bound	0.07	0.08	0.08	0.09	0.10	0.11	0.12	0.13	0.15
	Lower Bound	0.07	0.06	0.06	0.05	0.03	0.03	0.03	0.03	0.03
SWH flat plate + evacuated tubes	Upper Bound	0.02	0.03	0.03	0.03	0.04	0.06	0.09	0.10	0.18
	Lower Bound	0.02	0.02	0.02	0.03	0.03	0.03	0.04	0.05	0.06
	Upper Bound	0.02	0.03	0.03	0.04	0.07	0.12	0.22	0.42	0.83
	Lower Bound	0.02	0.02	0.02	0.03	0.03	0.04	0.06	0.08	0.12
LPG Stove	Upper Bound	0.13	0.13	0.14	0.14	0.15	0.16	0.18	0.19	0.20
	Lower Bound	0.13	0.11	0.11	0.09	0.07	0.06	0.06	0.06	0.06

Table 67: The share of water heating technologies in low-income households in Gauteng (2007-2040)

Technology	Bound	2007	2010	2012	2015	2020	2025	2030	2035	2040
Electric kettle	Upper Bound	0.24	0.25	0.26	0.27	0.30	0.33	0.37	0.41	0.50
	Lower Bound	0.24	0.23	0.23	0.22	0.20	0.20	0.20	0.20	0.20
Electric Geyser	Upper Bound	0.24	0.24	0.25	0.26	0.28	0.30	0.33	0.35	0.37
	Lower Bound	0.24	0.23	0.22	0.21	0.19	0.18	0.17	0.16	0.15
Electric hot plate	Upper Bound	0.24	0.24	0.24	0.25	0.26	0.26	0.27	0.27	0.27
	Lower Bound	0.24	0.21	0.18	0.15	0.10	0.09	0.08	0.06	0.05
SWH flat plate + evacuated tubes	Upper Bound	0.01	0.01	0.01	0.01	0.02	0.03	0.07	0.07	0.15
	Lower Bound	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
	Upper Bound	0.01	0.01	0.01	0.02	0.03	0.05	0.09	0.18	0.35
	Lower Bound	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.03	0.05
LPG Stove	Upper Bound	0.01	0.01	0.02	0.02	0.03	0.04	0.04	0.05	0.05
	Lower Bound	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Paraffin Stove	Upper Bound	0.24	0.25	0.25	0.26	0.27	0.29	0.30	0.32	0.33
	Lower Bound	0.24	0.21	0.19	0.15	0.09	0.08	0.07	0.06	0.05
Wood Stove	Upper Bound	0.01	0.02	0.03	0.05	0.07	0.07	0.08	0.09	0.10
	Lower Bound	0.01	0.00	0.00	0.00	0.00	0.01	0.02	0.02	0.02
Coal Stove	Upper Bound	0.01	0.02	0.03	0.04	0.07	0.07	0.08	0.08	0.09
	Lower Bound	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02

Table 68: The share of water heating technologies in poor households in Gauteng (2007-2040)

Technology	Bound	2007	2010	2012	2015	2020	2025	2030	2035	2040
Electric kettle	Upper Bound	0.39	0.40	0.41	0.43	0.46	0.51	0.56	0.59	0.65
	Lower Bound	0.39	0.36	0.34	0.31	0.25	0.25	0.25	0.25	0.25
Electric Geyser	Upper Bound	0.06	0.07	0.07	0.08	0.09	0.10	0.12	0.14	0.16
	Lower Bound	0.06	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.05
Electric hot plate	Upper Bound	0.20	0.22	0.22	0.22	0.23	0.24	0.25	0.26	0.27
	Lower Bound	0.20	0.18	0.16	0.14	0.10	0.09	0.08	0.06	0.05
SWH flat plate + evacuated tubes	Upper Bound	0.00	0.00	0.01	0.01	0.02	0.03	0.05	0.07	0.12
	Lower Bound	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01
	Upper Bound	0.00	0.00	0.01	0.02	0.05	0.08	0.12	0.17	0.30
	Lower Bound	0.00	0.00	0.00	0.01	0.01	0.01	0.02	0.02	0.03
LPG Stove	Upper Bound	0.01	0.01	0.01	0.02	0.03	0.04	0.04	0.05	0.05
	Lower Bound	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Paraffin Stove	Upper Bound	0.27	0.27	0.28	0.29	0.30	0.31	0.33	0.34	0.35
	Lower Bound	0.27	0.23	0.21	0.17	0.11	0.10	0.09	0.08	0.07
Wood Stove	Upper Bound	0.03	0.05	0.06	0.07	0.10	0.11	0.13	0.14	0.15
	Lower Bound	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02
Coal Stove	Upper Bound	0.03	0.05	0.06	0.07	0.10	0.10	0.11	0.11	0.12
	Lower Bound	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02

The share of space heating technologies used in Gauteng (2007-2040)

Table 69: The share of space heating technologies in high-income households in Gauteng (2007-2040)

Technology	Bound	2007	2010	2012	2015	2020	2025	2030	2035	2040
Electric oil	Upper bound	0.82	0.83	0.84	0.84	0.85	0.86	0.87	0.88	0.89
	Lower bound	0.82	0.80	0.78	0.75	0.71	0.66	0.63	0.60	0.59
Electric infrared	Upper bound	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	Lower bound	0.05	0.04	0.04	0.04	0.03	0.03	0.02	0.02	0.02
Electric forced convect.	Upper bound	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	Lower bound	0.05	0.04	0.04	0.04	0.03	0.03	0.02	0.02	0.02
LPG Heater	Upper bound	0.02	0.04	0.05	0.07	0.10	0.12	0.14	0.14	0.15
	Lower bound	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01
NG Heater	Upper bound	0.03	0.05	0.07	0.09	0.13	0.15	0.17	0.19	0.20
	Lower bound	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Paraffin Heater	Upper bound	0.03	0.03	0.02	0.02	0.01	0.00	0.00	0.00	0.00
	Lower bound	0.03	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00

Table 70: The share of space heating technologies in mid-income households in Gauteng (2007-2040)

Technology	Bound	2007	2010	2012	2015	2020	2025	2030	2035	2040
Electric oil	Upper Bound	0.82	0.83	0.84	0.85	0.86	0.88	0.89	0.91	0.92
	Lower Bound	0.82	0.80	0.77	0.74	0.69	0.65	0.62	0.59	0.58
Electric infrared	Upper Bound	0.05								
	Lower Bound	0.05	0.04	0.04	0.04	0.03	0.03	0.02	0.02	0.02
Electric forced convection	Upper Bound	0.05								
	Lower Bound	0.05	0.04	0.04	0.04	0.03	0.03	0.02	0.02	0.02
LPG Stove	Upper Bound	0.01	0.04	0.05	0.07	0.11	0.13	0.15	0.15	0.16
	Lower Bound	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
NG Stove	Upper Bound	0.04	0.06	0.07	0.10	0.14	0.16	0.19	0.21	0.23
	Lower Bound	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Paraffin Stove	Upper Bound	0.03	0.03	0.03	0.02	0.02	0.01	0.00	0.00	0.00
	Lower Bound	0.03	0.03	0.02	0.01	0.00	0.00	0.00	0.00	0.00

Table 71: The share of space heating technologies in low-income households in Gauteng (2007-2040)

Technology	Bound	2007	2010	2012	2015	2020	2025	2030	2035	2040
Electric infrared	Upper Bound	0.60	0.62	0.62	0.65	0.68	0.70	0.72	0.73	0.74
	Lower Bound	0.60	0.58	0.56	0.54	0.50	0.48	0.47	0.45	0.44
Electric forced convection	Upper Bound	0.12	0.12	0.12	0.12	0.13	0.14	0.15	0.16	0.16
	Lower Bound	0.12	0.10	0.10	0.09	0.08	0.07	0.06	0.06	0.05
LPG Stove	Upper Bound	0.01								
	Lower Bound	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.03	0.03
Paraffin Stove	Upper Bound	0.16	0.18	0.19	0.21	0.24	0.26	0.27	0.29	0.30
	Lower Bound	0.16	0.14	0.13	0.10	0.07	0.06	0.05	0.04	0.03
Wood Stove	Upper Bound	0.04	0.05	0.07	0.08	0.11	0.12	0.13	0.14	0.15
	Lower Bound	0.04	0.03	0.03	0.02	0.01	0.01	0.01	0.00	0.00
Coal Stove	Upper Bound	0.08	0.09	0.09	0.10	0.11	0.13	0.14	0.15	0.15
	Lower Bound	0.08	0.08	0.07	0.07	0.06	0.05	0.05	0.04	0.04

Table 72: The share of space heating technologies in poor households in Gauteng (2007-2040)

Technology	Bound	2007	2010	2012	2015	2020	2025	2030	2035	2040
Electric infrared	Upper Bound	0.66	0.66	0.66	0.68	0.71	0.74	0.77	0.79	0.81
	Lower Bound	0.66	0.63	0.62	0.59	0.55	0.54	0.53	0.51	0.50
LPG Stove	Upper Bound	0.01								
	Lower Bound	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.03
Paraffin Stove	Upper Bound	0.20	0.22	0.23	0.25	0.28	0.29	0.30	0.32	0.33
	Lower Bound	0.20	0.18	0.16	0.13	0.09	0.08	0.07	0.06	0.05
Wood Stove	Upper Bound	0.05	0.06	0.07	0.09	0.11	0.15	0.18	0.20	0.21
	Lower Bound	0.05	0.04	0.04	0.03	0.02	0.01	0.01	0.01	0.01
Coal Stove	Upper Bound	0.08	0.09	0.09	0.10	0.11	0.13	0.15	0.17	0.18
	Lower Bound	0.08	0.08	0.08	0.07	0.06	0.05	0.05	0.05	0.04

The share of lighting technologies used in Gauteng (2007-2040)

Table 73: The share of lighting technologies in high-income households in Gauteng (2007-2040)

Technology	Bound	2007	2010	2012	2015	2020	2025	2030	2035	2040
CFL	Upper Bound	0.00	0.23	0.38	0.62	0.80	1.00	1.00	1.00	1.00
	Lower Bound	0.00	0.07	0.12	0.18	0.30	0.29	0.28	0.26	0.25
fluorescent	Upper Bound	0.00								
	Lower Bound	0.00	0.00	0.01	0.01	0.02	0.02	0.02	0.02	0.03
incandescent bulb	Upper Bound	1.00	0.90	0.65	0.31	0.10	0.10	0.10	0.10	0.10
	Lower Bound	1.00	0.88	0.62	0.23	0.00	0.00	0.00	0.00	0.00
LED	Upper Bound	0.00	0.01	0.05	0.10	0.20	0.28	0.38	0.45	0.50
	Lower Bound	0.00	0.00	0.00	0.00	0.01	0.03	0.05	0.09	0.12
	Upper Bound	0.00	0.01	0.05	0.10	0.20	0.28	0.38	0.45	0.50
	Lower Bound	0.00	0.00	0.00	0.00	0.03	0.08	0.13	0.20	0.25
Lighting paraffin pressure	Upper Bound	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
	Lower Bound	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Candle	Upper Bound	0.03	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	Lower Bound	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01

Table 74: The share of lighting technologies in mid-income households in Gauteng (2007-2040)

Technology	Bound	2007	2010	2012	2015	2020	2025	2030	2035	2040
CFL	Upper Bound	0.00	0.23	0.38	0.62	0.80	1.00	1.00	1.00	1.00
	Lower Bound	0.00	0.07	0.12	0.18	0.30	0.29	0.28	0.26	0.25
fluorescent	Upper Bound	0.00								
	Lower Bound	0.00	0.00	0.01	0.01	0.02	0.02	0.02	0.02	0.03
incandescent bulb	Upper Bound	1.00	0.93	0.76	0.51	0.21	0.12	0.12	0.12	0.12
	Lower Bound	1.00	0.92	0.72	0.44	0.10	0.00	0.00	0.00	0.00
LED	Upper Bound	0.00	0.01	0.03	0.05	0.10	0.18	0.28	0.35	0.40
	Lower Bound	0.00	0.00	0.00	0.00	0.01	0.02	0.03	0.07	0.10
	Upper Bound	0.00	0.01	0.05	0.10	0.20	0.28	0.38	0.45	0.50
	Lower Bound	0.00	0.00	0.00	0.00	0.02	0.05	0.10	0.18	0.22
Lighting paraffin pressure	Upper Bound	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
	Lower Bound	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Candle	Upper Bound	0.03	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	Lower Bound	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01

Table 75: The share of lighting technologies in low-income households in Gauteng (2007-2040)

Technology	Bound	2007	2010	2012	2015	2020	2025	2030	2035	2040
CFL	Upper Bound	0.00	0.13	0.22	0.35	0.57	0.78	0.80	0.80	0.80
	Lower Bound									
incandescent bulb	Upper Bound									
	Lower Bound	1.00	0.87	0.78	0.65	0.43	0.22	0.20	0.20	0.20
Lighting paraffin pressure	Upper Bound	0.06	0.08	0.09	0.11	0.15	0.16	0.14	0.12	0.10
	Lower Bound	0.06	0.05	0.05	0.04	0.02	0.02	0.02	0.01	0.01
Lighting paraffin wick	Upper Bound	0.01								
	Lower Bound	0.01								
	Upper Bound	0.14	0.14	0.15	0.15	0.15	0.15	0.15	0.15	0.15
	Lower Bound	0.14	0.13	0.13	0.12	0.12	0.11	0.11	0.10	0.10

Table 76: The share of lighting technologies in poor households in Gauteng (2007-2040)

Technology	Bound	2007	2010	2012	2015	2020	2025	2030	2035	2040
CFL	Upper Bound	0.00	0.13	0.22	0.35	0.57	0.61	0.67	0.72	0.75
	Lower Bound									
incandescent bulb	Upper Bound									
	Lower Bound	1.00	0.87	0.78	0.65	0.43	0.39	0.33	0.28	0.25
Lighting paraffin pressure	Upper Bound	0.08	0.11	0.12	0.15	0.20	0.21	0.19	0.17	0.15
	Lower Bound	0.08	0.07	0.07	0.06	0.05	0.05	0.04	0.04	0.03
Lighting paraffin wick	Upper Bound	0.01								
	Lower Bound	0.01								
	Upper Bound	0.18	0.19	0.20	0.21	0.22	0.23	0.24	0.25	0.25
	Lower Bound	0.18	0.04	0.04	0.03	0.15	0.14	0.14	0.13	0.12

The share of cooking technologies used in Gauteng (2007-2040)

Table 77: The share of cooking technologies in high-income households in Gauteng (2007-2040)

Technology	Bound	2007	2010	2012	2015	2020	2025	2030	2035	2040
Electric Stove	Upper Bound	0.92	0.94	0.95	0.95	0.95	0.95	0.95	0.95	0.95
	Lower Bound	0.92	0.89	0.87	0.84	0.79	0.77	0.76	0.74	0.72
Elect. Induction Stove	Upper Bound	0.02	0.02	0.03	0.04	0.06	0.08	0.10	0.10	0.10
	Lower Bound	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LPG Stove	Upper Bound	0.01	0.03	0.05	0.07	0.10	0.15	0.20	0.23	0.25
	Lower Bound	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
NG Stove	Upper Bound	0.00	0.04	0.06	0.09	0.15	0.20	0.25	0.30	0.35
	Lower Bound	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Paraffin stove	Upper Bound	0.04	0.03	0.03	0.02	0.01	0.00	0.00	0.00	0.00
	Lower Bound	0.04	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00

Table 78: The share of cooking technologies in mid-income households in Gauteng (2007-2040)

Technology	Bound	2007	2010	2012	2015	2020	2025	2030	2035	2040
Electric Stove	Upper Bound	0.95	0.95	0.96	0.97	0.97	0.98	0.98	0.99	0.99
	Lower Bound	0.95	0.92	0.91	0.89	0.85	0.85	0.85	0.85	0.85
LPG Stove	Upper Bound	0.01	0.03	0.04	0.06	0.10	0.15	0.20	0.23	0.25
	Lower Bound	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
NG Stove	Upper Bound	0.00	0.04	0.06	0.09	0.15	0.20	0.25	0.30	0.35
	Lower Bound	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Paraffin stove	Upper Bound	0.04	0.03	0.03	0.02	0.01	0.00	0.00	0.00	0.00
	Lower Bound	0.04	0.03	0.02	0.00	0.00	0.00	0.00	0.00	0.00

Table 79: The share of cooking technologies in low-income households in Gauteng (2007-2040)

Technology	Bound	2007	2010	2012	2015	2020	2025	2030	2035	2040
Electric Stove	Upper Bound	0.06								
	Lower Bound	0.06	0.06	0.06	0.07	0.07	0.07	0.07	0.07	0.08
Electric Hot plate	Upper Bound	0.71	0.72	0.73	0.75	0.78	0.80	0.81	0.82	0.83
	Lower Bound	0.71	0.66	0.64	0.60	0.53	0.53	0.52	0.52	0.52
LPG Stove	Upper Bound	0.01	0.02	0.03	0.05	0.08	0.10	0.13	0.17	0.20
	Lower Bound	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Paraffin Stove	Upper Bound	0.21	0.22	0.23	0.25	0.27	0.29	0.30	0.32	0.33
	Lower Bound	0.21	0.18	0.16	0.13	0.09	0.08	0.07	0.06	0.05
Wood Stove	Upper Bound	0.01	0.03	0.05	0.07	0.11	0.12	0.13	0.14	0.14
	Lower Bound	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00
Coal brazier	Upper Bound	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	Lower Bound	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Coal basanjengo	Upper Bound	0.01	0.02	0.04	0.06	0.09	0.10	0.11	0.11	0.12
	Lower Bound	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

Table 80: The share of cooking technologies in poor households in Gauteng (2007-2040)

Technology	Bound	2007	2010	2012	2015	2020	2025	2030	2035	2040
Electric Hot plate	Upper Bound	0.71	0.71	0.71	0.73	0.76	0.79	0.82	0.85	0.87
	Lower Bound	0.71	0.67	0.65	0.61	0.55	0.55	0.55	0.55	0.55
LPG Stove	Upper Bound	0.01	0.02	0.02	0.03	0.05	0.06	0.08	0.09	0.10
	Lower Bound	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Paraffin Stove	Upper Bound	0.27	0.29	0.30	0.32	0.35	0.37	0.38	0.39	0.40
	Lower Bound	0.27	0.23	0.21	0.18	0.12	0.11	0.10	0.09	0.08
Wood Stove	Upper Bound	0.01	0.04	0.07	0.10	0.16	0.17	0.18	0.20	0.20
	Lower Bound	0.01	0.01	0.01	0.01	0.01	0.03	0.04	0.06	0.08
Coal brazier	Upper Bound	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Lower Bound	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Coal basanjengo	Upper Bound	0.00	0.02	0.04	0.06	0.09	0.10	0.11	0.12	0.13
	Lower Bound	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Technology ranges/bounds for various technologies in different income groups

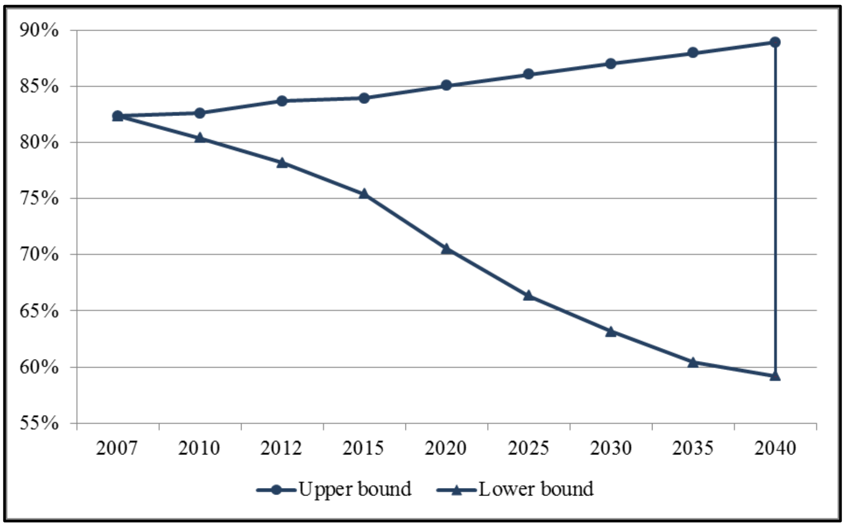

Figure 107: Technology ranges for elec. oil filled heaters in high-income households (EnerKey 2010; Burth, 2013)

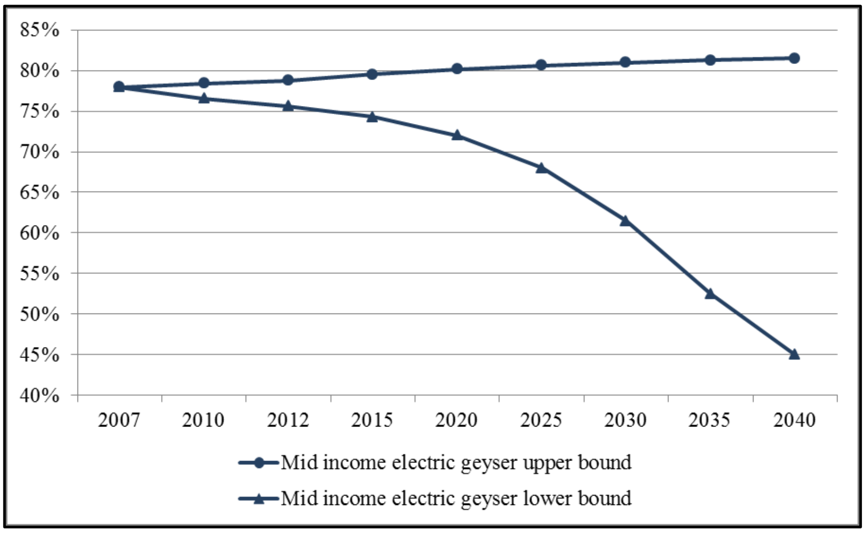

Figure 108: Technology ranges for electric geyser in mid-income households (EnerKey 2010; Burth, 2013)

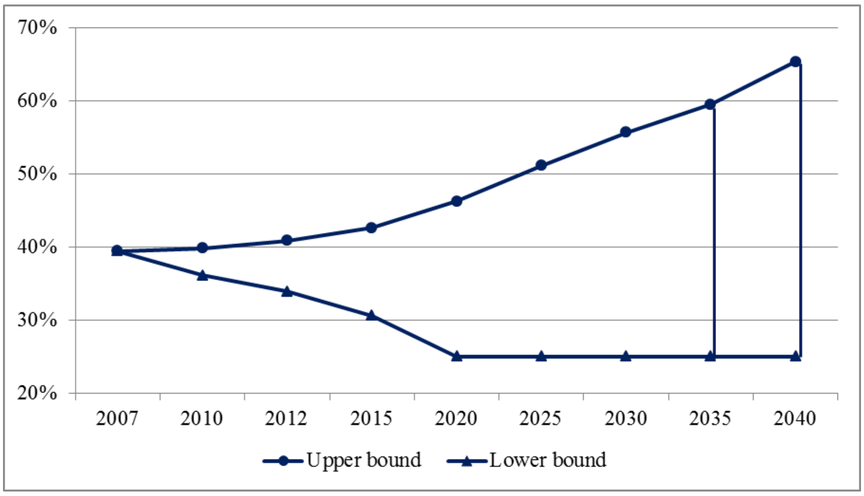

Figure 109: Technology ranges for electric kettles in poor income households (EnerKey 2010; Burth, 2013)

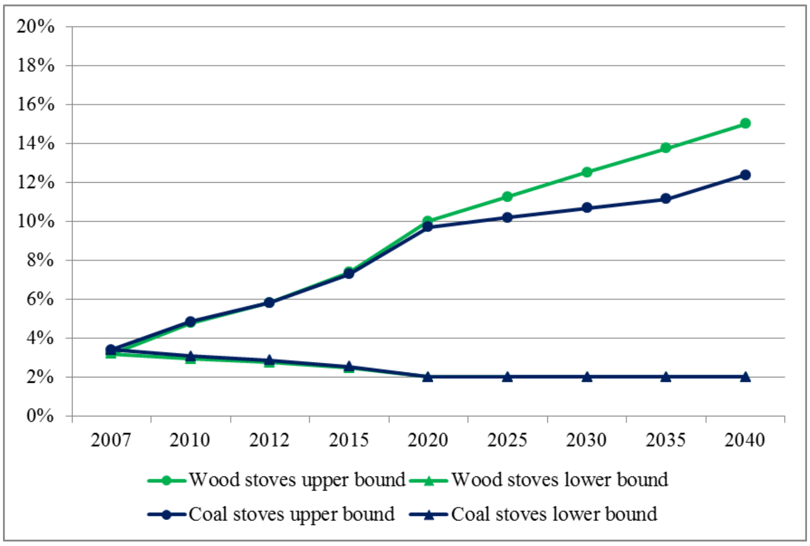

Figure 110: Technology ranges for wood and coal stoves in poor households (EnerKey 2010; Burth, 2013)

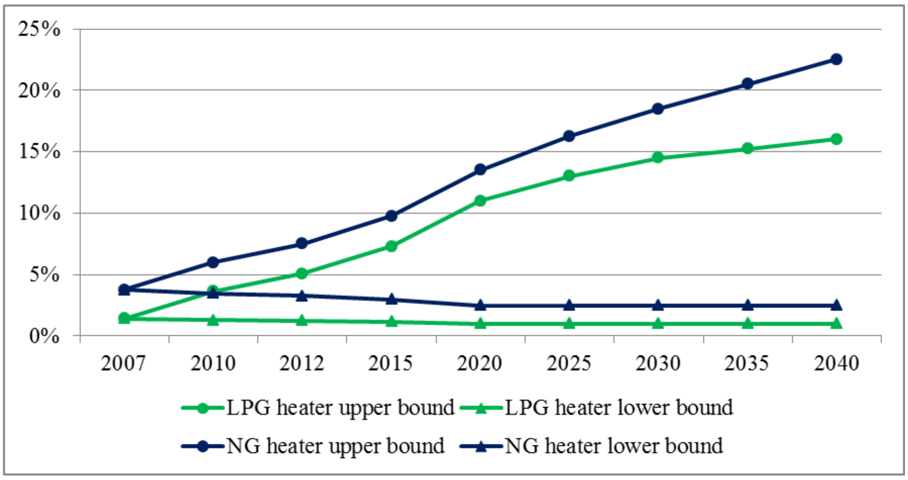

Figure 111: Technology ranges for gas heating technologies in mid-income households (EnerKey 2010; Burth, 2013)

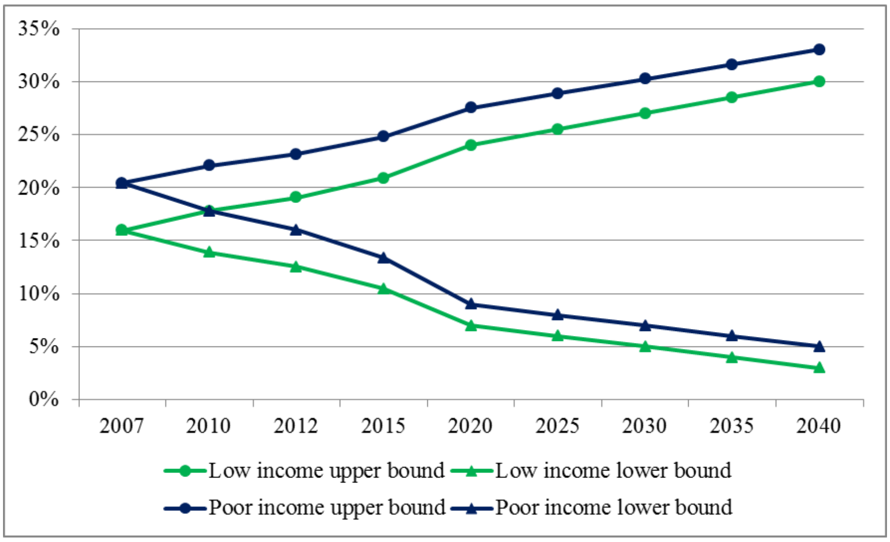

Figure 112: Technology ranges for paraffin heating for poor and low-income households (EnerKey 2010; Burth, 2013)

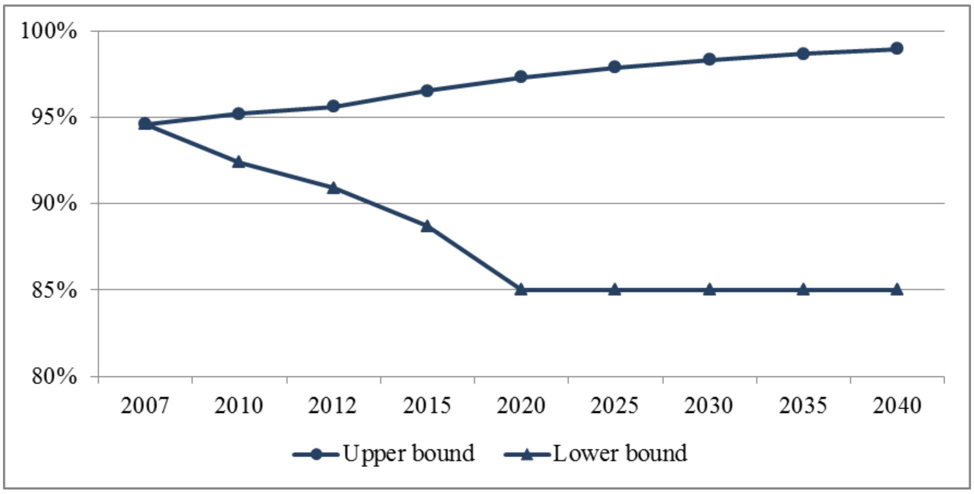

Figure 113: Technology ranges of the elec. stove in mid-income households (EnerKey 2010; Burth, 2013)

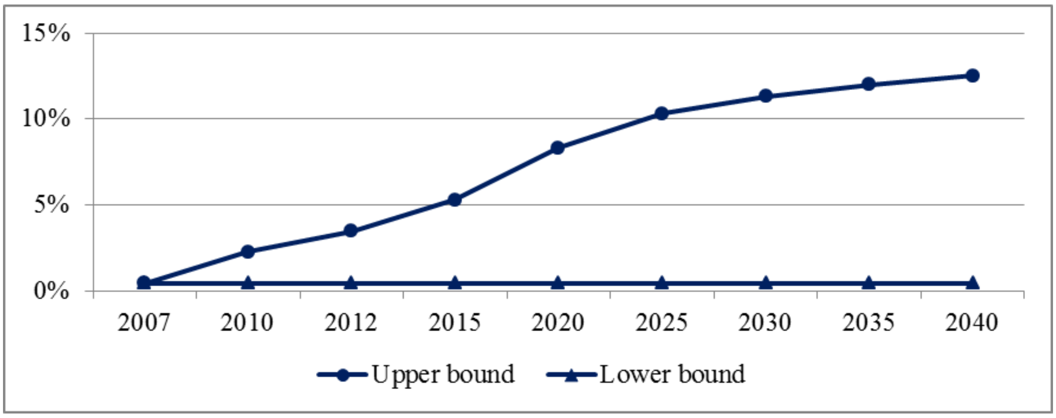

Figure 114: Technology ranges of the coal basinthutu in poor income households (EnerKey 2010; Burth, 2013)

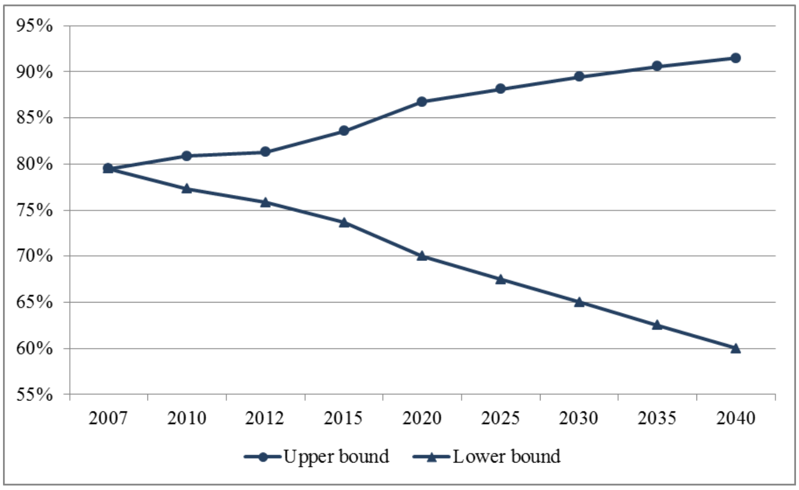

Figure 115: Technology ranges of electric lighting technologies in low-income households (EnerKey 2010; Burth, 2013)

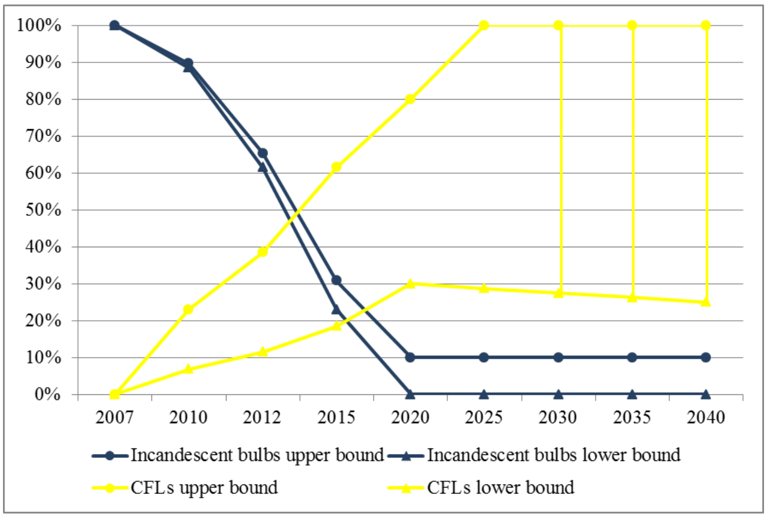

Figure 116: Technology ranges of incandescent bulbs and CFLs in high-income households (EnerKey 2010; Burth, 2013)

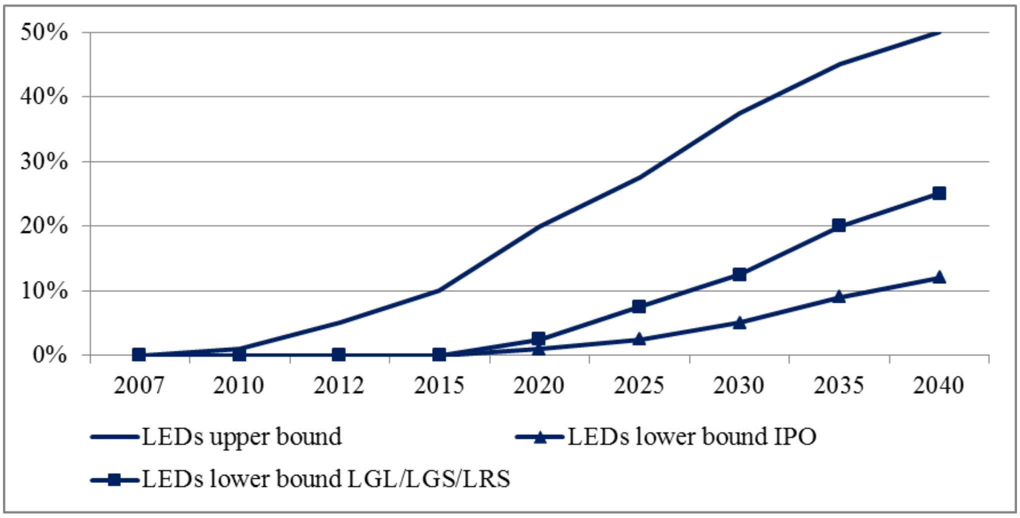

Figure 117: Technology ranges of LEDs in high-income households (EnerKey 2010; Burth, 2013)

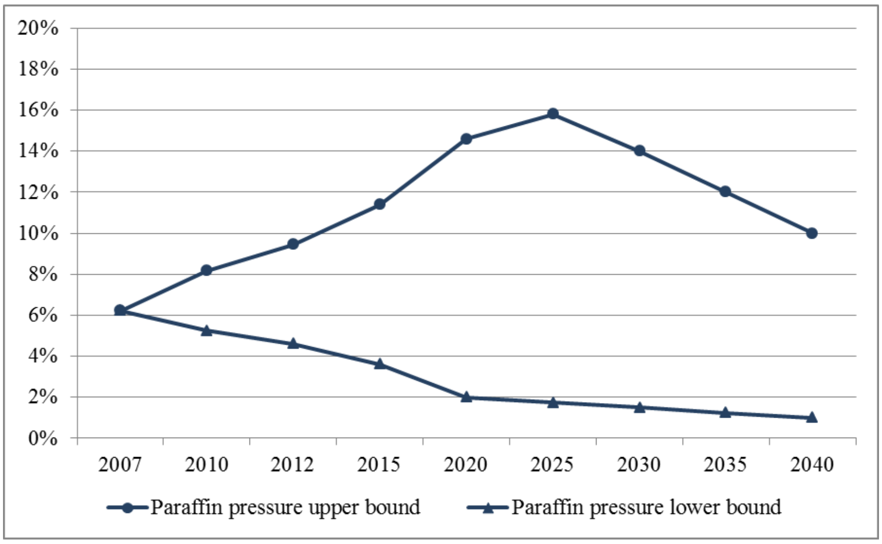

Figure 118: Technology ranges of paraffin lighting in low-income households (EnerKey 2010; Burth, 2013)

Appendix M **Population forecast: Spectrum 4**

SPECTRUM is a suite of easy to use policy models which provide policymakers with an analytical tool to support the decision-making process.

SPECTRUM consists of several software models including:

- DemProj: Demography
- FamPlan: Family Planning
- LiST: Lives Saved Tool (Child Survival)
- AIM: AIDS Impact Model
- Goals: Cost and impact of HIV Intervention
- RAPID: Resources for the Awareness of Population Impacts on Development

DemProj (Demography)

DemProj projects the population for an entire country or region by age and sex, based on assumptions about fertility, mortality, and migration. A full set of demographic indicators can be displayed for up to 50 years into the future. Urban and rural projections can also be prepared. A companion model, EasyProj, supplies the data needed to make a population projection from the estimates produced by the Population Division of the United Nations.

FamPlan (Family Planning)

FamPlan projects family planning requirements needed to reach national goals for addressing an unmet need or achieving desired fertility. It can be used to set realistic goals, to plan for the service expansion required to meet program objectives, and to evaluate alternative methods of achieving goals. The program uses assumptions about the proximate determinants of fertility and the characteristics of the family planning program (method mix, source mix, discontinuation rates) to calculate the cost and the number of users and acceptors of different methods by source.

LiST Lives Saved Tool (Projects Child Survival)

LiST projects the changes in child survival in accordance with changes in coverage of different child health interventions.

AIM (AIDS Impact Model)

AIM projects the consequences of the HIV epidemic, including the number of people living with HIV, new infections, and AIDS deaths by age and sex; as well as the new cases of tuberculosis and AIDS orphans. AIM is used by UNAIDS to make the national and regional estimates it releases every two years.

The Goals Model helps efforts to respond to the HIV/AIDS epidemic by showing how the amount and allocation of funding is related to the achievement of national goals, such as reduction of HIV prevalence and expansion of care and support.

RAPID (Resources for the Awareness of Population Impacts on Development)

RAPID projects the social and economic consequences of high fertility and rapid population growth for sectors as labour, education, health, urbanisation, and agriculture. This program is used to raise policymakers' awareness of the importance of fertility and population growth as factors in social and economic development.

Appendix N GDP Analysis

As a starting point for the EnerKey scenario assumption on economic development in Gauteng, an analysis of historic data was conducted. Key outcomes are:

- Economic growth in Gauteng province has been quite volatile in the past. The mean growth over the last 14 years was 4% per year. In the last 8 years before the economic crisis in the year 2009, it was 4.6%.
- Economic growth patterns of Gauteng, South Africa and (Sub-Saharan) Africa are generally comparable and aligned (see Figure 119). The economic growth in Gauteng has been 0.3% p.a. higher than in South Africa (1996 – 2008). On this basis very long-term economic outlooks for South Africa and Africa can be used to determine the margin in which economic growth is expected to happen up till 2040 in Gauteng.

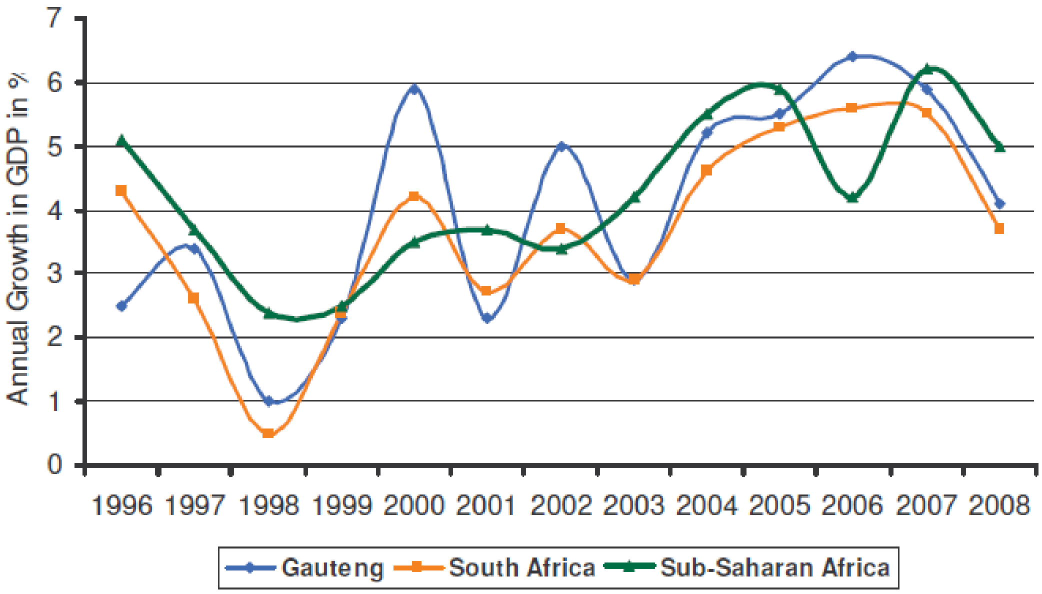

Figure 119: Historical economic growth (1996 - 2008) (Wehnert et al, 2011)

Key messages from outlooks analysed

- Short-term: The Gauteng Provincial Economic Review and Outlook 2009 (PERO, 2009) estimates a recovery from the economic crisis with annual growth rates of 4.5% by 2013.
- Mid-term: Business Monitor International (BMI 2009) estimates a peak of economic growth for South Africa in 2012 at 4.4% and a constant decline in annual growth rates down to 3.6%.
- Long-term: The World Energy Outlook (WEO) by the International Energy Agency (IEA) – which is an established benchmark for energy scenario modelling – varies greatly in its assumptions on economic development between 2006 / 2008 and 2009 issues, but assumes: 2 to 6% annual growth (different values for different issues of the WEO) up to 2015 for all of Africa 1.5 to 3% annual growth for Africa in the years 2015 till 2030.
- The Long-term Mitigation Scenarios developed for the Department of Environment, Agriculture and Tourism assume annual growth rates between 3 and 6%. (LTMS, 2007).

- Strategies: There are several policy papers / strategies which formulate economic growth targets. Most important are:
    - National Accelerated Shared Growth Initiative for South Africa (ASGI-SA) of 2004 states targets of 4.5% p.a. by 2009 and 6% by 2014
    - The Gauteng Provincial Growth and Development Strategy (PGDS) sets a target of 8% by 2014

It has to be pointed out, however, that these targets were set prior to the economic crisis of 2009. Furthermore, these targets are short to mid-term targets. With a very long term perspective (30 years up to 2040) an economic growth of 8% per year would lead to an increase in economic activity by a factor of 9 till 2040 – which is highly improbable. Generally, as countries move from developing countries to highly industrialised countries many saturation effects occur. Consequently, economic growth rates of industrialised countries cannot sustain tiger growth rates for long periods of time. One could argue that South Africa is in such a transition period. Doing so, one should assume that - with a 30 years perspective - the annual growth rate decreases over time.

Appendix O Gini-coefficient

The Gini coefficient is a measure of statistical dispersion intended to represent the income distribution of the whole population and is the most commonly used measure of equality/inequality. It was developed by the Italian statistician and sociologist Corrado Gini in 1912 (Gini, 1909; Gini, 1912).

The Gini coefficient measures the inequality among values of a frequency distribution (for example, levels of income). A Gini coefficient of zero expresses perfect equality, where all values are the same (for example, where everyone has the same income). A Gini coefficient of one (or 100%) expresses maximal inequality among values (for example, where only one person has all the income or consumption, and all others have none). For larger groups, (e.g. the whole population of a country) values close to 1 are very unlikely in practice.

While calculating the Gini-coefficient, the demographic structure should be taken into account. Countries with an ageing population, or with a baby boom, experience an increasing pre-tax Gini coefficient even if real income distribution for working adults remains constant. There are over a dozen variants of the Gini coefficient devised by different scientists (Blomquist, 1981; Yitzhaki, 1998; Sung, 2010).

Gini coefficients of income distributions

Gini coefficients of income are calculated on market income as well as disposable income basis. The Gini coefficient on market income, sometimes referred to as pre-tax Gini index is calculated on income before taxes and transfers, and it measures inequality in income without considering the effect of taxes and social spending already in place in a country. The Gini coefficient on disposable income—sometimes referred to as after-tax Gini index, is calculated on income after taxes and transfers, and it measures inequality in income after considering the effect of taxes and social spending already in place in a country (Kakwani, 1977; Chu et al, 2000).

Using the Gini can help quantify differences in welfare and compensation policies and philosophies. However, it should be borne in mind that the Gini coefficient can be misleading when used to make political comparisons between large and small countries or those with different immigration policies.

The Gini index for the entire world has been estimated by various parties to be between 0.61 and 0.68 (Sutcliffe, 2007; Hildebrand, 2009). The Figure 120 shows the values expressed as a percentage, in their historical development for a number of countries.

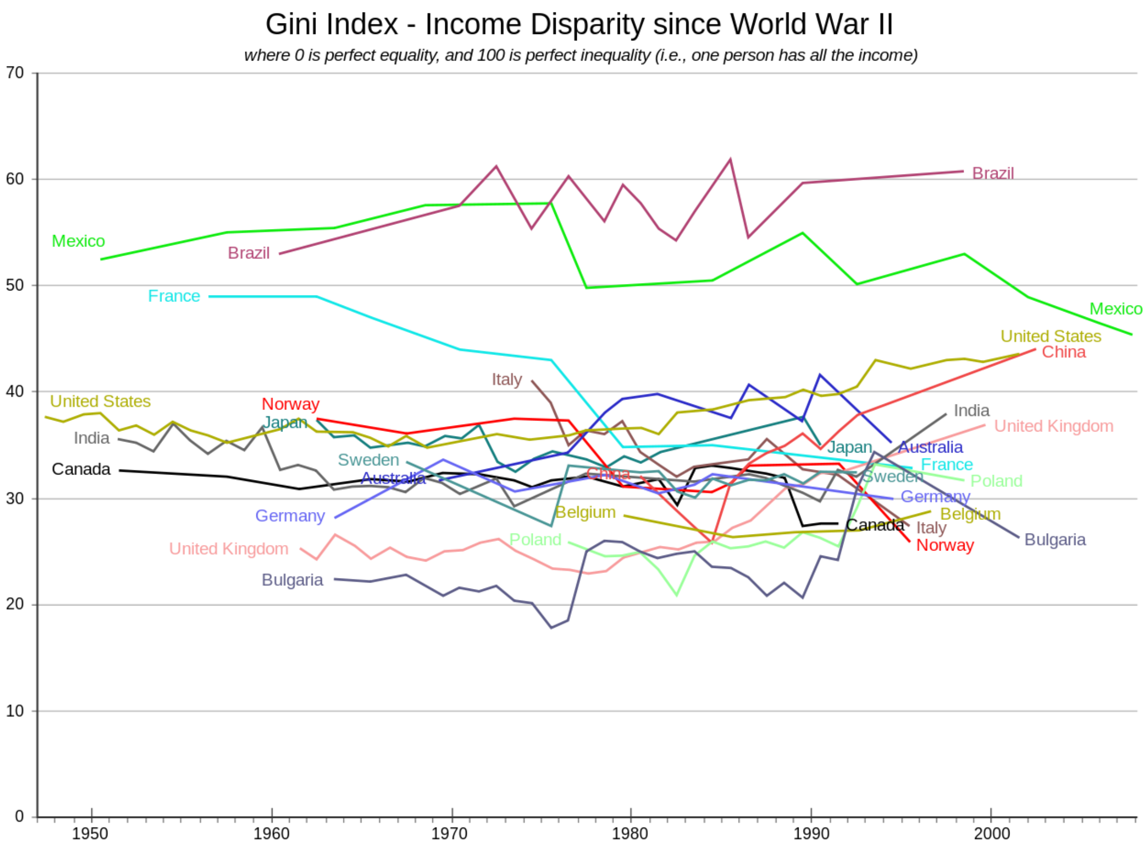

Figure 120: Gini-coefficient for various countries (Sutcliffe, 2007; Hildebrand, 2009)

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Content

The economic powerhouse of South Africa, Gauteng, has seen rapid urban growth since its formation in the early nineties. Today, more than 90% of its population lives in urban areas. This sudden rapid urban growth over such a small period has resulted in dispersed spatial structure. The thesis aims at recognising the change in the land use pattern and its impacts on energy demand and emissions in Gauteng. Furthermore, based on a scenario analysis, recommendations were drawn with regard to future urban sprawl and emission mitigation measures. At present, there is no scientific research available which deals with the complex phenomenon of urban growth and its impact on energy and emissions in Gauteng. In the thesis, the change in land use patterns between 1991 and 2009 in Gauteng was analysed which confirms that the region is affected by urban sprawl. Furthermore, based on two scenarios, the future urban developments in the region until 2040 were simulated using a cellular automata model. The scenario analysis concludes that the outward expansion of Gauteng must be restricted to stop further sprawl.

In Gauteng, the residential sector is the third largest energy consumer and has the second largest share in greenhouse gas (GHG) emissions. Heavily coal-based electricity generation (around 93%), a high share of fossil fuels used by the households and use of inefficient energy technologies are the main reasons for high GHG emissions in the residential sector in Gauteng. Furthermore, the income disparity is also mirrored in the energy consumption patterns in Gauteng. Most of the poor households are struggling to gain access to electricity, whereas the rich communities are met with frequent power cuts. As the government tries to reduce the share of coal and other fossil fuels to achieve mitigation targets, reduction in energy consumption plays a major role in Gauteng. A comprehensive analysis, based on various income groups and dwelling types was carried out to understand the energy consumption patterns in the residential sector. The scenario analysis also reveals how the share of different energy carriers used by households and their share in the final energy consumption affect the GHG emissions.

The spatial distribution of the final energy demand in the residential sector helped in identifying energy intensive as well low energy demand areas in Gauteng. Energy intensive areas are located near the economically developed regions such as central business districts (CBD) in Johannesburg and Pretoria. The spatially explicit energy consumption could be a valuable tool for determining policies for implementing energy efficiency and renewable energy programs at the local level. Though the residential sector is not the highest energy consumer in Gauteng, the consumption and emissions in this sector can be easily influenced by the government by introducing various subsidies and incentives for renewable energy which would also help in minimising the high share of direct emissions by 2040.

In addition, a thorough potential analysis for energy generation from woody biomass, energy crops, photovoltaic (rooftop and open space), solar water heaters and wind energy was carried out at the municipal and the provincial level which exhibits various possibilities to implement the use of renewable energy in the region.

To sum up the thesis, the developed simulation model has been proven suitable to understand future urban patterns of a fast growing region like Gauteng. The simulated land use pattern would help in understanding what problems will occur in the future, as well as preparing the government to tackle these issues and develop new energy policies and strategies for Gauteng. Additionally, the spatial distribution of energy demand and renewable energy potential, which was assessed using a GIS-based model, helped in providing energy efficient and renewable energy-based solutions at the local level. It can be concluded that the constantly rising residential energy demand is not heavily influenced by the urban pattern and can only be reduced by increased use of efficient technologies and energy saving measures.

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