Rooftop Solar PV Potential Assessment in the City of Johannesburg

by

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Declaration

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Abstract

Cities are the modern era's undisputed drivers for economic growth and development. But cities are also highly energy and resource intensive. Therefore, it is predictable that cities would be active participants in the global effort to creatively strike a balance between resources consumption and economic growth for a sustainable future. Part of this is exploiting the often neglected, but vital, solar photovoltaic (PV) resource and rooftop real estate within cities.

At face value, a city with the real estate infrastructural sophistication of the City of Johannesburg (CoJ), presents an attractive opportunity for generating renewable energy from its building rooftops. However, the magnitude of this potential is yet to be fully characterised. Assessments of the rooftop solar PV potential of buildings in inner city locale are made complex by the variety of building typologies and rooftop accessibility.

The main objective of this research was to assess the technical potential of rooftop PV generation in the inner city core of the CoJ, using a rapid, simple, accessible, effective, and computationally light methodology. The sample for the study was the entire population of buildings located in the central business district (CBD) of the CoJ, made up of 202 buildings across a 1.64 km^2 area. Digital images of the individual building rooftops were used.

The inner city core of the CoJ was found to have a rooftop availability factor of 46% (375 985 m^2), 17% (140 995 m^2) of which was considered to be available and suitable for system installations. The area could accommodate a system with a technical capacity of 22.6 MW and an average annual production of 38 399 915 kWh, which constitutes a mere 0.23% of the CoJ's current annual electricity consumption. The full installation of such a system would reduce the CoJ's electricity services revenue by 0.31%, whilst positively impacting its carbon emissions inventory through the offsetting of 36 096 tCO_2e.

The outcome of the research shows that the technical potential for rooftop PV installation in the central business district of CoJ, whilst seemingly attractive at face value, was, in reality, insignificant. The immateriality of the determined technical potential – as is reasonable to expect – would be aggravated further by the incorporation of economic and financial constraints, as well as real-time building-to-building shadow analysis.

Whilst the research has demonstrated that rooftop PV in the inner city core of the CoJ, and possibly in CBD areas of other cities displaying similar building typology, is limited in scope and impact, the same argument cannot be made about the entirety of the building rooftops in the CoJ. After all, building typology beyond the inner city core boundaries is dominated by less dense, low-rising, residential, industrial and commercial roof space, which possibly holds immense potentials for rooftop PV. This means that the CoJ, in seeking to transform its energy supply options through exploitation of its real estate, should focus attention away from the inner city core for optimised impact.

Opsomming

Stede is die moderne era se onbetwiste drywers van ekonomiese groei en ontwikkeling. Maar stede is ook hoogs energie en hulpbronne intensief. Daarom is dit voorspelbaar dat stede aktiewe deelnemers in die globale poging om kreatief 'n balans tussen die verbruik van hulpbronne en ekonomiese groei vir 'n volhoubare toekoms sal wees. Deel hiervan is die ontginning van die dikwels verwaarlose, maar noodsaaklike, fotovoltaïese (PV) bron en dak eiendomme in stede.

Op sigwaarde, bied 'n stad met die eiendomsbedryf infrastrukturele gesofistikeerdheid soos die Stad van Johannesburg (CoJ), 'n aantreklike geleentheid vir die opwekking van hernubare energie vanaf sy gebou dakke. Maar die omvang van hierdie potensiaal is nog nie ten volle gekenmerk nie. Aanslae van die dak sonkrag PV potensiaal van geboue in die middestad is kompleks weens die verskeidenheid van die bou-tipologieë en toeganklikheid van dakke.

Die hoofdoel van hierdie navorsing was om die tegniese potensiaal van PV dak elektrisiteitsgenerasie in die middestad kern van die CoJ the evalueer, met behulp van 'n vinnige, eenvoudige, toeganklike, en doeltreffende metode. Die monster vir die studie was die hele bevolking van geboue geleë in die sentrale sakegebied (CBD) van die CoJ, wat bestaan uit 202 geboue oor 'n 1,64 km^2 gebied. Digitale beelde van die individule gebou dakke was gebruik.

Vir die middestad kern van die CoJ is daar 'n beskikbaarheid dak faktor van 46% (375 985 m^2) gevind, 17% (140 995 m^2) van wat beskou word as beskikbaar en geskik is vir die installering van PV sisteme. Die gebied kan 'n stelsel met 'n tegniese kapasiteit van 22,6 MW akkommodeer, en 'n gemiddelde jaarlikse produksie van 38 399 915 kWh, wat 'n blote 0.23% van die huidige jaarlikse elektrisiteitsverbruik die CoJ uitmaak. Die volledige installasie van so 'n stelsel sal die CoJ se elektrisiteit dienste inkomste verminder met 0,31%, terwyl, as 'n positiewe impak, sy koolstofvrystellings inventaris verminder met 36 096 tCO_2e.

Die uitkoms van die navorsing toon dat die tegniese potensiaal vir PV dak installasie in die sentrale sakegebied van CoJ, terwyl skynbaar aantreklike op sigwaarde te wees, in werklikheid weglaatbaar klein is. Die onbelangrikheid van die vasgestelde tegniese potensiaal sou verder vererger deur die inlywing van ekonomiese en finansiële beperkings, sowel as gebou-tot-gebou skaduwee analises.

Terwyl die navorsing getoon het dat PV pontentiële dakke in die middestad kern van die CoJ, en moontlik in middestad gebiede van ander stede wat soortgelyke gebou tipologieë vertoon, beperk is in omvang en impak, kan dieselfde argument nie gemaak word oor die geheel van die geboudakke in die CoJ nie. Na alles, is die bou van tipologie buite die middestad kern grense oorheers deur minder dig, lae-styg, residensiële, industriële en kommersiële dak ruimte, wat di moontlik inhou vir groot potensiaal vir PV generasie. Dit beteken dat die CoJ, in die soeke na sy energievoorsiening opsies, omskep deur uitbuiting van sy gebouinfrastruktuur, moet aandag weg fokus van die middestad kern vir optimale impak.

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List of Acronyms and Abbreviations

ac	Alternating Current
AM	Air Mass Ratio (spectral power distribution of solar radiation)
BNEF	Bloomberg New Energy Finance
BRICS	Brazil, Russia, India, China and South Africa
CBD	Central Business District
CDM EB	Clean Development Mechanism Executive Board
CoCT	City of Cape Town
CoJ	City of Johannesburg
COP	Congress of the Parties
CSP	Concentrated Solar Power
DC	Direct Current
DEA	Department of Environmental Affairs
DME	Department of Mineral and Energy
DOE	Department of Energy
DSM	Demand Side Management
EE	Energy Efficiency
EPG	Embedded Power Generation
EU	European Union
FIT	Feed-in Tariff
FSF&M	Frankfurt School of Finance & Management
ft	Feet
GCR	Ground Coverage Ratio
GDID	Gauteng Department of Infrastructure Development
GDP	Gross Domestic Product
GDS	Growth and Development Strategy
GEF	Global Environmental Facility
GHG	Greenhouse Gas
GIES	Gauteng Integrated Energy Strategy
GIS	Geographic Information Systems
GJ	Giga Joule (also 1000 MJ)

GW	Gigawatt (also 1000 MW)
HVAC	Heating, Ventilation and Air Conditioning
IRP2010	Integrated Resource Plan for Electricity for 2010-2030
IRP2010_Update	The Updated Integrated Resource Plan for Electricity for 2010-2030
ISEP	Institute for Sustainable Energy Policies
JDA	Johannesburg Development Agency
JHB	Johannesburg
Joburg	Johannesburg
Joburg 2040	Johannesburg 2040 Growth and Development Strategy
KSEF	KZN Sustainable Energy Forum
kW	Kilowatt (1000W)
kWh	Kilowatt hours
LCOE	Levelised Cost of Energy
LiDAR	Light Detection and Ranging
LMTS	Long Term Mitigation Strategies
MJ	Mega Joule
Mt	Million tonnes
MVA	Mega Volt Amp
MW	MegaWatt (1000kW)
MWh	MegaWatt hours
NERSA	National Energy Regulator of South Africa
NMBMM	Nelson Mandela Bay Metropolitan Municipality
NREL	National Renewable Energy Laboratory
NRS	National Regulation Standards
PV	Photovoltaic
PPA	Power Purchase Agreement
RAF	Roof Availability Factor
RBT	Representative Building Typology
RCF	Roof Coverage Factor
RCR	Roof Coverage Ratio
RDP	Reconstruction and Development Program
RE	Renewable Energy

RES	Renewable Energy Systems
RET	Renewable Energy Technologies
REN21	Renewable Energy Policy Network for the 21st Century
REFIT	Renewable Energy Feed-In Tariff
REIPPPP	Renewable Energy Independent Power Producer Procurement Programme
SABRE-Gen	South African Bulk Renewable Energy Generation
SALGA	South African Local Government Association
SBR	Set Back Ratio
Small IPP	Small (1 MW – 5 MW) Independent Power Producers
SOC	State-Owned Company
SSPVEG	Small Scale Photovoltaic Embedded Generation/Generator
SSREG	Small Scale Renewable Embedded Generation/Generator
SSREPP	Small Scale Renewable Energy Pilot Programme
STC	Standard Test Conditions: Irradiance: 1000W/m^2 Module Temperature: 25 °C AM: 1.5
tCO_2e	Tonnes carbon dioxide equivalent
US	United States
USA	United States of America
US$	United States Dollar
W	Watt (unit of power)

Chapter 1 – Introduction

1.1 Introduction

The signs of anthropogenic global warming and its negative impacts are there for all to see and experience. Therefore, there is a strong moral imperative for the mobilization of all humanity to participate in efforts to effectively control and manage its impact. Energy generation remains one of the largest contributors of carbon dioxide emissions in the world. It is for this reason that renewable energy implementation has emerged as an essential energy policy component for national, regional and local level governments to address global warming. Embedded energy generation, led by solar PV in particular, has also emerged as an essential constituent of renewable energy policy responses (Ordóñez, Jadraque, Alegre & Martinez, 2010).

Although embedded energy generation, in principle, encompasses a variety of energy technologies, rooftop-mounted solar PV has developed into a dominant embedded renewable energy generation option. Coupled to an enabling policy support mechanisms as well as effective planning and implementation, rooftop solar PV generation is set to permanently alter the electricity industry supply and generation dynamics, and usher in an entirely new market paradigm. Being a new and innovative energy paradigm, it will redefine new roles for existing players in the sector, possibly spell the demise of some existing or mature business models, and open space for new players to come into the sector. An orderly development of the sector, which fully exploits the sustainable development benefits thereof, can only come about provided there is enough information about its impact, benefits, limitations, and potential.

Being an emerging sector in South Africa, not enough attention has been paid to the quantification of the potential of rooftop solar PV, especially in urban environs, where it is expected to enjoy higher levels of market penetration. Present estimates of rooftop solar PV potential are based on simplified extrapolations and opaque assumptions, the foundations of which are not always transparent enough for them to be of any use in policy development. Literature available on this emerging solar PV industry, especially in the local context, goes only as far as gauging the level of interest prevalent amongst electricity consumers to install such systems, and the market barriers to industry growth (Millson, 2014; Tshehla, 2014; eThekwini Municipality, 2013). Semi-scholarly publications and reports dealing with municipal regulations and processes to accommodate rising consumer interest in rooftop solar PV installations, are also available (Mckenzie, Knox & Ramayia, 2012). The study done by Reinecke, Leonard, Kritzinger, Bekker, van Niekerk & Thilo (2013), although geographically confined to a relatively small town in a mid-size municipality, is the only known locally-based assessment of rooftop solar PV potential. No potential assessment studies could be found covering large metropolitan municipalities, such as the cities of Johannesburg, Cape Town, Tshwane, Ekurhuleni, eThekwini, Mangaung, Polokwane, or Nelson Mandela Bay. These municipalities are experiencing increased demands and inquiries from their consumers to accommodate rooftop solar PV installations (Bischof-Niemz, 2013a; Mahama, 2012; Eskom, 2012; Mckenzie et al., 2012).

This study sets out to close the information gap that exists in embedded solar PV generation on rooftops, with an emphasis on generation potential assessment in a large metropolitan city environment. A demarcated geographic area within the inner city core of the City of Johannesburg will be the focus of the study. This area includes the City's Central Business District (CBD) and surrounds. An attempt will also be made to render the methodology and approach to the study applicable and replicable in other similar areas, subject to appropriate qualifications.

1.2 Background

1.2.1 Global Renewable Industry Status

Renewable energy has not only gained recognition as part and parcel of the overall long-term, climate change mitigation, energy security and diversification planning of most nations, but it is now also universally regarded as a mainstream policy response to matters of social equity, health, poverty, empowerment, and employment (REN21 2014).

The global renewable energy industry has experienced record-breaking growth in the last decade, not only in capacity deployment and energy output, but also in the amount of investment capital injected into the sector. The growth in capacity deployment of renewables has subsequently fuelled a technology cost reduction trend and rolling adoption of policy-driven support mechanisms for the sector on every continent (REN21 2014b). Strong policy support, capital investment, maturing technology, and improved manufacturing efficiency, have all been identified as key drivers for the sector's stellar performance (REN21 2014).

The 2014 renewable energy global status report estimated a 19% contribution of renewable energy to the final global energy consumption in 2012, with modern renewable energy technologies (solar, wind and hydro) accounting for about 10% of the share, whilst biomass accounted for the balance, as depicted in Figure 1 (REN21 2014).

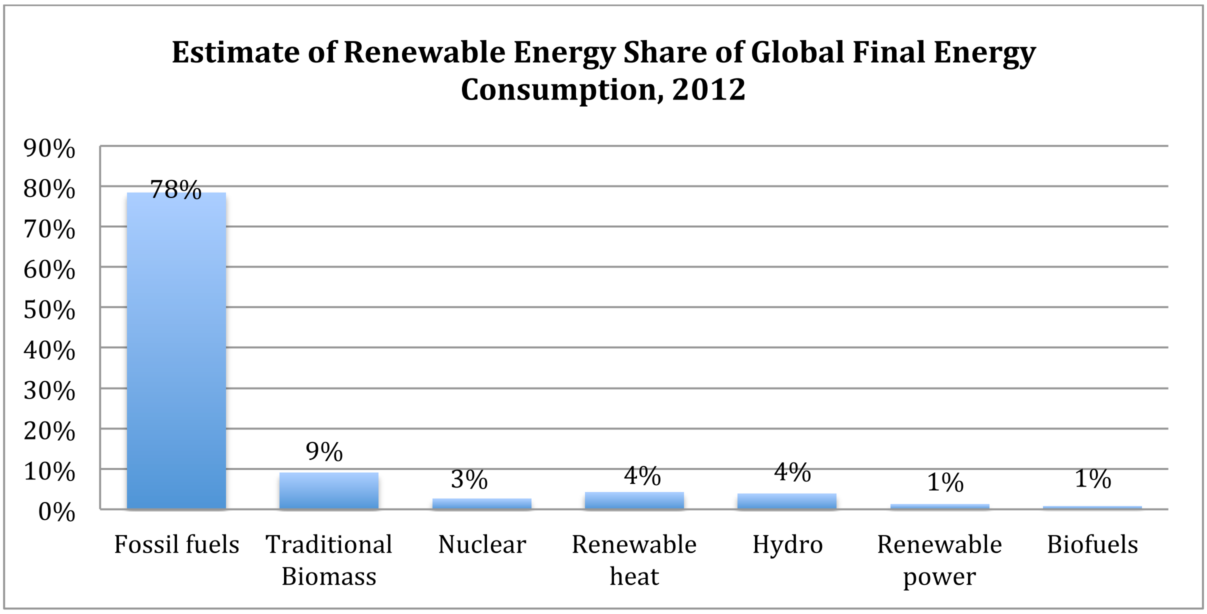

Figure 1: Estimate of Renewable Energy Share of Global Final Energy Consumption, 2012.
Source: REN21 2014.

Renewables now comprise an estimated 26.4% of global power generating capacity, enough to supply about 22.1% of global electricity (REN21 2014a). According to a study by the Frankfurt School of Finance & Management (2015), renewables, with the exclusion of hydro, reached 100GW of installations for the first time in 2014. Conservative scenarios for the future share of renewable energy in the global energy mix are in the range of 15-20%, whilst moderate scenarios place the figure at 30 to 45%, and high scenarios place the figures at 50 to 95% (REN21 2013).

1.2.2 Continental, Regional and National Role-players

The European Union (EU) still leads, with a 72% share of new renewable energy capacity additions in the power sector, but BRICS countries, led by China, had the most renewable energy capacity addition in 2013, at 38% (REN21 2014a). It is the increasing renewable energy capacity additions by China and India that is also driving the emergence of the developing countries market for renewables (see Figure 2).

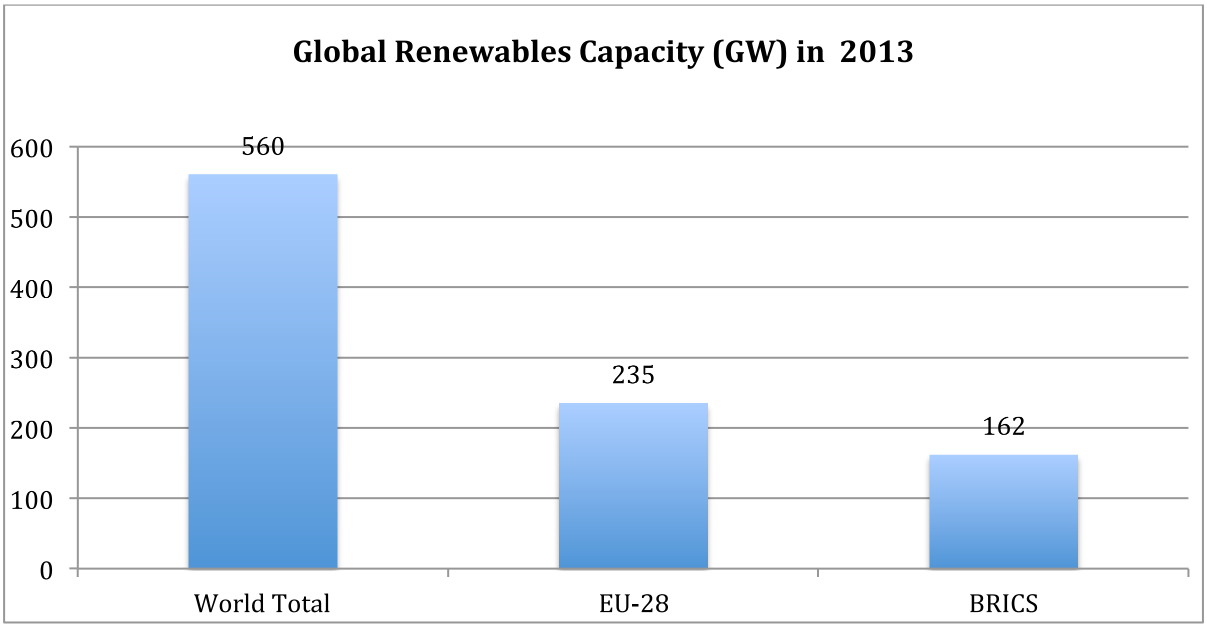

Figure 2: Global Regional Renewables Capacity
Source: REN21 2014

In China, new power capacity additions in renewable energy surpassed new fossil fuel and nuclear capacity for the first time in 2013, at about 24% of global renewable electric capacity (REN21 2014a). The emerging dominance of developing countries in the renewable energy industry is not an exclusively Chinese narrative. Other BRICS countries, namely Brazil (US$ 7.6 billion), India (US$ 7.4 billion) and South Africa (US$ 5.5 billion), have all made it to the top ten of investment destination countries for the sector, according to a report by Frankfurt School of Finance & Management (2015).

Early-starter markets in countries like Germany and USA are also maintaining their sturdy market positions (see Figure 3). In Italy, solar PV achieved penetration levels of 7.8% of the national electric power demand, whilst Denmark and Spain recorded wind capacity penetration levels of 33.2% and 20.9%, respectively (REN21 2014a).

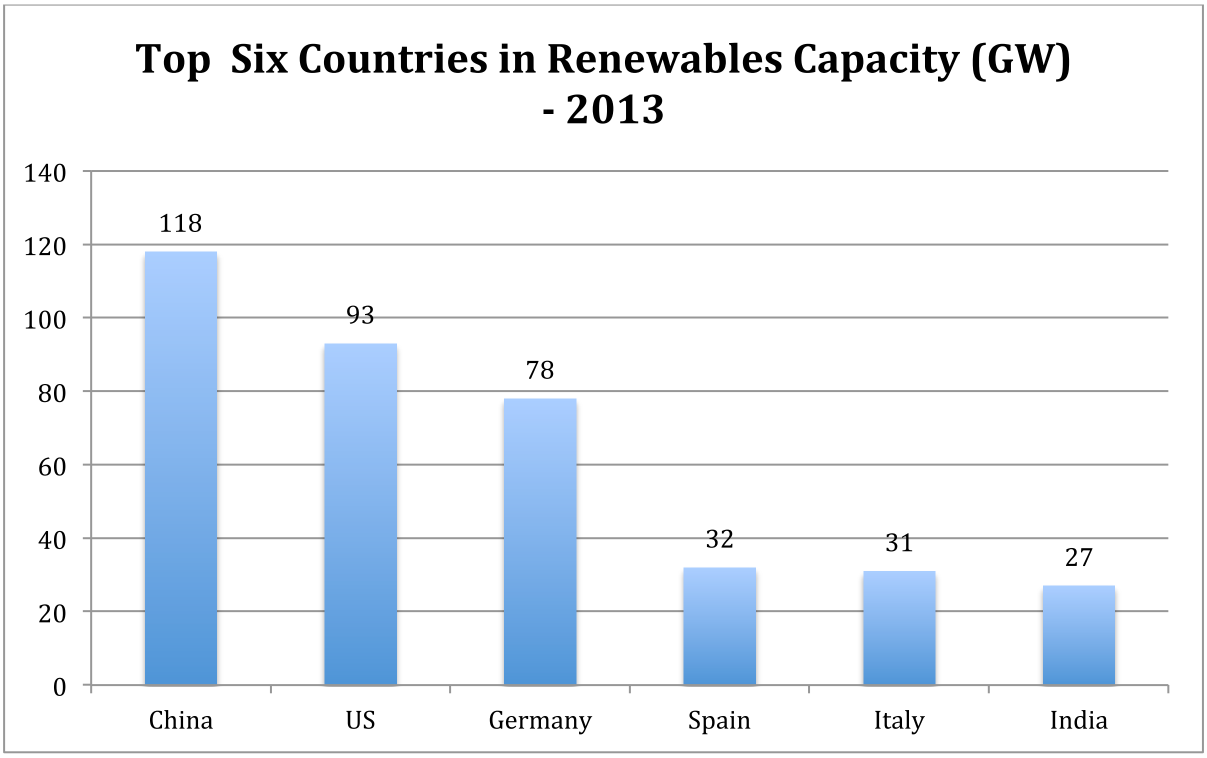

Figure 3: Country-Level Penetration of Renewables in 2013
Source: REN21 2014.

1.2.3 Investment Mobilisation in the Renewables Sector

Prior to 2013, when a decline in new investment levels for renewable energy was recorded, new investment in renewables for power and fuels were on an unbroken growth streak from 2004 to 2011, led by both developed and developing markets (see Figure 4).

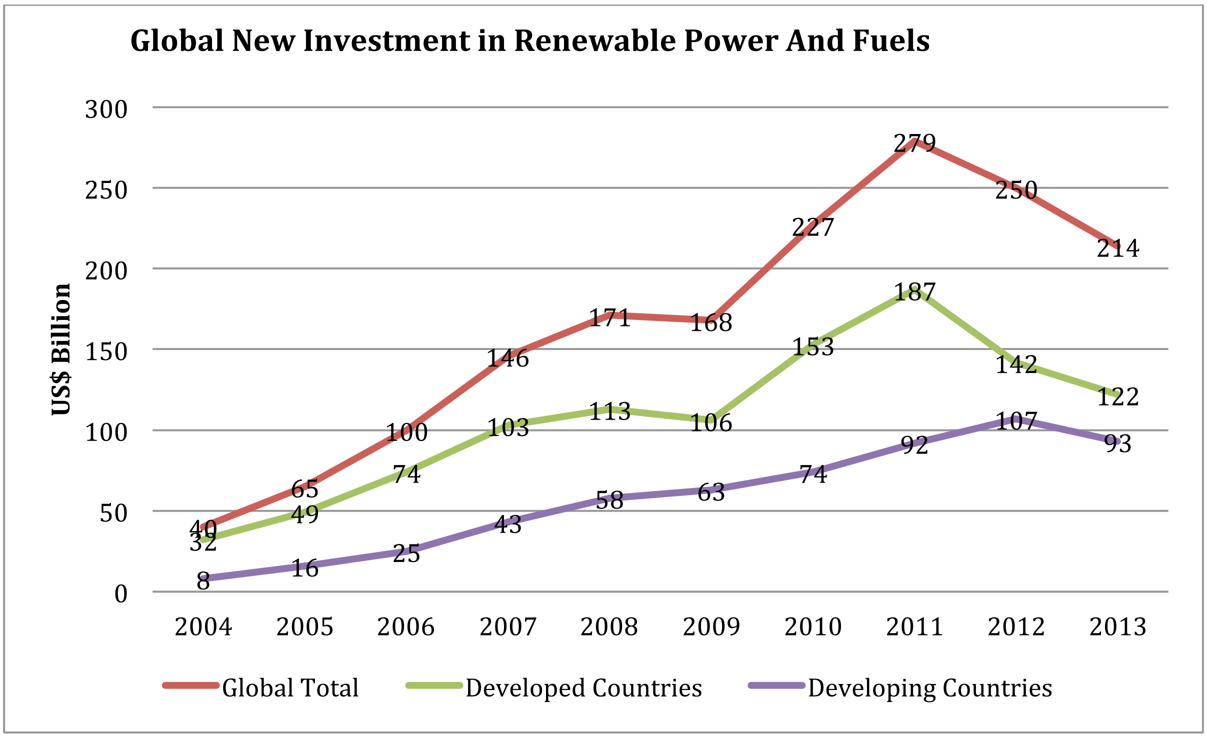

Figure 4: Global New Investment in Renewable Energy Power, 2004 to 2013.

Source: REN21 2014

Declining investment levels in developed markets, and rising influence of developing markets led by China and its other BRICS colleagues is evident in Figure 5.

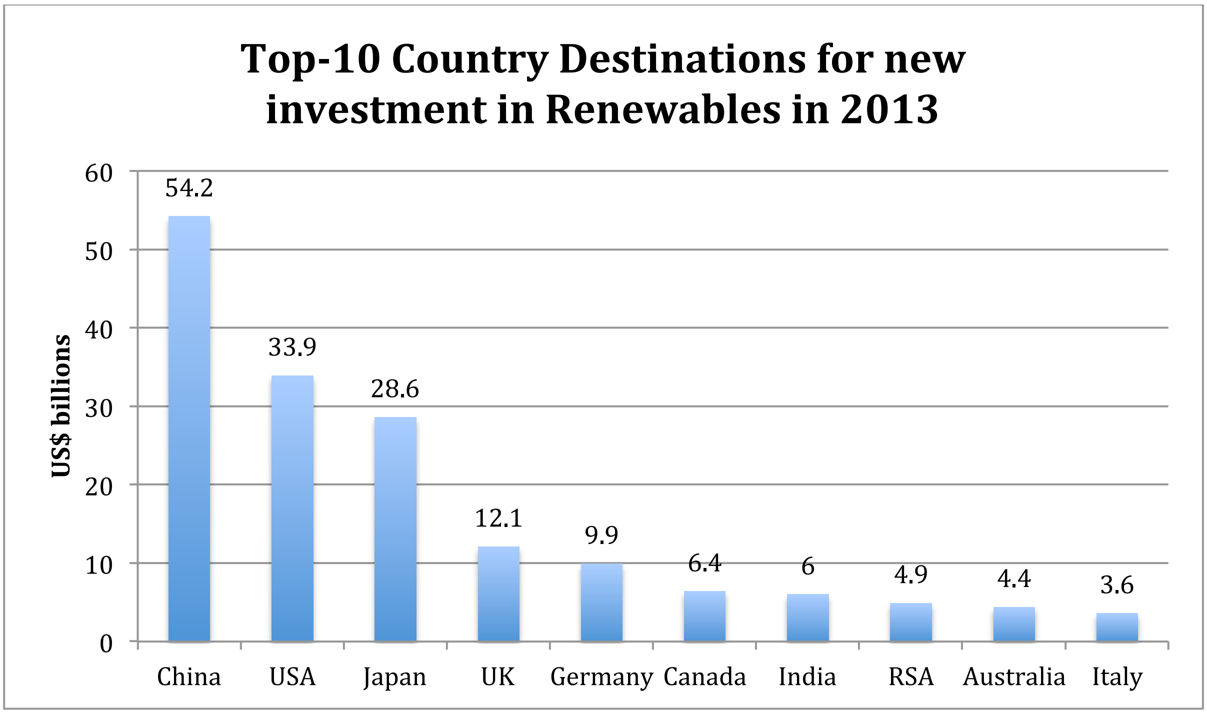

Figure 5: Top-10 Investment Destination Countries for Renewables in 2013.

Source: figures obtained from REN21 2014.

Notable from the figures of leading investment destination countries for renewables in 2013 is the rise of China, which, together with Japan, delivered a record US$ 119 billion in new investment in renewable energy. Japan's investment was overwhelmingly in support of distributed solar PV installations (rooftop and ground-mounted) (REN21 2014a). South Africa retained its position in the top ten of investment destination countries ranking, on the back of US$ 5.5 billion in investment in 2014, a 5% increase, on the back of an exclusively utility-scale project portfolio (Frankfurt School of Finance & Management 2015).

By 2020, expectations are of annual investment in renewables ranging between US$ 400 and US$ 500 billion, representing a substantial increase from the 2013 investment of about US$ 250 billion (REN21 2014b).

1.2.4 Emergence of Regions, Towns and Cities

The renewables sector has also witnessed the emergence of regions, states, cities and towns as strong players in the sectors, as demonstrated by their adoption of local-level policies, targets, regulations, standards and incentives that often surpass those set by nations and regions (REN21 2014a; REN21 2014b; REN21 2013). A city like Sydney (Australia), has adopted a target of 15% contribution of renewable energy to its total energy mix by 2020, whilst some cities like Los Angeles (USA) have technology-specific targets for renewable energy contribution to their total energy mix (REN21 2013). Cities, local governments and regions are experiencing an expanding installation base of small-scale, distributed renewable energy covering remote, off-grid and grid-connected systems, especially in urban localities, where consumers are pursuing energy independence, amongst other objectives (REN21 2014). It is this rising tide of energy independence that is leading the strong emergence of a new paradigm in energy generation, especially one where the largely underexploited rooftop real estate of large cities is utilized for solar PV technology deployment (Byrne, Taminiau, Kurdgelashvili & Kim 2015).

1.2.5 The Rise of Solar PV

Over the period between 2011 and 2013, solar PV experienced the fastest capacity growth rates of any known energy technology (REN21 2014a). Figure 6 illustrates the superior growth in capacity of both solar PV and solar CSP when compared to other renewables. For the first time, solar PV overtook wind in new capacity additions, with more than 33% of new power capacity added (REN21 2014a).

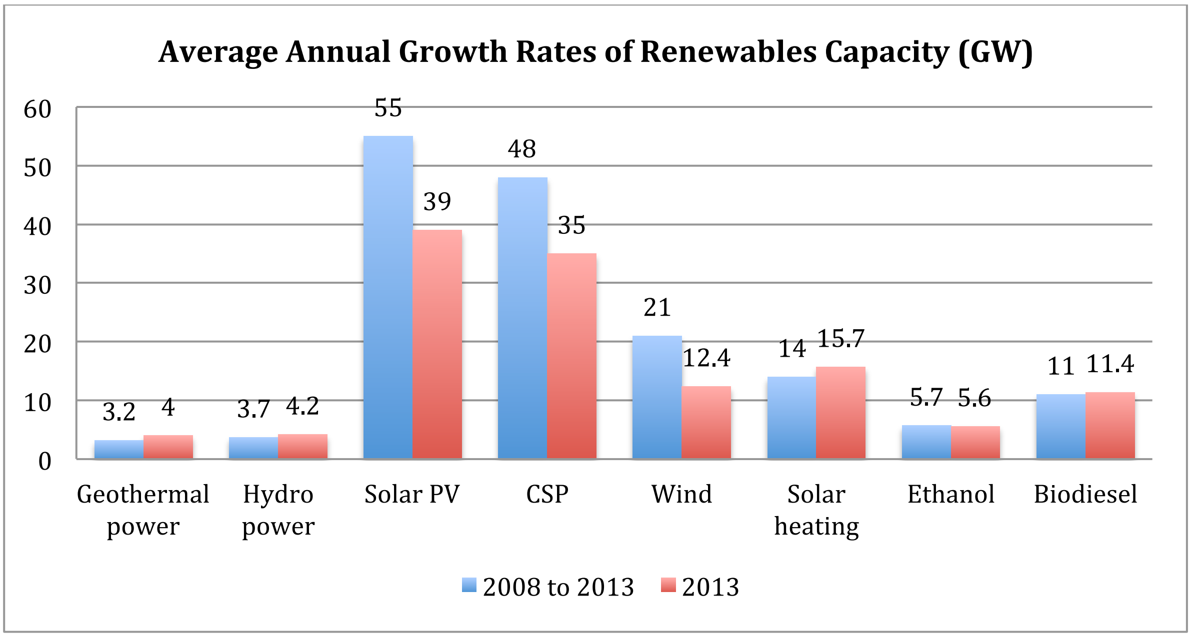

Figure 6: Annual growth rates of renewables

Source: REN21 2014.

More than 39 GW of solar PV was added to the market in 2013, to take total global installed solar PV capacity to more than 139 GW, as shown in Figure 7 (REN21 2014a). Growth in global installed solar PV capacity has averaged about 55% annually over the last five years (see Figure 7).

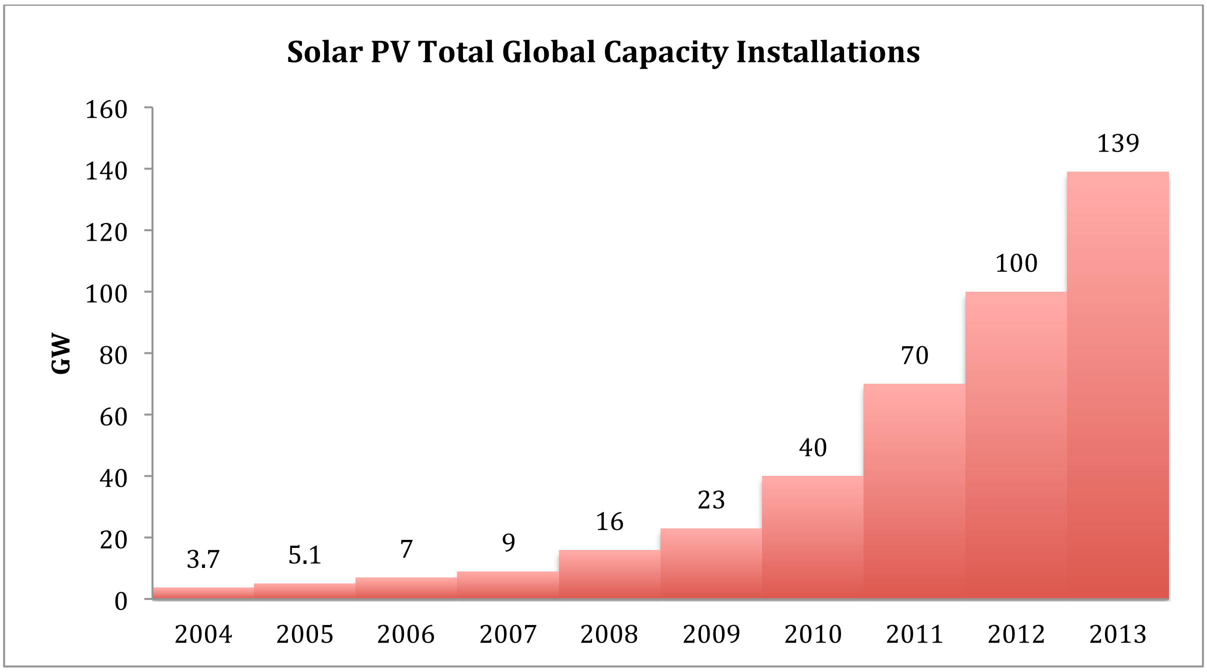

Figure 7: Growth of solar PV in the last decade.
Source: REN21 2014.

By the end of 2013, five countries had at least 10 GW of installed solar PV capacity each, versus only two in 2012, whilst at least seventeen countries had at least 1 GW capacity installation (REN21 2014a). Germany's current cumulative capacity installation of about 36 GW of solar capacity still puts it far ahead of any country in the world, whilst the USA, with a total of 12.1 GW installed, still leads North American markets (REN21 2014a). Noteworthy of the USA capacity installation narrative is the case of California, accounting for more than 50% of the new capacity installations, and thus signalling both the significant emergence of non-state level participants in the global solar PV market, as well as the rise of the residential rooftop solar PV market in particular (REN21 2014a). Asia also overtook the EU with China and Japan leading the market development (REN21 2014a).

Solar PV attracted the most new investment capital for renewable energy technologies in 2013, although it endured a 20% decline in investment when compared to 2012 (REN21 2014a). It rebounded in 2014 with an increase of 29% to US$ 149.6 billion (Frankfurt School of Finance & Management 2015). The rebound was led by China and Japan, respectively recording a 45% jump in investment mainly for utility-scale projects and 13% on 2013 figures, for small-scale projects (Frankfurt School of Finance & Management 2015).

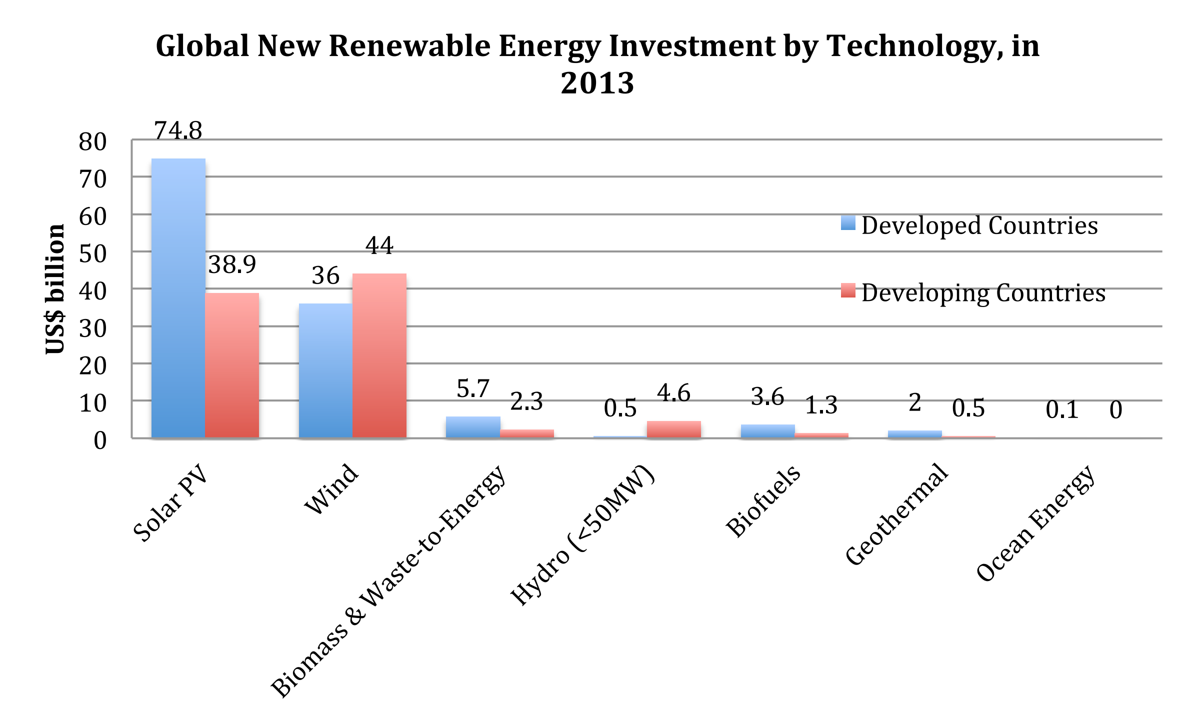

Figure 6: New Investment in Renewable Technologies Globally, in 2013.

Source: REN21 2014

Whilst utility-scale solar PV farms accounted for much of the growth, the rooftop residential and commercial solar PV market also experienced strong capacity growth (REN21 2014).

It is therefore becoming increasingly harder to ignore the rise of rooftop solar PV, and along with it, a need for its full accommodation in the total energy supply mix. As impressive as solar PV market growth has been thus far, we concur with REN21 (2014b) when they argue that this represents a very small part of what is an enormous global market potential that is yet to be exploited, especially in African, Middle Eastern and Latin American markets, all of which have rich solar resource endowments.

1.2.6 The Rise of Distributed Solar PV

The growth of distributed small-scale generation across the world has also been noteworthy, with more than a quarter (US$ 73.5 billion) of all new investment in renewable energy being channelled towards it (Frankfurt School of Finance & Management 2015). Whilst the European markets continued in their contraction, Japan remained the leader in small-scale distributed solar PV, with China expected to lead the next boom, and the USA having attained favourable economic conditions for their wide scale deployment (Frankfurt School of Finance & Management 2015). Figure 7 shows the growth in investment in distributed solar PV.

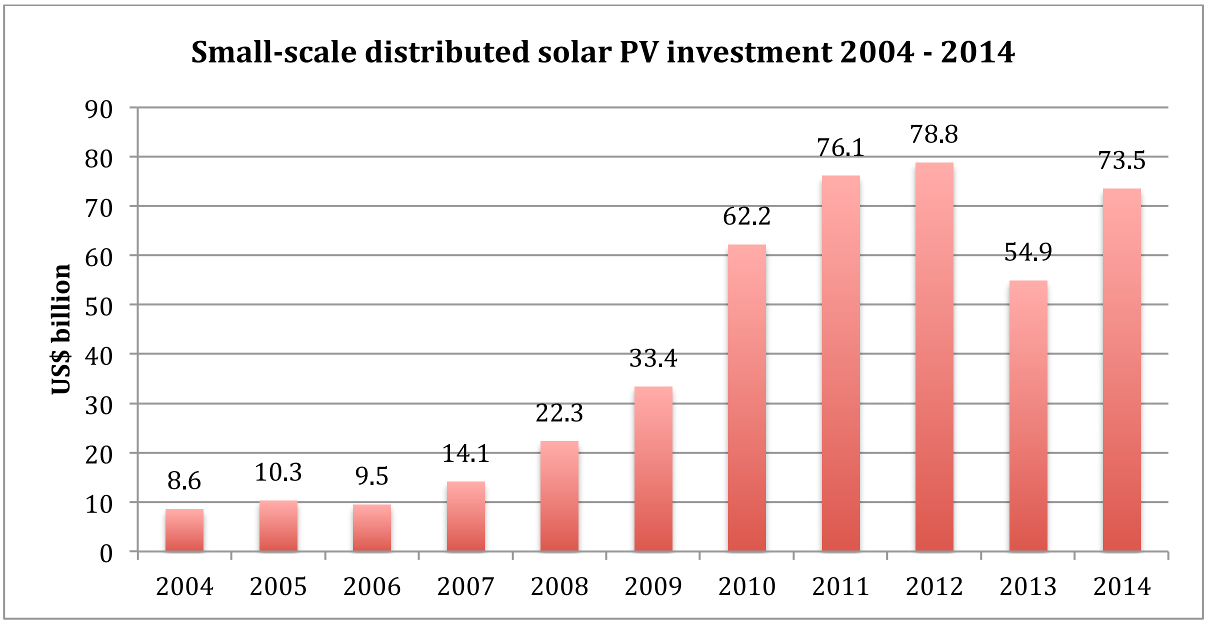

Figure 7: Distributed small-scale solar PV capacity investment: 2004-2014 (<=1MW)
Source (FSF&M 2015).

Japan, following its introduction of a feed-in tariff (FIT), added 6.9 GW of rooftop solar PV in 2013, to take its cumulative installed total to 13.6 GW (REN21 2014a). Australia was also a strong player in the rooftop market for solar PV. The Australian market grew from 8,000 rooftop solar PV installations in 2007, to one million installations by 2013, to bring the total installed capacity to 3.3 GW, which covered 14% of all residences and 25% of homes in South Australia (REN21 2014a).

Although the investment levels for small-scale solar PV declined in 2013, on account of reduced technology costs (Frankfurt School of Finance & Management 2015), the dominant trend has been upward over the last decade, with progressively more markets opening up.

1.2.7 Market Drivers

Policy support is the common factor accounting for the growth witnessed in renewable energy markets across the globe (REN21 2014b; REN21 2014a). This has led to a reduction in technology costs and the introduction of innovative financing instruments into the sector.

Renewable energy is becoming accessible to consumers in developing and developed markets alike, due to increasing affordability when compared to established fossil fuels. Renewables energy is also gradually shedding its niche technology status, and moving into the mainstream energy sector, due to its proven ability, not only as a sustainable source of energy supply, but as an engine for job creation, economic development, energy access and diversification of supply, carbon emissions reduction and rural development (REN21 2014a). The sharp decline in levelized cost of energy (LCOE), for solar PV in most markets, is making renewable energy cost-competitive with fossil fuels, and enabling industrial and commercial consumers to reduce their energy cost and reliability of supply (REN21 2014a).

Technology costs reduction in the last five years has been the singular market force behind the significant development witnessed in solar PV, in particular. Primarily because of the decline in the costs of module prices, by 2013, the cost of a rooftop solar PV kWh unit of electric energy breached the retail electricity barrier in several countries, including Australia, Brazil, Denmark, Germany and Italy, and became competitive without subsidies in at least 15 countries (REN21 2014a). The industry also saw the emergence of innovative funding instruments, such as third-party financing and leasing models, as well as bond-like funding structures, all of which have contributed to the growth of the sector (REN21 2014a).

1.3 Rationale for the Study

Cities are the engine for economic growth and development. Equally, cities are significant centres of consumption for energy and other natural resource, which are the results of a rapidly urbanising world. Therefore, Cities are having to face up to the challenge of transitioning to become spaces of sustainable urban development by actively engaging in the emerging discourse around how to support economic growth and development in a manner that decouple the historical relationship between energy and materials consumption on the one hand, and economic growth and development for a sustainable future, on the other. It is during these progressive engagements that Cities are realising that they are host to infrastructure and resources that can be utilised in the transition to a green economy. Byrne et al. (2015) propose a restructuring of the energy supply and demand economy at a city level as an essential component of the response to energy security and climate change binary of challenges. Part of this is exploiting the often neglected but vital solar PV resource and rooftop real estate of cities (Byrne et al. 2015).

Izquierdo, Montanes, Dopazo & Fueyo (2011), Melius, Margolis & Ong (2013) and Wiginton, Nguyen & Pearce (2010) all make strong arguments in their emphasis of the criticality of estimating the potential quantities of renewable energy that can be generated in an area, to policy-makers, regulators and the private sector alike. Where such potential estimates exist, especially in the local context, they have a bias towards large-scale utility generation, to the total neglect of the contribution of building facades and rooftop spaces to energy generation. After all, an estimation of solar PV potential in buildings, especially in an urban environment, is made complex and challenging by their scale and geographic spread of the buildings, as well as their varying architectural configurations, as encountered within and across the residential, commercial and industrial sectors (Kumar & Shekhar 2014).

South Africa has experienced phenomenal increase in the deployment of solar PV energy systems in the last five years. Utility-scale plants (solar farms) lead this technology penetration. However, rooftop solar PV systems are catching up very fast, and their adoption is expected to grow phenomenally as soon as an enabling policy framework is introduced. The overwhelming majority of rooftop installations are on residential, industrial and commercial rooftops, away from inner city vicinities. Inner city areas present unique challenges for the deployment of rooftop systems on account of their compact, high-rise buildings typology, which is characterised by unique architectural and rooftop morphologies. These unique challenges are, of course, multiplied a few times over when a mass rollout of solar PV technology is being considered.

Both the City of Johannesburg and the Gauteng Province have clearly stated policy positions on energy security and climate change. One of the four major outcomes of the City's consolidated and updated Joburg 2040 Growth and Development Strategy (Joburg 2040 GDS) is the provision of a resilient, liveable and sustainable urban environment, underpinned by infrastructure supportive of a low-carbon economy (CoJ 2011, p.9). The provincial Integrated Energy Strategy (GIES), amongst other pronouncements, also seeks to move the province to a low-carbon economy by scaling-up renewable energy options in order to enhance its climate change resilience and adaptation (Department of Local Government and Housing 2010; Colloquium et al. 2012; Africa 2009). However, both these key policy and strategy documents of the CoJ hardly recognise the potential of the rooftop real estate within the CoJ as a source of solar PV energy production, rainwater harvesting or urban rooftop food production. Yet the implementation of all of these, following an assessment of their potential, should constitute a holistic and uncontested city or provincial transition to a low-carbon and climate-change resilient economy. Rooftop PV mass rollout promises significant socio-economic benefit for all stakeholders, yet its potential, benefits and challenges are not clearly characterised within the CoJ.

In a broad sense, the research problem, and the research answers that are pursued, will contribute to the body of knowledge on rooftop solar PV generation in the South African context, especially in an urban or inner city locality. Although there are always valuable lessons to be learned from countries and cities that have acted as pathfinders in the rollout of rooftop systems, there are unique local contexts and circumstances that must be assimilated into any local approach for rooftop solar PV systems. Thus, locally generated information and knowledge about the challenges and opportunities presented by large-scale roll-out of rooftop PV systems in an urban or city environment has become urgent.

Beyond the CoJ and Gauteng Province, energy regulators and policy-makers have accepted rooftop solar PV as a mainstream technology that merits integration into long term energy supply and demand planning. Therefore, NERSA, as the national energy regulator, is a key benefactor of the research. NERSA has embarked upon a task to develop and introduce regulations incorporating safety standards, grid integration and installation incentives for rooftop solar PV (NERSA 2014; NERSA 2015). However this critical task is being carried out in an information vacuum about the realistic rooftop solar PV capacity from rooftops, especially within the inner cities. The Department of Energy (DOE) is another beneficiary of the outcome of this study. The DOE is confronted by the need to incorporate rooftop solar PV generation into the national energy mix to meet the long term energy demand and supply, as envisaged in the IRP2010 (DoE 2011; DoE 2013). Whilst the rising importance of rooftop solar PV is gaining appreciation, policy-makers lack the data to support the basis of their long-term penetration projections of rooftop solar PV in our energy mix.

At a specific level, the research will assist local, district and metropolitan municipalities to be able to develop a fairly accurate methodology to quantify the potential for rooftop solar PV generated power in their areas of jurisdiction. A keen appreciation of the amount of electricity that can be generated from their available, and suitable, roof spaces is important in installing the appropriate response mechanisms, plans and institutional arrangements to address consumer applications for installations and connections to the local grid. Being able to realistically quantify potential rooftop solar PV capacity in a specific area will enable a reasonably accurate assessment of the social, economic and environmental impact of rooftop solar PV rollout, and thus facilitate appropriate planning at a localised level.

The development of relevant policies and support mechanism to encourage the deployment of solar PV systems in urban environments, such as appropriate funding schemes, utility planning, and grid capacity accommodation of large number of distributed generating units, can only be addressed adequately, provided the technical potential of solar PV generation is clearly quantified (Wiginton et al. 2010; Brito, Gomes, Santos & Tenedório 2013).

Therefore, the outcome of this study is important for key stakeholders such as the private sector, local communities, energy policy developers, energy regulators and transmission and distribution grid owners and operators (Kumar & Shekhar 2014). It is also relevant for city planners as they develop infrastructure plans to create green cities and pursue sustainable urban spaces and infrastructure.

Although the study focuses on rooftop Solar PV, the estimates of building roof areas derived from it can also be used in solar thermal technology deployment, rooftop food gardens and rainfall harvesting applications in buildings within cities and other urban environments. (Johannesburg Development Agency (JDA) 2015, p.35)

1.4 Problem Statement

The City of Johannesburg Metropolitan Municipality, through its wholly owned subsidiary, City Power, and in line with an emerging trend in other large metropolitan municipalities in the country, is involved in discussions to introduce measures to accommodate rooftop solar PV systems on suitable rooftops of commercial, industrial and residential properties within its geographic jurisdiction. However, there are no known studies assessing the potential of rooftop PV generation in the CoJ. Thus, there is no realistic estimate of how much rooftop solar PV-based electricity can be harnessed from rooftops in the City. Without such information, the City cannot realistically anticipate how wide adoption of rooftop solar PV will affect its ability to deliver electricity to the consumers. Depending on the level of rooftop solar PV adoption, the city will find that it has to revisit its long-term plans regarding distribution network planning and deployment, sustainable revenue generation, and long-term climate change mitigation, amongst other considerations. Thus, the ability to anticipate the level of solar PV defection from the City's electricity distribution grid will become one of the key inputs into the City's electricity planning process.

Kumar & Shekhar's (2014) argue that beneficial inclusion of rooftop solar PV generation into an existing energy supply structure depends on a detailed knowledge of the solar potential. Izquierdo, Rodrigues & Fueyo (2008) advance a similar argument by stating that "a rigorously founded" rooftop solar PV potential assessment is "essential for the development of energy policy and regulations". Therefore, we concur, in arguing that the absence of detailed knowledge about the amount of solar PV electricity that can be harnessed from suitable rooftops within the City is a barrier for the City's stated intention to deploy the technology on rooftops in the city. Before the CoJ, or any other city, can commit to implementing rooftop solar PV generation across its real estate endowment, it must start with a detailed analysis of the available rooftops within its jurisdiction, followed by a carefully determined generation potential. After all, accurate information is one of the bases for effective policy-making and implementation. Such information is critical and an important missing step in the CoJ's and other cities' intentions regarding deployment of rooftop solar PV.

The main research problem can be broken down into the following sub-problems, the answers to which make up the response to the main research problem:

- What is the available rooftop space (area) within the CoJ?
- How much of this available rooftop space (area) is suitable for embedded rooftop PV installations?
- How much embedded rooftop PV power and electricity can be generated from the suitable roof space within the area?
- What would be the estimated impact of such renewable, solar PV electricity on the City's total carbon emissions?
- What would be the impact of the estimated, self-generated rooftop solar PV electricity on the electricity revenue of the City?

1.5 Research Objectives

The objective of this study is to assess the technical potential of rooftop solar PV in the inner city core of the CoJ, as well as its impact on revenue and carbon emissions within the City. The overall objective therefore is to arrive at an estimate of the total rooftop space area in the CoJ that is available for hosting solar PV installations. By incorporating solar PV resource attributes and assumptions to the available rooftop space, together with solar PV systems technical performance attributes, a determination of the total electricity capacity that can be generated from the total rooftop area in the inner city core will be arrived at. The implication of the derived technical solar PV power generation and its impact on the CoJ's long-term growth and development program as well as low-carbon economy strategies will be tested.

The key proposition arising from the main research questions is therefore that a demonstrably simple, accurate and affordable analytical method or tool, which is applicable across rooftops covering various geographic expanses, can be found to assess the potential of rooftop solar PV systems electricity generation in the CoJ.

1.6 Research Design, Methodology and Methods

The research approach consisted of a comprehensive review of published literature, reports and other sources of information focussing primarily on Renewable Energy, Solar PV, embedded rooftop solar PV, roof area assessment methods, solar PV electricity generation, characterisation of the chosen study location (CoJ), and generating capacity determination. This was followed by a sampling of an area within the inner urban core of CoJ, which is representative of the larger city area, upon which the chosen assessment methodology was applied. The roof spaces in the chosen sample were determined, using a chosen method, supplemented by an appropriate tool/instrument. The choice of the sample was driven by a need to render the methodology replicable across different areas of the broader CoJ limits, and other cities within the country. Following the filtering of the overall roof areas for shading, orientation, pitch and other obstructions, solar PV energy yield calculations were done. The data generated from the study are of a quantitative nature in the main and therefore, quantitative data analysis techniques were used. The overall research strategy is shown in Figure 8.

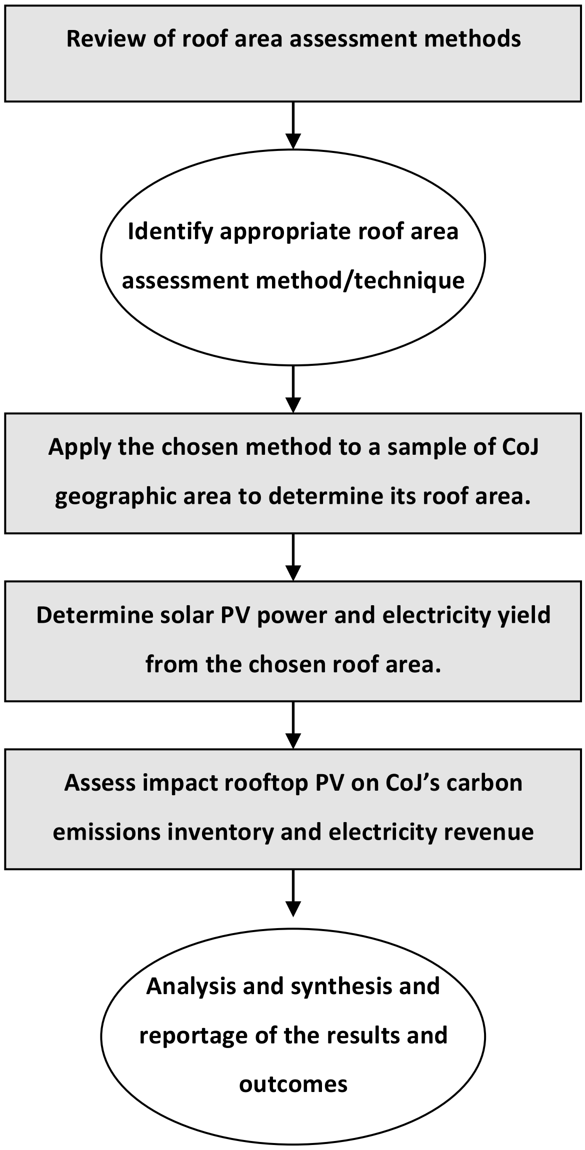

Figure 8: Strategy of the research study.

1.7 Limitations, Assumptions and Exclusions of the Study

This study covers rooftop solar PV, and thus excludes ground mounted systems, building facades systems or parking bay covers and canopy systems, all of which are equally viable and potentially deployable in an embedded or distributed configuration. The study is also deliberately confined to technical potential assessment in a manner that is distinct from economic, market or social potential assessments. Economic, market and social potential assessments represent further refinements of the technical assessment in their application of financial, economic and social demographics data to arrive at a practically installable capacity estimation.

Therefore, the final and realistically installable rooftop system capacity will be predictably less than the technical potential determined by this study, following further refinements to accommodate economic and commercial considerations, amongst others. Furthermore, and as Lopez, Roberts, Heimiller, Blair & Porro (2012) argue, because technical resource assessment includes assumptions about technology performance, the assessment will change as the technology performance improves and changes over time, in keeping with technology development trends. Therefore, the technical potential assessment determined from this study merely reflects the current technology development status of rooftop solar PV systems.

Due to variability of solar PV energy yield data across different geographic areas, aspects of the study relating to the energy yield from solar PV rooftop systems would not be applicable across different geographic areas, thus limiting repeatability of the energy yield estimates across different terrains. However, the choice of potential assessment methodology in this study accounts for repeatability and application across different geographic urban fabrics.

The structural integrity and load-bearing capabilities of the rooftop structures of the individual buildings normally require detailed, on-site characterisation, by a qualified structural engineer, to determine whether they are suitable for installations. Although, such an assessment falls outside the scope of this study, a deliberate attempt was made to exclude buildings which were deemed to be observably, either structurally inferior, degraded, abandoned, illegally-occupied or simply without any discernible signs of care and maintenance over an extended period.

The Google Earth imagery captured for the aerial buildings was captured on 2 August 2010, at an eye-level elevation of about 2 kilometres. The five-year gap between the date of uploading of the aerial imagery of the buildings in Google Earth and the date on which area measurements were performed is not expected to impact area measurements because the building population is unlikely to have changed much between then and now.

Chapter 2 – Literature Review

2.1 Introduction

The literature review is organised into three main themes, starting with a broad contextualisation of the research, followed by a progressive narrowing down to focus on the research problem and the related sub-problems. The first theme presents a sequential, broad perspective and status update of renewable energy technologies, followed by the solar PV sector, and more specifically, rooftop solar PV. Both global and a local contexts are adopted in the generalised broad perspective. The second theme deals with renewable energy technology potential assessments at a theoretical level, followed by a review, organisation and critique of available methodologies and approaches. The third and final theme covers the City of Johannesburg as the study area. The inverted pyramid in Figure 9, as recommended by Leedy & Ormond (2001), illustrates the organisation of the entire literature review. As the first level of the of the pyramid was addressed in Chapter 1, this chapter focuses on the bottom two levels of the pyramid.

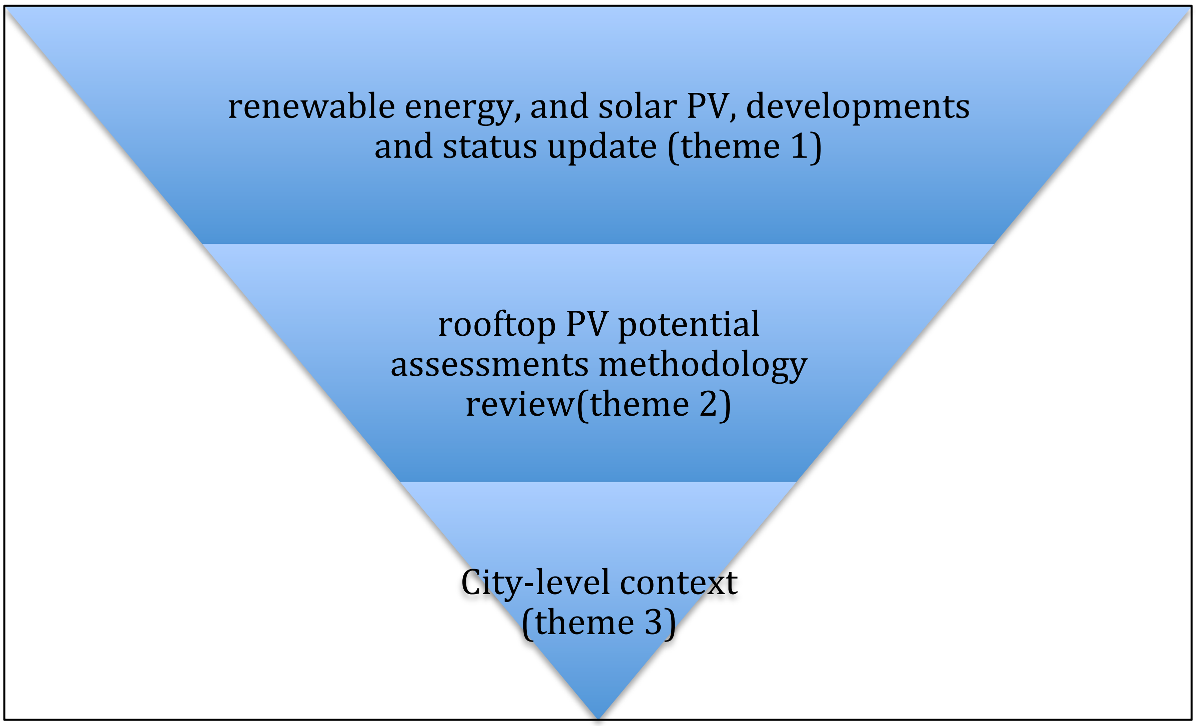

Figure 9: Illustrative organisation of the literature review.

2.2 Rooftop Potential Assessment

Rooftop solar PV potential varies across locations, depending on topographic conditions, system technical performance attributes, and building architectural characteristics (Brito et al. 2012). In order to estimate the energy generation potential of rooftop solar PV systems, technology-aspects of solar PV systems, based on resource quality and availability, technical system performance, topographical limitations, environmental constraints, and land-use restrictions that are applicable to the technology, need to be taken into consideration (Lopez, Roberts, Heimiller, Blair & Porro 2012).

Although a solar PV potential assessment in urban areas has received extensive scholarly attention over the years, what has emerged is an assortment of assessment methodologies that vary across geographic localities, and yield different results on application, depending upon assumptions made. This has ruled out the emergence of a generic, one-size-fits-all method for rooftop PV potential assessment. Although some enduring aspects of proven methodologies and their core principles can be applied across different locations, necessary adjustments of the assumptions underpinning the method, to align with local conditions, are unavoidable. Departing from a localised basis, the process to determine the energy potential from solar PV at a regional level is hindered by the absence of data for rooftop area estimation, with the problem being just as acute in developed countries, as it is in developing countries (Izquierdo et al. 2008; Wiginton et al. 2010; Izquierdo, Montanes, Dopazo & Fueyo 2011).

2.3 Defining Renewable Energy Potential

"Potential" embodies a number of critical qualifications or hierarchies, which are relevant for purposes of this study, namely: resource potential, technical potential, and economic potential or market potential (Lopez et al. 2012). Izquierdo, Rodrigues & Fueyo (2008) also refer to three potential hierarchies that are relevant for rooftop solar PV energy, namely: physical potential, which encompasses the total amount of solar radiation in an area of the study; geographic potential, which applies site restrictions on the energy to be captured; and finally, technical potential, which accounts for the technical attributes of the energy conversion technology that applies.

In the same way as Izquierdo et al. (2008), Sun, Hof, Wang, Liu, Lin & Yang (2013) define three levels of potential, but starting at geographic, through to technical and finally, economic potential. Each of these hierarchies is a sub-set of its predecessor, with a progressively diminishing magnitude as you ascend through the levels. The all-encompassing geographical potential is derived from the physical potential, through the successive exclusion of areas reserved for other uses, such as rivers, national parks, beaches and other facilities (Izquierdo et al. 2008). Figure 10 depicts the various levels of potentials that are assessable.

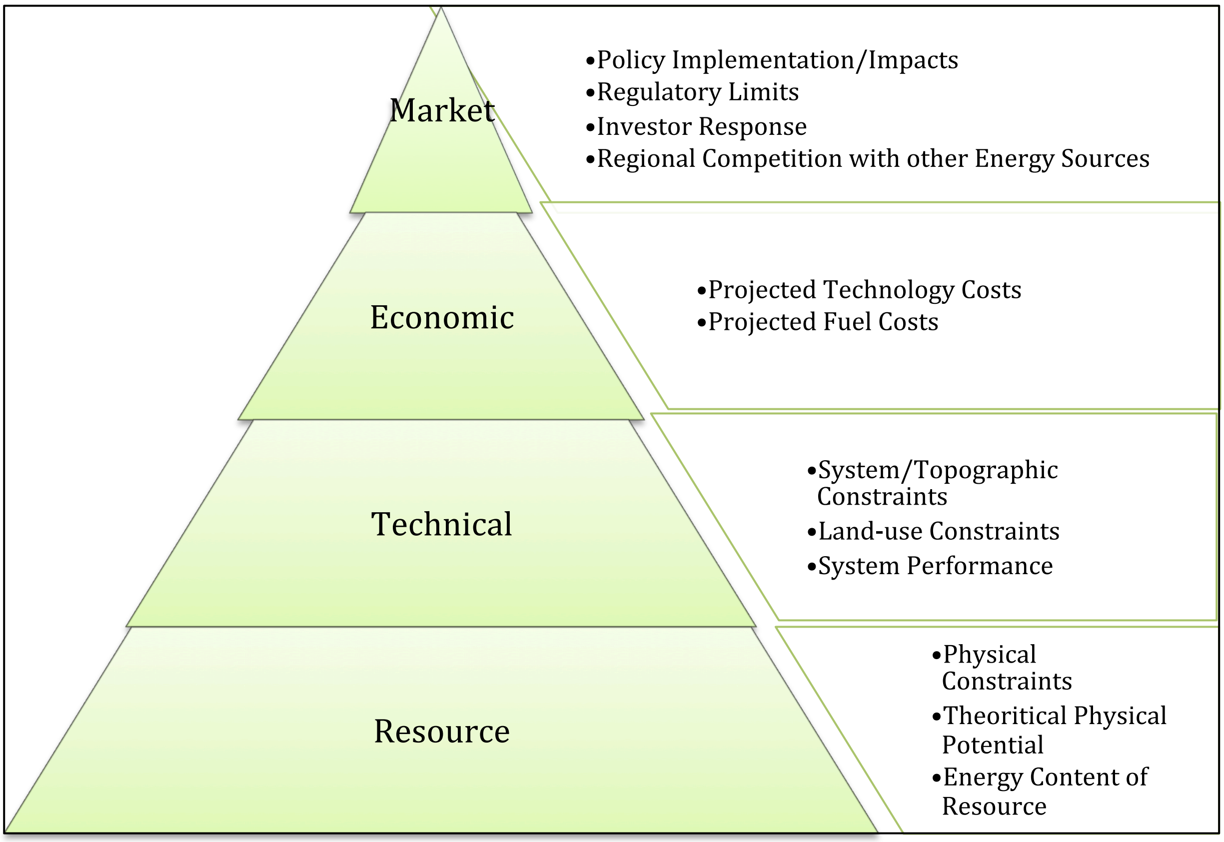

Figure 10: A hierarchy of possible Potential Assessments.

Source: Lopez et al. (2012).

Computation of the technical potential entails the consideration of three aspects: (a) radiation incident over a tilted surface, and computation of various types of radiation; (b) module spacing for shading avoidance; and (c) module efficiency (Izquierdo et al. 2008). The technical potential alone is not an indicator of the total capacity of rooftop solar PV that will be eventually deployed in the area under consideration. For such, one needs to determine the economic and social potential (Lopez et al. 2012). Technical potential, as Lopez et al. (2012) correctly assert, sets an upper boundary for the development of rooftop solar PV, as used in this study. The resource potential, which represents the starting point towards technical potential determination within the area of the study, was obtained from published literature. Further, because the technical potential is partly dependent on technology performance, as the technology performance improves over time, the technical potential would be expected to change positively as well (Lopez et al. 2012).

2.4 Technical Potential Assessment Methodologies

2.4.1 Overview of Existing Methodologies

The determination of the solar PV potential in urban environments is made complex by the wide variety of building typologies encountered, their spatial distribution, diverse elevations and contesting architectural structures, and natural vegetation that is part and parcel of the urban or city landscape (Kumar & Shekhar 2014). For this reason, it is often impossible to find a one-size-fits-all methodology that is applicable across various urban buildings typologies or regions.

Efforts to develop a somewhat universally-applicable methodology have been guided by the pursuit of a faster, easier, data-light, and affordable process for determining rooftop solar PV technical potential (Bryan et al. 2010). Many methods have been developed over the years following the wide deployment of rooftop solar PV. However, the more modern methodologies have tended to be nothing more than refinements of older ones, in their exploitation of innovative computational image capturing, database manipulation, and microprocessor speeds.

Existing assessment methods range from econometric-based approaches, to studies of individual building typologies, which are then extrapolated to a large building population in the area of study (Ordóñez et al. 2010). Other approaches entail the estimation of potential, relative to the total roof surface area and total geographic area under study (Ordóñez et al. 2010). Therefore there is a number of methodological approached that have evolved through the years.

Melius et al. (2013) identified three categories of methodologies: (a) quick and easy methods that use a constant value to estimate generalised roof area results, (b) detail-specific and time-consuming methods that use manual techniques, and (c) GIS-based methods that are both time consuming and computationally intensive. Each of these three groups of methods, presented in the order that they are here, represents a refinement of the preceding one. Thus, with the emergence of powerful computational data processing capability, GIS methods have risen to dominance, on account of their high levels of relative accuracy, replicability and ease of automation. But, GIS-based methods can also be time-consuming and computationally intensive. GIS-based analytical tools also dominate the number of patents filed on methodologies; yet another indication of the increasing automation and technology influences in the preferred methodologies (Melius et al. 2013).

Taken together, the majority of the available methodologies share a distinctive outline of sequential steps to determine potential assessment of rooftop solar PV potential. Although they might differ in number, the sequential steps all include the following: (a) determination of gross rooftop surface area, extracted from digital building imagery, using analytical tools, (b) determination of usable or effective building rooftop surface area, after filtering and correcting for shading and other roof characteristics, (c) estimation of peak capacity per building rooftop, (d) estimation of energy generated, and finally (e) determination of other metrics such as number of modules per area or building utilisation factors, and so forth (see Figure 11) (Kumar & Shekhar 2014; Ordóñez et al. 2010; Wiginton et al. 2010; Izquierdo et al. 2008).

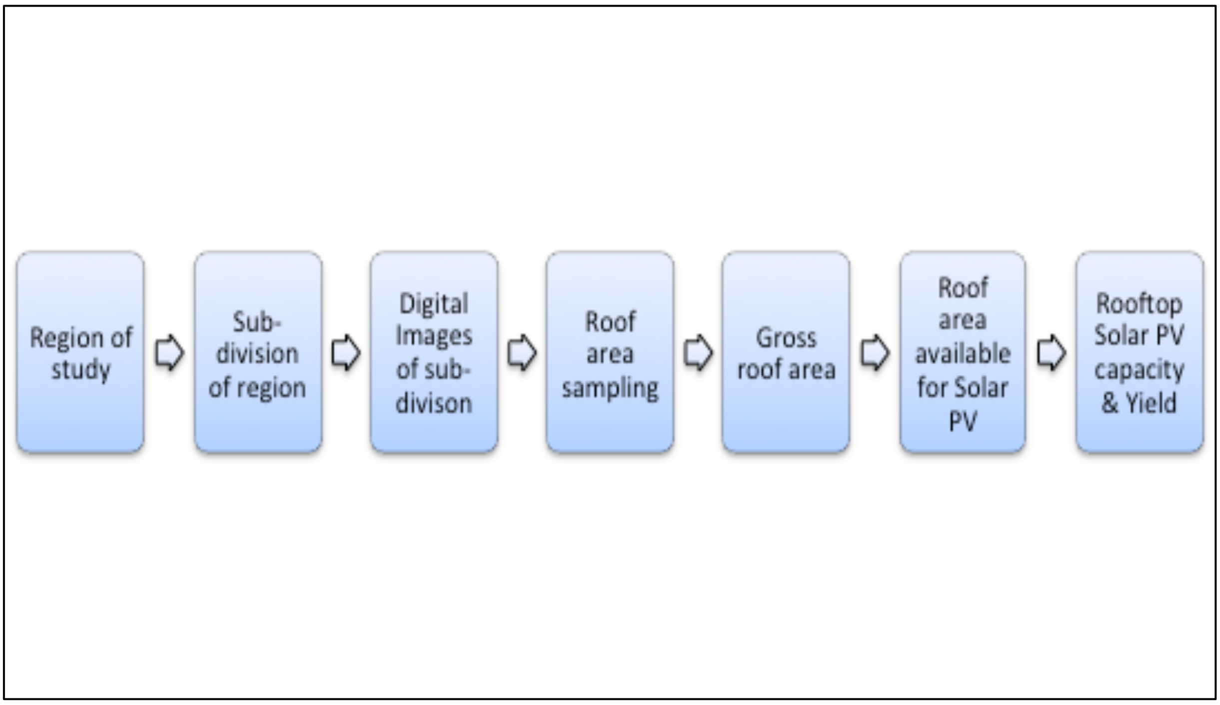

Figure 11: Flow diagram of methodological steps for rooftop PV potential assessments.
Source: Modified from (Wiginton et al. 2010; Izquierdo et al. 2008)

Irrespective of the method applied to arrive at an assessment of the PV potential in an area, Izquierdo et al. (2008) have been able to accurately capture the essential elements of an idealised methodology to calculate available roof area by stating that it must:

> (a) be accurate; (b) be reliable, with the possibility of computing or bounding the error of the roof area estimation; (c) be inexpensive (low cost); (d) be efficient (low calculation times); (e) require few, global, available and standard input data; (f) produce geo-referenced results; (g) be scalable from local to global scales; and (h) be structured and flexible, so that new or unforeseen aspects can be introduced, and that the method can be used for the estimation of the long-term evolution of available roof surfaces.
>
> (Izquierdo et al. 2008:p930)

2.4.2 Methodological Assumptions

All the methodologies that were examined include location-specific assumptions, which inherently would have to be adjusted across various applications. For example, Reinecke et al. (2013), in their assessment of PV potential of Riversdale, excluded RDP houses and similarly small dwellings on account of roof structural integrity and system costs considerations, amongst other factors. What is clear is that most of these assumptions must be explicitly stated, as they are challengeable in most cases. For example, Reinecke et al. (2013) would have arrived at a different potential estimate, had they made the equally reasonable assumption that DC appliances could be used in RDP houses, thus obviating the need for inverters, which proved to be a cost barrier, or by excluding determination of market potential.

2.4.3 Basic Data Availability

The availability of basic data is the cornerstone of all methodologies reviewed. Therefore access to databases of gross roof space, especially in cities, municipalities or regions, is a major barrier, and therefore a key determinant of methodological choices. Izquierdo et al. (2008) in their proposed methodology, address this absence of gross roof area data in large territories by arguing for a methodology based on easily accessible data, such as land uses, and population and building densities. The availability of building construction and population data was also used to complement data extracted from analytical tools in a number of methodologies that were reviewed (Bryan et al. 2010; Ordóñez et al. 2010; Reinecke et al. 2013). Thus, once again, the emphasis is being placed on the importance of basic buildings data, even in instances where it compliments data extracted from the application of analytical tools, like GIS. The availability of construction statistics from government were particularly key in the study by Ordóñez et al. (2010), for purposes of establishing gross roof surface area for buildings. The availability of high quality data has therefore played a key role in dictating methodological choices in some cases (Wiginton et al. 2010). Access to such data, whilst easier in most developed countries, as Wiginton et al. (2010) assert, might prove to be a challenge in developing countries like South Africa.

A number of methodologies relied upon national census as the source of key input data (Wiginton et al. 2010). Wiginton et al. (2010) utilised census data to determine land area and population for each of the sub-divisions making up the total area they considered in their study. Kumar & Shekhar (2014) used satellite imagery of buildings obtained from GIS, and DEM data sets, together with topographic information and meteorological data. Ordóñez et al. (2010) applied a combination of statistical construction data and Google Earth^{TM} digital urban maps to calculate the energy capacity of grid-connected solar PV rooftop systems Andalusia (Spain). Denholm and Margolis (2008) estimated the total rooftop area for commercial and residential buildings in each state of the USA, using data from McGraw-Hill, which was scaled to estimate total building area, based on the number of floors in each building class, e.g. a three-story building with 3 000 ft^2 floor space would be assumed to have a roof space of 1 000 ft^2.

Therefore basic building and demographic data, as found in statistical sources such as census data, is a critical building block for any methodology for roof area assessment.

2.4.4 Areas of Study

The size of the area being studied is an important consideration, because it appears that no single method can be applied across different areas (Izquierdo et al. 2008). A methodology that delivers acceptable rooftop solar PV potential estimates in a densely populated urban or city environment, which is dominated by high-rising and sky-scraping buildings, will not be as effective in a sub-urban residential area or sparsely populated agricultural small-holding area. The size of the sample and scaling of the study area or sampled area, to a larger geographic area, appears to be critical. The ability to select a representative sample of a large area, for purposes of extrapolating the outcomes to a larger area, coupled with the applicability of the methodology to a cross-section of different areas, is another key consideration.

2.4.5 Building Sample Size

In their study, Bryan et al. (2010) assessed a total of 364 buildings within a city environment, a 100 of which were considered to have solar PV potentials, and out of which a further 85 were shortlisted for final analysis and the determination of the overall potential. Reinecke et al. (2013) covered a total building population of 3,638, which was filtered down to a sample of 40% (1,468 erven) of the original population size, out of which 1,074 (29.5% of original building population) commercial, industrial and residential buildings were assessed. Ordóñez et al. (2010) covered an entire region of Andalusia, a 87,597 km^2 area of southern Spain, whilst Izquierdo et al. (2008) covered the entirety of Spain (505,990 km^2) in their study of all buildings in urban areas, irrespective of their use, except industrial buildings. Wiginton et al. (2010) also considered a large-scale area in south-eastern Ontario, in Canada, covering a total land area of 48,000 km^2 with a total population of 1.9 million at the time of the study, which also included the cities of Ottawa, Kingston and Peterborough. Unlike Reinecke et al. (2013) and Bryan et al. (2010), Ordóñez et al. (2010) targeted only residential buildings in their study, which were classified according to building typology and roof type, namely: town house, detached house or high-rise building, and flat or pitched roof. Demonstrating yet again the importance of the availability of data, mean roof surface area for each building typology was obtained for all 1,400,000 in Andalusia, and extrapolation of sample characterisation to the broader total building portfolio became critical (Ordóñez et al. 2010). In order to establish useful roof surface area, Ordóñez et al. (2010) used proportionate stratified sampling technique to extract a representative sample of buildings from the entire building stock under study. Kumar & Shekhar (2014) focussed on a university campus, occupying 621 acres. Like Ordóñez et al. (2010), Izquierdo et al. (2008) also used a stratified statistical sampling technique, based on the definition of a representative building typology (RBT), which is descriptive of representative building characteristics in a given area, such as building height or roof structure.

A catchall sampling technique is not identifiable from the above studies. While other methods covered a portion of a city, others covered an entire city, a region or an entire country. Attempts at some level of sampling entailed stratified sampling, which relied upon the identification of a representative building typology. Whilst it might appear feasible to identify a dominant building typology, it becomes harder to do so as the study area grows in size. Yet, the benefit of sampling only comes to the fore when the study area is larger and the population of buildings grows in number.

However, as they grow in number, the ability to identify a dominant building typology diminishes at the same time.

2.4.6 Correlations and Extrapolation

A number of researchers have also explored and identified a causative link between the population density of a specific area, and the roof area available in that area. Wiginton et al. (2010) classified this approach to rooftop PV potential assessment as the constant-value method. Indeed, Wiginton et al. (2010) located a linear relationship with a strong correlation (R-squared value of 0.993) between population density and roof area in an assessment of a region in Ontario, Canada. However, this constant-value method was shown to be vulnerable to variations in building density and sprawl across different nations or countries (Wiginton et al. 2010). To illustrate, whilst the study suggested a 70.0 m^2 per capita gross building roof area for Canada, other researchers applying the same approach, recorded 24.4 – 180.5 m^2 per capita gross building roof area for Spain, 17.6 – 21.2 m^2 per capita for Brazil and 10.6 – 30.7 m^2 per capita for the United Kingdom. It appears that a country-specific constant-value factor needs to be established before the method can yield useful results. Once established, the correlation factor can be a useful approach to extrapolating the outcome of the samples area to a larger region, as Wiginton et al. (2010) and Izquierdo et al. (2008) have demonstrated.

2.4.7 Analytical Tools

Analytical tools are indispensable for gross building area determination. Google Earth and Google Maps were the analytical tools of choice for acquiring aerial images of buildings (Bryan et al. 2010; Reinecke et al. 2013). These analytical tools were also utilised for setting image reference points for scaling up the images when uploading them into other measurement tool like AutoCad or Sketch-up, which enabled additional manipulation of the captured building imagery (Bryan et al. 2010). Reinecke et al. (2013) used Geographic Information System (GIS) software to estimate available roof spaces, using Google Earth Pro and the “create polygon” tool to demarcate suitable roofs. Ordóñez et al. (2010) also used Google Earth to generate digital urban maps, complimented by statistical building construction data, obtained from government, to measure useful roof surface area. Wiginton et al.

(2010) utilised geographic sampling techniques with image recognition, using ArcGIS (Feature Analyst), to extract rooftop images from high resolution digital orthophotos. Wiginton et al. (2010) emphasised yet again the importance of “simple and easy-to-learn” software analytical tools, in their choice of ArcGIS and its Feature Analyst functionality as key analytical tools.

Nguyen et al. (2012) also applied a GIS-based method, using Light Detection and Ranging (LiDAR), technology together with automated solar PV deployment analysis, on a regional scale. This methodology adopted an inter-disciplinary approach that infused remote sensing (RS), GIS and computer vision and urban environmental studies (Nguyen et al. 2012). The essence of the methodology is a rapid, efficient and computationally-light approach to the extraction of roof models, without sacrificing generality and wider application (Nguyen 2012). GIS and LiDAR methods shared similarities in their pursuit of simple, effective and computationally light approaches. Although LiDAR can be costly, as it requires the use of aerial imagery obtained using light aircrafts, it has proved to be the preferred method currently (Melius et al. 2013).

2.4.8 Roof Filtering and Determination of Useful Roof Area

Delineation of installation areas on roofs was done using computation tools in the main. Bryan et al. (2010) marked out suitable roof spaces for solar PV installation from the AutoCad/Sketch-up images, basing their selection on factors like roof orientation, roof inclination, shading (by trees as well as from adjacent buildings), and presence of obstructions and alternative features occupying the roof space. The extent of the incidence of these factors were used to rank the roofs, on a five-point scale, in order of suitability for solar PV installation (Bryan et al. 2010). Therefore, depending on extent of each of these attributes, a roof was either least, less, somewhat, quite feasible, or ideal for solar PV installation (Bryan et al. 2010). Whilst the ranking simplified the process as initially set out, it also introduced significant bias and subjectivity, depending on the person doing the ranking. Two rankers would invariable arrive at different rankings for the same building. Reinecke et al. (2013) used the Google Earth Pro and its polygon creating tool to mark out suitable roof spaces. Filtering of the roof spaces for shading and other obstructions was done via a combination of aerial images and visual inspection, whilst a similar approach was adopted for assessing roof inclination and orientation (Reinecke et al. 2013). Ordóñez et al. (2010) and Wiginton et al. (2010) considered building type, roof tilt angle and orientation, location, shading and competing uses such as HVAC, elevator shafts, roof terraces and penthouses in determining the useful roof surface area. Shadows in particular, cast upon solar PV modules at certain times of the day, either by trees or adjacent buildings, have been shown to limit solar PV access of rooftops. In a study conducted in residential neighbourhoods of California, Levison, Akbari, Pomerantz & Gupta (2008; 2009), were able to show that shading reduced insolation by between 13 and 16%, and that over time, with growth of the trees, shading can increase to between 19 and 22%. Therefore, in assessing shadows cast upon a rooftop system, a long-term perspective on the potential severity of the shading has to be taken into account as well.

2.4.9 Visual Surveys

Site visits are vital for filtering out buildings that are considered unsuitable because of heritage reasons or unique architectural structures. The structural strength of the roof, and its ability to carry the load of the solar PV array, is another exclusionary factor, although this can be mitigated by a structural integrity assessment survey by a professional (Bryan et al. 2010). In their study, Reinecke et al. (2013) used visual inspections, complimented by erven-specific municipal data, to obtain spatial characterisation of the buildings and their roofs, as well as to estimate inclination and azimuth orientation of roofs. Site surveys are not always possible, however, because of the geographical expanse of the regions often chosen in the study. Ordóñez et al. (2010) made no use of field visits because their study area, being a region, would have been impossible to cover. No field visits were undertaken by Izquierdo et al. (2008) and Wiginton et al. (2008) to validate their theory-based available roof area estimates either. Both studies relied on the outcome of other theoretical methodologies to validate their results. Although no explanation for the exclusion of field visits is offered, it is possible that the large regions covered in their study also obviated the need for actual site visits to validate the results. However, since the regions were sub-divided and sampled, it would have been possible to approach field visits for validation in the same way.

2.4.10 Energy Yield Calculations

The determination of solar PV capacity and energy yield was aided by the utilisation of freely available (open source) software-based analytical tools in the methodologies assessed. Based on available roof space for solar PV, Bryan et al. (2010) used RETScreen PV to calculate power capacity and energy generation. Reinecke et al. (2013) used satellite-derived data (HelioClim v2) to calculate the latitude tilt irradiance (LTI) at a plane angle of 30 degrees, and used this to calculate PV potential using a reference solar PV module. Correction factors were also applied to account for varying roof orientation and inclination angle in arriving at electricity generation, for which PVPlanner software was used (Reinecke et al. 2013). Ordóñez et al. (2010), unlike Reinecke et al. (2013), opted to use mathematical formulations, instead of software, to calculate energy yield of the system, for which different module influences as well as installation configurations (flat or tilted) were also tested. Kumar & Shekhar (2014) also used mathematical equations to derive available roof surface areas from gross surface areas. In order to arrive at an estimation of available roof area, adjustment coefficients were progressively applied to the total surface area occupied by buildings (Izquierdo et al. 2008). Melius et al. (2013), Izquierdo et al. (2008) and Wiginton et al. (2010) concentrated their efforts on what they correctly identified as the most critical element of their proposed methodology, being the determination of available roof area, and the inherent errors, and not so much on the estimation of solar PV capacity or energy generation, which can easily be determined.

2.4.11 Validation of Results

Lack of explicit validation of the outputs of some of the methodologies is a serious shortcoming (Melius et al. 2013: 16). Along with validation against other computational models (Wiginton et al. 2010) and existing solar resource data (Nguyen & Pearce 2012), walking surveys (Reinecke et al. 2013; Bryan et al. 2010) are an indispensable validation measure, in view of the wide ranging results output obtainable from each of the methods (Melius et al. 2013). Of these three techniques, validation against real, installed solar PV systems offers the most advantaged because of the high data quality. The downside is that installed systems are not only the outcome of technical potential assessments; instead, they also incorporate economic and market potential considerations (Melius et al. 2013).

2.5 Technical Potential Assessments in South Africa

Solar PV potential assessments for rooftop systems in South Africa is still in its infancy, when contrasted against regional potential assessments in support of utility scale solar farms. Reinecke et al. (2013) undertook the only work of a scholarly quality in this area. The focus of the study was in the residential sector, as it was based on the small town of Riversdale, in the Western Cape Province. The Gauteng Department of Infrastructure Development (GDID) performed the only other existing study. The study was focussed on assessment of rooftop spaces in 98 out of a total of 9,000 public buildings in the Province, as part of a roll out of rooftop solar PV systems in the Province (GDID 2014). Although no further methodological detail of the GDID study was provided, it was clearly lacking in originality and scholarly rigour, and loosely based upon the methodological approaches of Reinecke et al. (2013). Thus, the study by Reinecke et al. (2013) remains the only scholarly attention that rooftop space assessment for solar PV systems deployment has received thus far. Therefore, no large-scale potential assessment has been done in South Africa, focussing on industrial or city areas.

2.6 South African Cities and Rooftop PV

Cities, acting either individually or as part of a collective network, are the single most important driving force for economic growth and development in any country. The UN-Habitat (2011) heralds a city as one of the highest pinnacles of human creation, and CoJ (2011) and SEA (2015) proclaim them as engine rooms of regional and national economic development, or more pointedly, as the frontline of the developmental state in South Africa. The unique abilities of cities to concentrate people into dense, interactive and shared spaces, in manner that delivers unique advantages for innovation, wealth creation and enhanced quality of life, is undeniable. But cities also face complex challenges of rapid urban migration, climate change and unsustainable resource utilisation (CoJ 2011). According to UN-Habitat (2011), more than half of the global population now lives in towns and cities, and projections are that this will increase to two-thirds by the year 2050. Such high levels of urbanisation are straining the ability of Cities to meet the basic needs of their citizens, such as energy, clean air, water, food and liveable spaces, in a sustainable manner. UN-Habitat (2011) cautions that in order for cities to survive, they must development and grow their economies in a manner that respects and rehabilitates the ecosystem. Thus, Cities must alter the way they use spaces, building architecture and infrastructure to address the challenges facing their continued existence.

A number of the bigger cities in South Africa have been rethinking ways of transitioning into low-carbon economies by investigating rooftop solar PV from around 2008.

2.6.1 eThekwini Metro

Despite its relatively low – by South African standards - average solar resource of about 1,450 kWh/m^2, eThekwini is held up as one of the first-mover municipalities in its efforts to accommodate rooftop solar PV. The City developed a six-steps Durban Solar City Framework to guide its promotion of solar in the City (Morgan et al. 2013; U.S. Department of Energy 2011). Some of the early steps in the six sequential steps framework have already been completed by the city, whilst the rest are being pursued over the two-year life of the framework implementation timeline. An analysis of market barriers for solar technologies study was also completed, as was the legislative and regulatory review relevant to embedded generators in the City (Morgan et al. 2013). Further work to be undertaken as part of the program includes: solar-friendly bylaws and town planning regulations, improvement of local grid access policies and processes, as well as the creation of a city solar map and information portal for consumers. The Durban Solar Map was published in March 2015 (eThekwini Municipality 2015). The map is intended as a consumer tool for high level planning of installation of solar PV systems of less than 100kW on their rooftops, and enables, not only yield calculations, but also system costs and electricity savings computations. As early as September 2011, the City Council approved conclusion of Power Purchase Agreements (PPAs) with embedded generators, albeit for a period limited to three years, and at a rate capped at Eskom's Megaflex Tariff structure (Ethekwini Electricity Unit n.d.; Morgan et al. 2013). Although the short PPA agreement duration, as well as the low tariff, hardly serve as incentives for the wide deployment of embedded solar PV generators within the City, it, together with the highly transparent and simple applications guidelines and processes, are hailed as an important step in the development of the industry in South Africa.

2.6.2 Cape Town Metro

The City of Cape Town has also made strong strides in the deployment of rooftop PV generation. The City published guidelines for connection of embedded generators on the distribution network and an online application form for facilitating smooth applications to connect to its distribution network (CoCT 2014; CoCT 2015). The City has also published NERSA approved tariffs for residential rooftop solar producers. The City also hosts one of the largest rooftop solar PV installations in South Africa and the world, the 1.2 MW Black River Park rooftop solar PV system. This project is the first one to enter into a contract with the City, in terms of which, it is able to connect onto, and sell excess power back, into the grid at the newly approved tariffs and guideline regulations (CoCT 2015).

2.6.3 Johannesburg Metro

Outcome 2 of the City of Johannesburg's updated and comprehensive, long term growth and development strategy, addresses the provision of infrastructure within the City, which is supportive of a low-carbon economy by 2040. The outcome of this strategy is the provision of sustainable energy, water, food, eco-mobility and waste reduction services. Implementation of the strategy has resulted in installation of a remarkable portfolio of green technologies around the CoJ. The City's global reputation has also been enhanced by its willingness to participate in international knowledge-sharing platforms dealing with challenges of climate change and urbanisation (CoJ 2016b). Some of the City's noteworthy global accolades include the C40 Cities Award, which was made at COP21, for its highly successful green bond, as well as a top-five ranking for its 2015 climate change adaptation plan.

For all its impressive collection of green and sustainable projects, covering waste management, bioenergy, water harvesting, solar water heaters, green living and recreational spaces, the CoJ's achievements are equally remarkable for their total exclusion of rooftop solar PV. Unlike CoCT and eThekwini, both of whom can be described as having embraced rooftop solar PV as a key component of their economic, environmental and social development and growth strategy, at best, CoJ can only be described as a reluctant participant in the enablement of its citizens to install rooftop solar PV system (CoJ 2015). The CoJ does not have a single, self-developed, flagship rooftop solar PV project of note, nor systems and procedures in place to accommodate consumer's interest in self-generation.

The reason for this underwhelming support for rooftop solar PV within the City is, perhaps, because, unlike eThekwini and City of Cape Town, the CoJ has a wholly-owned entity in the form of City Power, to which it has fully delegated its electricity services supply mandate. It appears that the CoJ has in the process, also delegated the responsibility for the rooftop PV sector to City Power, although no such delegation seem to apply in respect of other embedded generation technologies in the city.

2.7 City Power and Rooftop PV

City Power Johannesburg (SOC) Ltd. (City Power) is a wholly-owned municipal entity that was established by the City of Johannesburg in November 2000, with a mandate to purchase, distribute and sell electricity within the CoJ (City Power 2016b). City Power is not the sole provider of electricity services in the CoJ. It shares the responsibility with Eskom, which is responsible for supply to areas such as Soweto, Sandton and the CBD (City Power 2016b).

City Power distributes electricity to about 410 000 domestic, industrial and commercial customers within its licenced area of service, all of whom, together, represent a power demand of 3,500 MVA (City Power 2016b). The bulk of electricity distributed by City Power is purchased from Eskom, although Kelvin Power Station also supplies City Power through a long-term purchase agreement.

City Power's belated response to the mushrooming demand for rooftop solar PV systems within the City has been to issue a tender for installation of rooftop PV systems at two of its operational depots. The objective of this pilot project, according to City Power (2015b), is to align its operations with the provincial mandate for the pursuit of green economy, whilst also showcasing their commitment to sustainable development and reduction of carbon footprint. On the face of it, City Power's objectives cannot be faulted, except that City Power also states that the project is intended to afford it the necessary experiencing of installation and operation of a large-scale, grid-tie PV system (City Power 2015:p7). For a project whose tender closing date was April 2016, and for which actual work can only be reasonably expected to start in August 2016, it is rather telling that City Power is still looking to gain experience in what it terms a city-wide rollout in the next few years, whilst other lesser cities are grabbling with mass roll out of rooftop systems. It is reasonable to expect that City Power would view rooftop solar PV generation by its captive consumers as a threat to its revenue base in the long-term. After all, City Power derives 95% of its revenue from electricity sales, and therefore it cannot be expected to consciously aid the emergence of a market force whose impact is the erosion of its commercial sustainability.

2.8 Eskom and Rooftop PV

Eskom is a supplier to some of the areas within the CoJ, notably, Sandton and Soweto Eskom established a Renewable Energy Unit in 2011, with a mandate to focus on wind, solar PV and CSP technologies (Eskom 2014). The unit has developed a 150 MW solar PV project portfolio for self-consumption (Eskom 2014). Eskom's project portfolio of rooftop and ground-mounted solar PV systems is expected to reach 2,000 in number, with potential energy yield of 250,000 MWh (Eskom 2014). About 2 MW of this project portfolio is already operational (Eskom 2014), and is included in the total installed embedded solar PV capacity estimates alluded to earlier.

Prior to the launch of the now discontinued, Small Scale Renewable Energy Pilot Programme (SSREPP) in June 2012, Eskom did not have prescribed policies or regulations for connecting embedded generators to their grid (Mckenzie et al. 2012; Eskom 2012). The SSREPP planned to procure a total of 10 MW of renewable energy capacity from embedded power generators with installed capacities ranging between 10kW and 1 MW (Mckenzie et al. 2012; Sustainable Energy Africa 2012). Although the program was not exclusive to rooftop solar PV, it did serve to incentivise the installation of rooftop solar PV generation capacity, and thus aided in the development of the local industry.

Eskom was also key in setting up working groups to develop the National Regulation Standards (NRS) NRS 097-2-series, dealing with utility interface, product type testing and utility frameworks, amongst others, in response to increasing levels of interest in rooftop solar PV directed by households to municipalities (Eskom 2012; Sustainable Energy Africa 2012).

2.9 Electricity Revenue in the City of Joburg.

Electricity sales and distribution revenue is the largest source of income for cities and municipalities. Under the current fiscal framework, cities and municipalities rely on the revenue to cross-subsidise non-revenue-generating social service delivery expenditure budgets. Middle-to-high income residential as well as industrial and commercial customers are the source of the cross-subsidisation revenue, and yet, they are also the most likely customer base to partially or fully defect from the municipal grid. A modelling of the impact of municipal revenue loss as a direct consequence of consumer uptake of energy efficiency (between 50 and 85% penetration) and solar PV (between 3 and 50% uptake), in the cities of Cape Town, Ekurhuleni and eThekwini, over a period of ten years, was able to demonstrate overall revenue loss of 3-11% for CoCT, 5-15% for eKurhuleni and 8-15% for eThekwini (Sustainable Energy Africa 2013; Sustainable Energy Africa 2014). It seems that the concerns, as expressed by the South African Local Government Association (SALGA), and cited by Sustainable Energy Africa (2015, p.38), of negative impact of municipal revenue arising from mass customer defection from the grid, are well-founded.

Millson (2014) seems to underestimate the impact by suggesting that it can be offset by socio-economic benefits that rooftop PV installation will unlock. But, In addition to appreciating the negative impact of rooftop solar PV to municipal revenue collection, Reinecke et al. (2013) liken it to that of solar water heating and other energy efficiency projects that have not encountered resistance from municipal officials. But Reinecke et al. (2013, pp.92–97) also make the important concession to the uniqueness of rooftop solar PV and its potential to disrupt the traditional electricity utility market paradigm when compared to other initiatives that potentially reduce municipal revenue income,. After all, unlike solar water heating and energy efficiency technologies, rooftop solar PV systems can be designed and sized to fully replace consumer's municipal electricity demand to zero or to produce excess electricity, which, where possible, can be fed back into the municipal distribution system. Further to this, is that although energy consumption reduction through energy efficiency measures does reduce electricity sales revenue through reduction in demand, it seems such demand curtailment does not pose a commercial sustainability threat to municipalities and their utilities.

Revenue loss due to uptake of renewable energy also affects utilities. Germany's experience, where decentralised power generation accounts for about 48% of the country's total installed capacity (Edelmann 2013), is a better indicator of the extent of the impact. In 2013, RWE AG was forecasting declining electricity peak demand, and, therefore, sales revenue, of about 20%, from 24 GW to 19 GW, through to 2035 due to self-generation (Edelmann 2013, p.35). Also in Germany, traditional utilities like RWE AG and E.ON SE are now grappling with reinvention of their business models in order to offset the impact of revenue loss due to distributed generation, or face financial ruin (Edelmann 2013; Bloomberg 2016). It would therefore be expected that City Power and Eskom, as the two utilities supplying CoJ, would also be anxious about the revenue loss they are predicted to suffer due to the high penetration rates of rooftop PV amongst their high-value consumers, following their defection from the grid. After all, large metros like the CoJ generate about 30% or more of their revenue from electricity sales, with profit margins of about 15 to 20%, and utilities like City Power generate about 95% of their revenue from electricity sales and distribution (Breytenbach 2016, p.10; City Power 2016b).

2.10 Greenhouse gas Emissions in the CoJ

South Africa ranks amongst the top greenhouse gas (GHG) emitters in the world due to its complete reliance on fossil fuels sources in their total energy mix. Although its high ranking betrays the primary bias of its economic structure, it is nonetheless incongruent with its global GDP or population ranking. By extension, and because the CoJ is the economic hub of the country, and host to a high concentration of economic activity, it is a significant contributor to South Africa's GHG inventory. It stands to reason that a reduction in the CoJ's carbon emissions will result in a significant dent in the overall GHG inventory of the country.

Reducing reliance on fossil fuels through adoption of renewable energy is a well-known means of reducing greenhouse gases. However, what is often forgotten is that reducing the distance over which energy is transported also reduces greenhouse gases (Van Hoesen & Letendre 2010). This assertion holds true for decentralised energy generation systems, as epitomised by rooftop solar PV. Rooftop PV also has a lighter carbon emissions footprint in comparison to centralised, utility-scale solar PV farms. Rooftop PV systems, deployed widely, are also less likely to suffer simultaneously failure on a large scale. That the deployment of solar PV systems will reduce reliance on fossil fuels, and thus, reduce carbon dioxide emissions holds true even when the energy payback time and life-cycle greenhouse gas emissions of the solar PV systems are accounted for. Boyle (2012, p.107) advances a similar argument when he cites research by Fthenakis et al. (2009), which was able to show that it takes about 1.8 years for a PV array to produce as much energy as was consumed during its manufacture.

Carbon dioxide emissions are one of the key policy objectives intended to drive the CoJ's transition towards a green city. Joburg 2040 GDS, as well as a number of publications by the City give expressions to this strategic pursuit (City of Johannesburg 2016b; Jordan 2016).

Electricity competes with petrol as the main sources of energy in the CoJ, as shown in Figure 12. The demand for electricity is driven by residential, industrial and commercial consumers' need for heating, lighting and cooling.

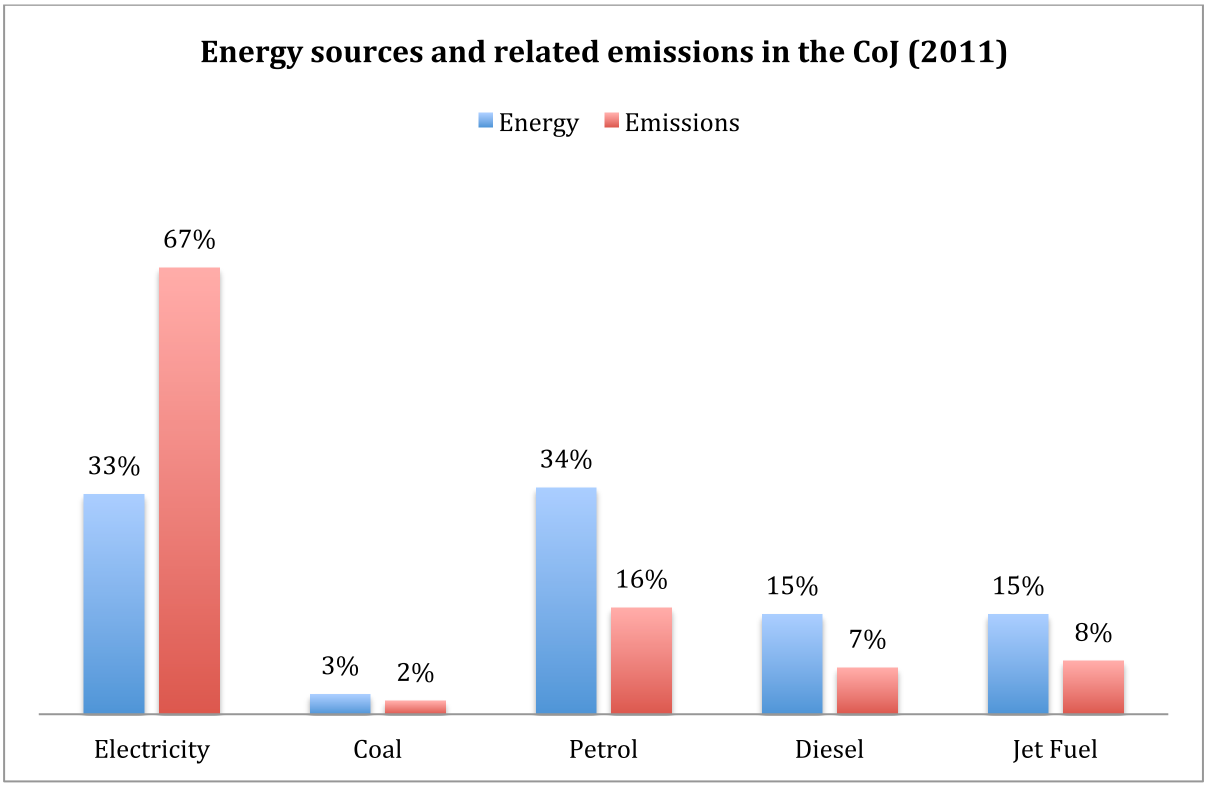

Figure 12: Energy by fuel and related emissions in CoJ. Source (SEA 2015).

Electricity and petrol differ substantially in their carbon dioxide emissions, and therefore, their contribution to the CoJ's emissions inventory (see Figure 12). Carbon emissions per unit of energy from liquid fuels are less than that from electricity.

Further examination of the demand sectors' contributing to the overall electricity demand in the City, and therefore, the carbon emissions, reveals the dominance of residential and industrial sectors (see Figure 13).

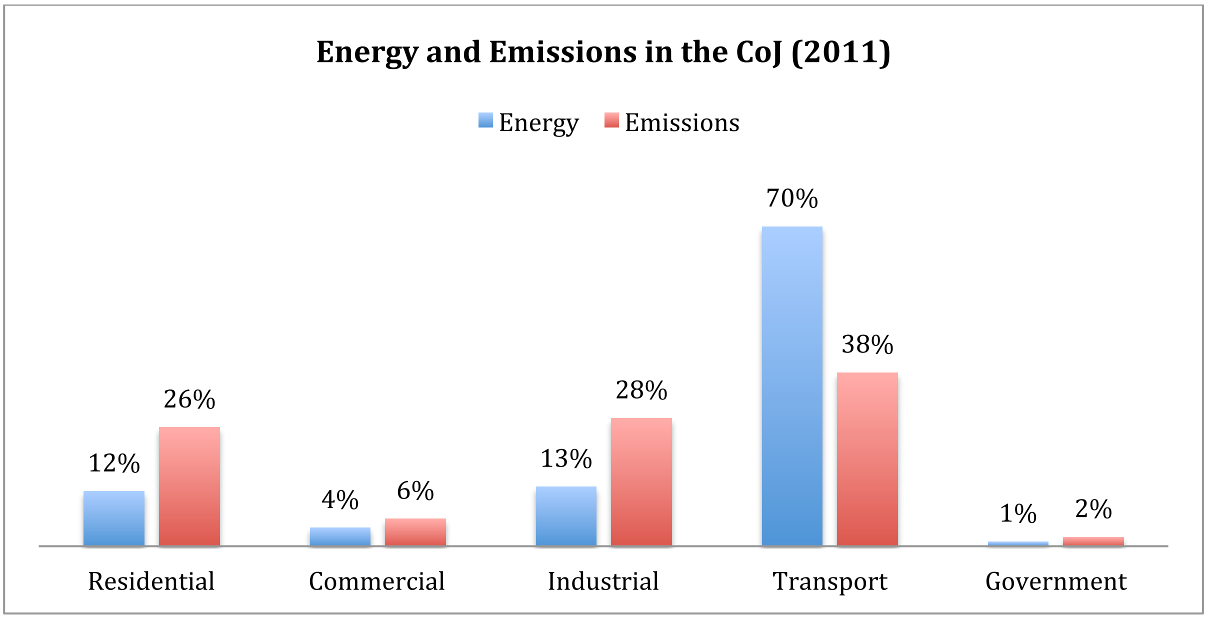

Figure 13: Sectoral breakdown of energy and carbon emissions in the CoJ (Source: SEA 2015)

The CoJ also dominates all the metropolitan municipalities in the country in the demand for electricity, and therefore, the associated carbon emissions (see Figure 14).

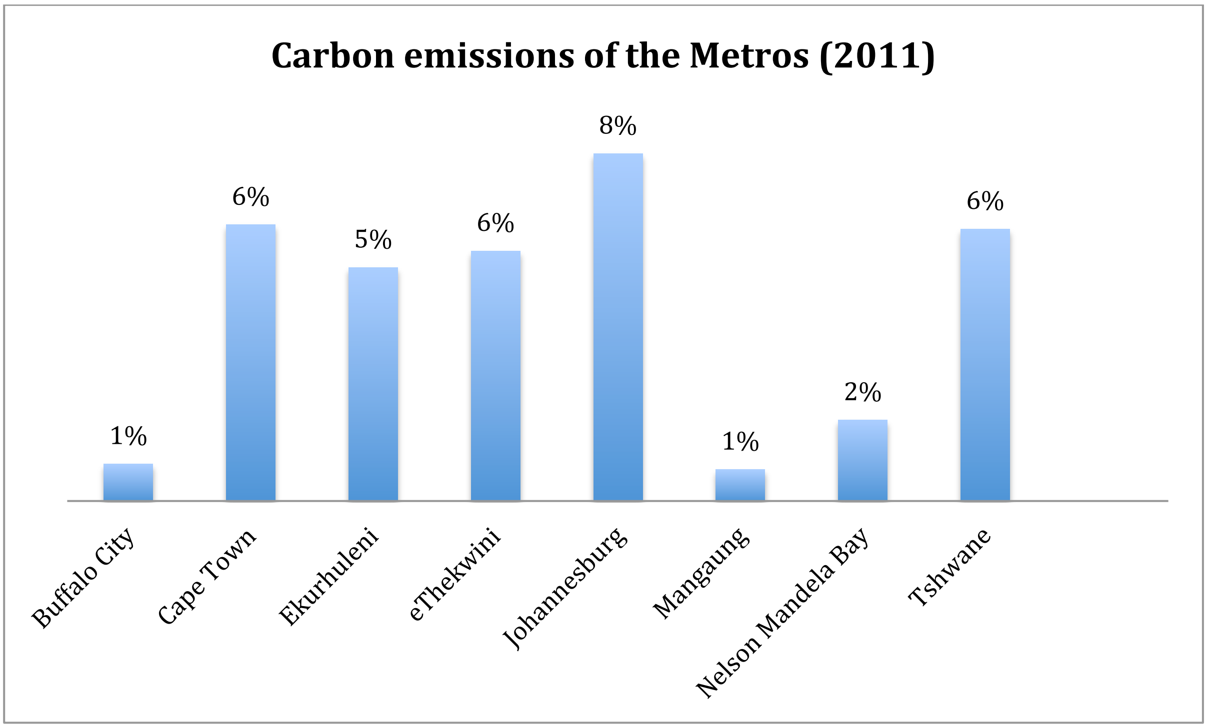

Figure 14: Carbon emissions from electricity in the Metros (Source: SEA 2015).

As a single administrative area, the CoJ's electricity consumption sector makes a significant contribution to the national GHG inventory, and the residential and industrial demand sectors are the main drivers of the city's carbon emissions profile.

In the report on the state of energy in South Africa cities, Sustainable Energy Africa (2015, p.131) has been tracking the energy consumptions and emissions inventories of cities, including the CoJ (see Table 1).

Table 1: The CoJ's energy and GHG emissions profile. (source: SEA 2015).

	2004	2007	2011
Energy (all fuels) (GJ)			
City of Johannesburg	130 941 453	142 612 254	175 720 664
South Africa	2 717 859 800	2 705 336 000	2 704 007 821
Energy Emissions (tCO_2e)			
City of Johannesburg	19 994 863	22 538 611	25 147 445
South Africa	391 327 499	433 527 000	460 124 000
Electricity (GJ)			
City of Johannesburg	44 895 773	52 493 812	58 839 270
South Africa	707 756 746	786 152 590	729 103 033
Emissions due to Electricity (tCO_2e)			
City of Johannesburg	12 845 179	16 063 106	16 834 569
South Africa	202 497 069	224 926 991	208 604 479

Table 1 not only shows the national GHG emissions inventory linked to both overall energy and, more particularly, electricity demand, but it also shows the CoJ's substantial contribution to both. Also evident from the table, is South Africa's and the CoJ's steadily increasing carbon dioxide emissions, in line with energy demand, and more particularly, electricity demand.

2.11 Summary

The renewable energy sector has been growing phenomenally over the last decade, with solar PV destined to take over from wind as the fastest growing renewable energy technology in the world. Projections of capacity growth, capital investment and policy support for solar PV, in particular, all point towards a sustained growth trajectory for the sector. The predicted growth is accompanied by a decline in technology cost, which will render the technology cheaper that fossil fuel electricity – all things considered.

Rooftop solar PV systems are also at the centre of a spreading, global, distributed energy generation drive. South Africa is joining China, India and Brazil in leading the transition towards renewable energy driven economies, with its superior solar PV resource at the forefront of that transition. Local regulators and policy-makers are making plans to accommodate and incentivise the wide deployment of rooftop solar PV through introduction of regulations and standards for installations. But as they do so, they seem to be concentrating attention on residential and industrial consumers, who are, in the main, located on the outskirts of the cities and beyond, to the total ignorance of the potential inherent in the inner city real estate to host rooftop installations.

There is an absence of estimates of the potential of solar PV that can be harnessed in the cities. There are many methodologies that have been developed over the years, mainly in the developed countries. Their applicability includes single buildings, city blocks, residential suburbs, states, regions and entire countries. The existing methodologies depend on the availability of data, correction factors, a national solar PV resource base, computation and manual analytical tools and technology attributes; to derive estimates of the solar PV potentials that are necessary to guide the optimal development of the rooftop solar PV sector.

All the major cities in South Africa, some with more commitment than others, have embraced the important contribution that wide scale adoption of rooftop PV can make to energy security of supply and climate change resilience in their domains.

Along with efforts to introduce a supportive environment for ease of technology deployment, large metropolitan municipalities, like the City of Johannesburg, are also decrying the revenue losses that are expected to accompany widespread grid defection, especially by high-value consumers. Equally, cities like the City of Johannesburg appreciate the carbon emissions offset potential of widespread deployment of rooftop solar PV systems in their areas.

Chapter 3 – Research Design and Methodology

3.1 Introduction

Research design and research methodology are related, but they are not similar. Research design is a framework that enables the researcher to collect and analyse research data in order to answer the research question (Bryman et al. 2011). The data collected through the chosen framework seeks to meet the validity, reliability and replicability criteria of the research, and enable the researcher to answer the research problem and sub-problems, as Bryman et al. (2011) so persuasively argue. Research methodology, on the other hand, is located within the framework of the research design, of which there are several. Once the research design has been chosen (i.e. the framework), the choice of the research methodology to be used, to collect the data, follows. Therefore, research design entails the planning and design of the overall structure of the research approach and the process of data collection necessary to address the research problems, whilst the methodology involves the actual data collection techniques and methodologies, which often involve the use of data collection instruments like surveys and measurements (Leedy & Ormond 2001; Bryman et al. 2011).

3.2 Research Design

The research approach adopted in the study is of a quantitative nature. Bryman et al. (2011) describe this approach as one that emphasises quantification in the data collection and analysis, as well as adoption of deductive approach to the relationship between theory and the research, where emphasis is placed on the testing of the theory. The building rooftop area data collected was quantified to arrive at usable roof space, from which generation capacity of installed PV systems could be determined. The overall planning and design of the overall frame of the research is illustrated diagrammatically in Figure 15.

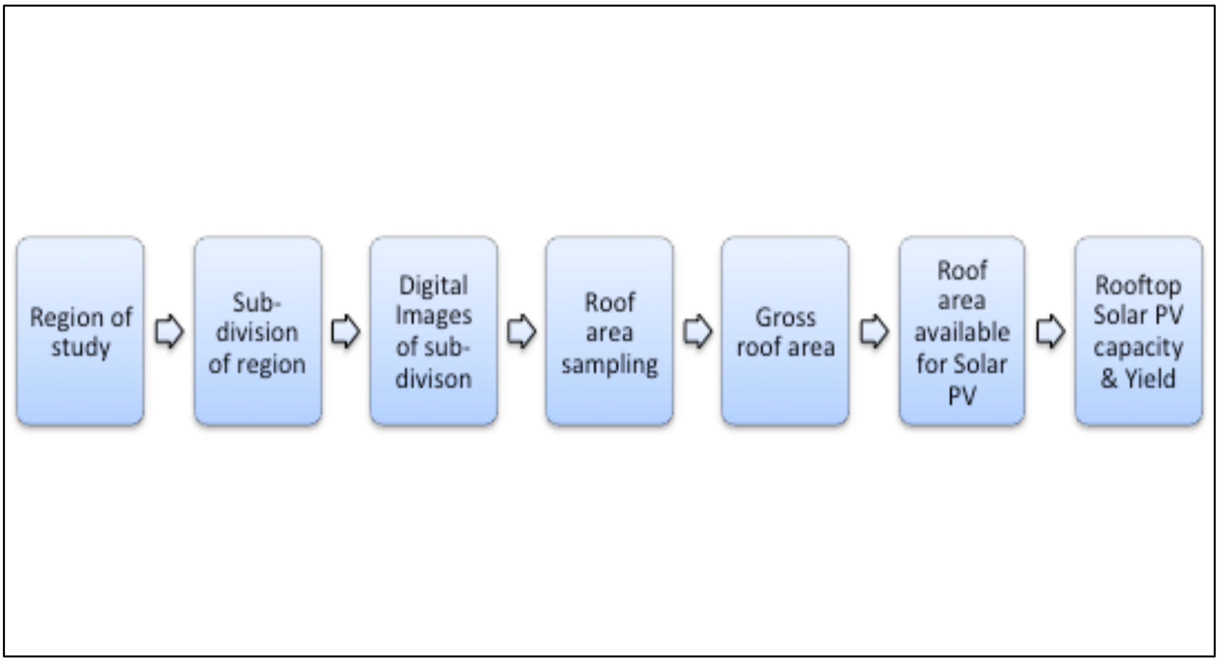

Figure 15: Research Design Framework.

3.3 Research Methodology

3.3.1 Study Area Characterisation

The CoJ is the largest of the nine metropolitan municipalities in South Africa, which include Cape Town, eThekwini, City of Tshwane, Buffalo City, Nelson Mandela Bay, Mangaung, Rand West and Ekurhuleni. These cities are the collective home to more than half of the population of South Africa. They produce more than 70% of South Africa's economic wealth, and consume about half (46%) of the electricity produced (Sustainable Energy Africa 2015, p.12).

The CoJ in particular, is one of the three metros that are located in the Gauteng Province. It shares its northerly border with the City of Tshwane, its eastern border with Ekurhuleni, its southern border with Sedibeng District Municipality and its western border with Rand West City (see Figure 16). The CoJ accommodates a population of 4,949,347 within a land area of 1,645 km^2 (StatsSA 2013; StatsSA 2016, p.16).

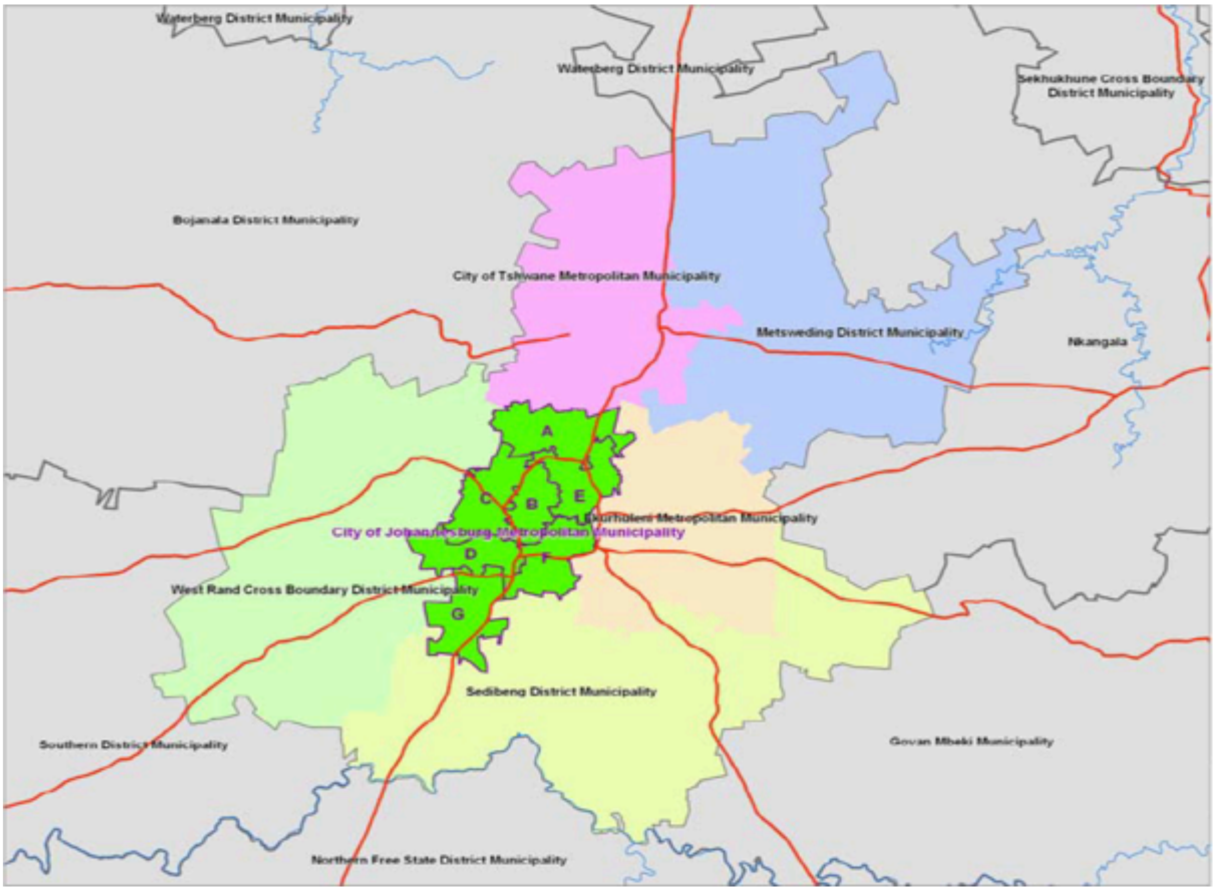

Figure 16: Locating CoJ with Gauteng Province municipal geography.

The City is divided into seven administrative regions, namely, Regions A to F, whose constituent regions and sub-regions are allocated in Table 2, whilst Figure 17 depicts their geographic location within the CoJ (JDA 2015, p.20).

Table 2. The seven administrative regions of the CoJ (Source: JDA 2015).

Regions	Sub-regions and Sub-urban areas
Region A	Diepsloot, Kya Sand
Region B	Randburg, Rosebank, Emmarentia, Greenside, Melville, Northcliff, Parktown
Region C	Roodepoort, Constantia Kloof, Northgate
Region D	Doornkop, Soweto, Dobsonville, Protea Glen
Region E	Alexandra, Wynberg, Sandton
Region F	Inner City
Region G	Orange Farm, Ennerdale, Lenasia

Region F, the inner city of the CoJ, represented the geographic area of the study. In its entirety, Region F hosts the financial, commercial and residential districts of Braamfontein, Braampark, Central Business District, Doornfontein, Hillbrow, Jeppestown, Joubert Park, Marshalltown, Newtown and Yeoville.

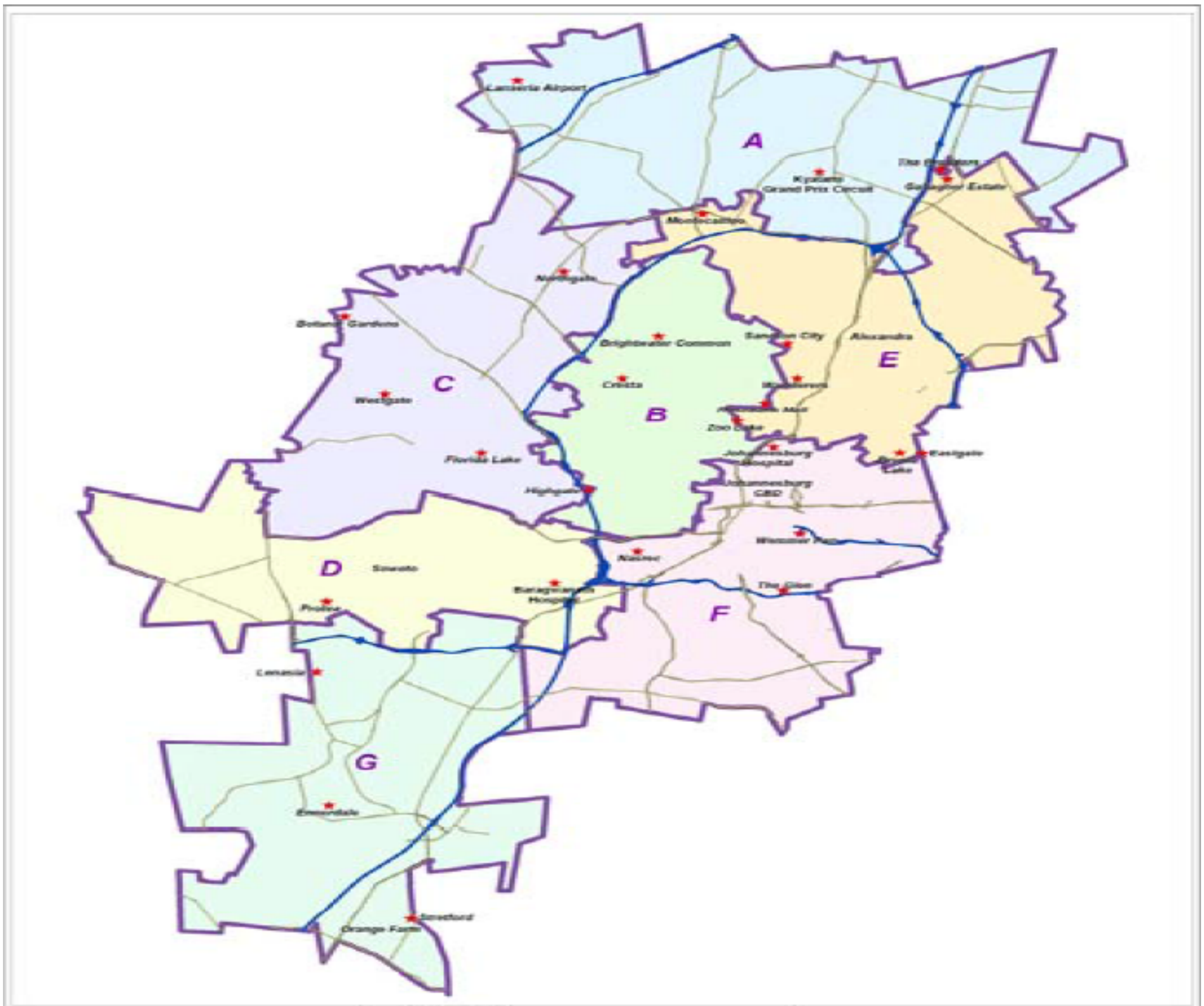

Figure 17: The seven administrative regions of the CoJ (Source: JDA 2015).

The Johannesburg Development Agency's (JDA) has demarcated the inner city into four precincts, which are useful in pinpointing the boundaries of the study area further. These are the Park Station Precinct to the north, Westgate Station Precinct in the west, Hillbrow Tower Precinct in the east and the Inner City Core in the south (JDA 2015, p.43). The inner city core precinct includes the retail improvement district and the commercial core of the CoJ. The retail commercial district is bounded by Jeppe Street in the North, Commissioner Street in the South, Harrison Street in the

West and Von Brandis Street in the East, whilst the commercial core is defined as the area between Sauer Street in the West, Bree Street in the North, Mooi Street in the East and Commissioner Street in the South (Johannesburg Development Agency (JDA) 2015, p.49).

The area is dominated by dense, high rising and sky scrapping buildings (see Figure 18), which serve as commercial office blocks in the main, although a few have been converted into residential flats. The majority of the skyscrapers in central Johannesburg date from the boom of the 70s and 80s when the City took on a mini Manhattan feel (Emporis 2016). No new high-rise buildings have been added to the city's landscape since. Although there is somewhat of a reversal in the degradation that the CBD has been experiencing, following a number of successful inner city redevelopment projects, which are part of the inner city renewal plan (Emporis 2016).

Figure 18: The typical building typology in the inner city core of the CoJ.
(Source: Foundation Wikimedia 2016).

Table 3 shows the spread of building typologies in the inner city of the CoJ. Clearly evident from the table is the dominance of high-rise buildings in the inner city of the CoJ, with other buildings, and skyscrapers, in particular, coming in a distance second.

Table 3: Building typologies in Johannesburg (Emporis 2016).

Building Type	Number of Buildings
High-rise buildings	294
Skyscrapers	12
Low-rise buildings	11
Stadiums	5
Telecommunication tower	2
Clock/bell tower	2
Roller coaster	1
Temple	1

Note: skyscraper: Any regular multilevel building with an architectural height of at least 100 meters.

3.3.2 Sampling

The focus of the study was rooftops of buildings falling within the geographic area, loosely termed the inner city core of CoJ. The geographic boundaries of what defines the central business district of the CoJ are, like those of any other city, open to interpretation. However, often there is universal agreement about what constitutes the centre of such an area. Thus, an area within the centre of the city, and radiating out towards the periphery, was taken as the central business district and area of the study. All the individual buildings falling within this defined area constituted the population of the study. The population size of buildings within the demarcated area was small, thus obviating the need for extracting a representative sample. Figures 22 and 23 depict the area of the study, viewed from different eye altitudes.

Figure 19: Digital image of the study area, observed at high eye altitude.

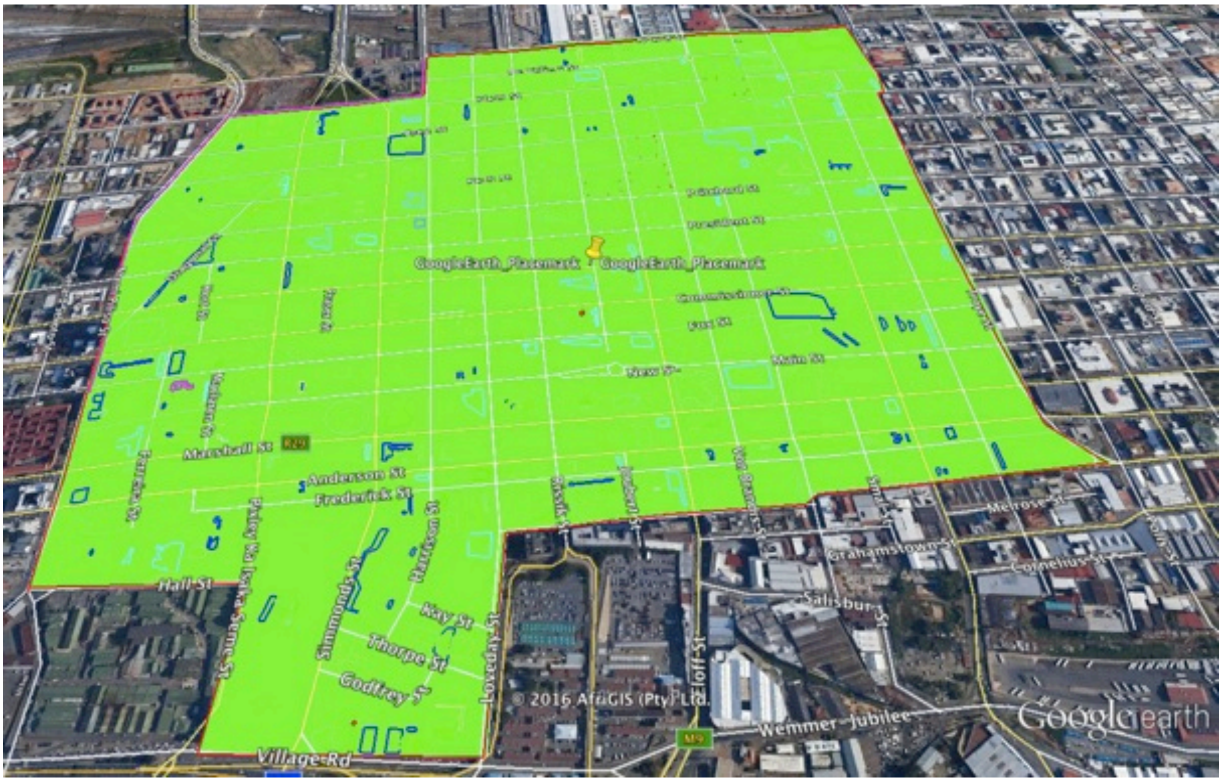

Figure 20: Digital image of the study area, observed at low eye altitude.

The area enclosed in red defines the area of the study (see Figures 22 and 23). This area represents a largely homogeneous population of high-rise buildings, which is used mainly by large businesses and government departments that constitute the core business activities of the City. All together, 202 building blocks within the CBD constitute the rooftop population covered by the study area. The buildings are spread over 1.64 square kilometres area within the inner city core. The area is bounded by Carr and Gwigwi Mrwebi Streets in the north, Twist and Troye Streets in the east, Albert, Loveday, Village, Pixley Ka Isaka Seme and Hall Streets in the south, and Ntemi Piliso Street in the west (see Figure 20). Each of these building blocks was made up of a number of rooftops of various configurations.

Buildings located north and northeast of the city were excluded. This area of the inner city core bears all the hallmarks of urban blight and degradation, which is typified by unmaintained, abandoned, illegally occupied and overcrowded buildings. Other buildings to the south, southwest and west of the area were excluded, because they were mainly low-rise light industries and factories. The building typology, especially in these buildings, is not typical of a CBD, which is characterised by high-rise buildings.

3.3.3 Data Collection Tools

The primary data that was collected as part of the research was the area of the rooftops of the individual buildings in the area of the study. The areas of shadows cast on the rooftops of the buildings by obstructive objects, including the areas occupied by the obstructive objects themselves, as well as areas of shadows cast by adjacent, neighbouring buildings on the building rooftop of interest, were also sources of the primary data of interest.

Google Earth Pro (version 7.1.5.1557 running on OS X El Capitan) was used as the primary measurement tool. Google Earth Pro is a freely available GIS programme. It maps the earth by superimposing images obtained from various sources, such as satellite imagery, aerial photography and geographic information system, on a three-dimensional image of the earth (Wikimedia n.d.). Although the degree of resolution achieved in the imagery varies across countries, most countries in the world, including South Africa, are covered by about 15 meters of resolution (Wikimedia n.d.).

Aerial digital images of the building rooftops were extracted from Google Earth Pro. Because Google Earth images are extracted from multiple sources, the dates on which the images were acquired by the various sources vary (Wikimedia n.d.). The digital aerial imagery of the buildings captured for this research was dated 2 August 2010.

The "polygon" function available in Google Earth Pro was used to take area measurements directly from the digital images projected to the computer monitor. Different eye altitudes used with the polygon function yielded different area measurements. This is because the aerial digital imagery of the rooftops lost definition and became fussy as the eye altitude of the images was reduced to zoom them closer. It was not possible to zoom the images even closer because at eye altitude of below 1.77 km, the digital image automatically transitioned to a street view level option. The simple experiment whose results are captured in Figure 21 appears to indicate that, all things kept constant, roof area measurement stabilises at eye altitudes of 1.80 kilometres and lower. It is for this reason that roof area measurements were captured at eye altitude of 1.80 kilometres. Although the contours of the aerial digital images of the rooftops were sharply defined at even lower eye altitudes, the measurements rendered were unstable (see Figure 21).

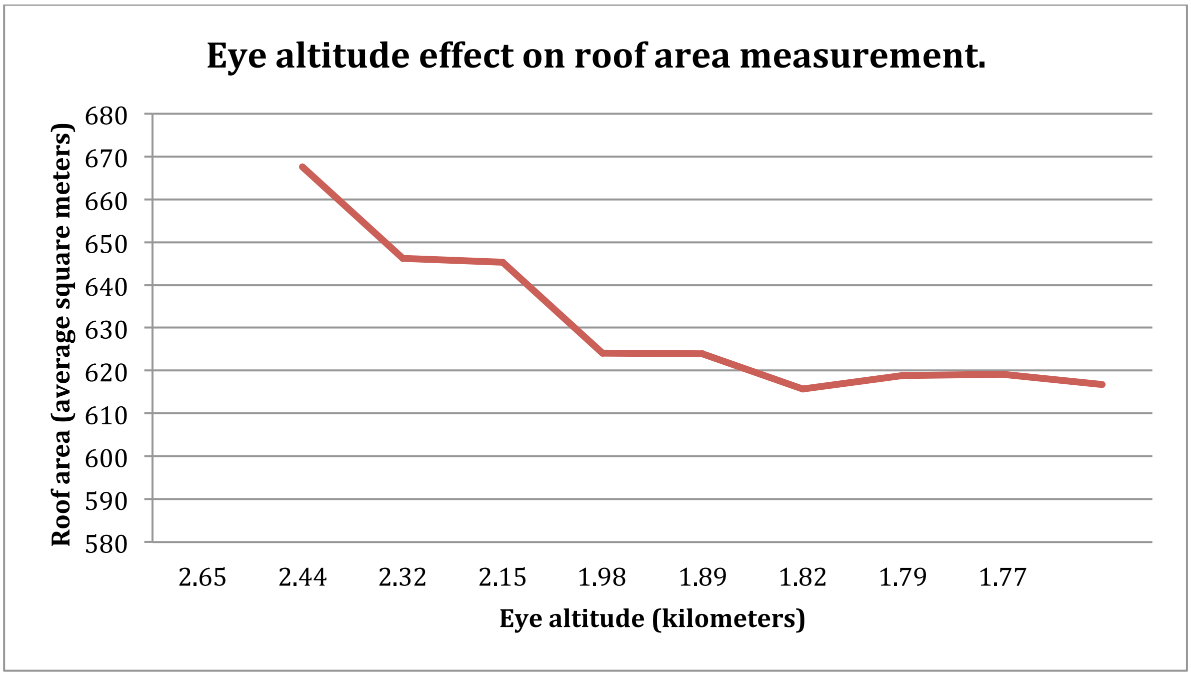

Figure 21: Effect of eye altitude on rooftop area measurement.

The street-view function was also used to examine the individual building typologies at street level. Google Earth Pro Street-view uses photo imagery from vehicle-mounted cameras to provide 360 degrees panoramic street-level views, which can be navigated to expose different sizes, angles and directionality of features (Wikimedia n.d.).

3.3.4 Data Collection and Processing

Digital images of individual building rooftops were zoomed up to about 1.8 km eye altitude level. The polygon tool was then activated to trace the outline of the rooftop. The same procedure was applied to trace out the outline of obstructive objects, and their shadows, on the roof. The outline of the overlapping shadows cast upon the rooftop-of-interest by neighbouring buildings was also traced out in a similar procedure. The outline of the rooftop block yielded the gross area of the rooftop in square meters. The outline of the permanent fixtures found on the roof and their associated shadows yielded the total unusable area of the rooftop, also in square meters; and lastly, the overlapping shadows from the adjacent buildings yielded an area measurement of the additional unusable portion of the rooftop. The extent of overlapping shades from adjacent building merited separate attention, as such shadowing is more pronounced in dense inner city high-rise buildings typology. Colour-coded outlines were used to differentiate the areas measured on a single rooftop (see Figure 22). Also noticeable from the figure is the area to the east of the study area, which has been excluded in the analysis.

Figure 22: Colour-coded area measurements of the buildings.

Figure 23 offers a closer view of the colour coding as applied to individual buildings. The gross rooftop area is outlined in red, whilst obstructing fixtures and overlapping shadows are coded in green and light blue respectively.

Figure 23: Colour-coded rooftop area measurements.

For each of the 202 buildings, the rooftop area available for the PV system (the available rooftop area) was determined by taking the difference of gross rooftop area, and the sum of the areas of obstructions and shadowing measured.

The PVWatts Calculator was used to process the available rooftop area data further. PVWatts Calculator is an online application/calculator developed by the US-based National Renewable Energy Laboratory (NREL). The PVWatts Calculator is relatively easy to use, computationally light and freely available online. It therefore fits some of the key methodological attributes of simplicity, ease-of-use, affordability and less coding complexity, which informed the choice of tool. The PVWatts Calculator relies upon simplified inputs of solar resource location and system design parameters to produce an estimate value for the system's electricity production (NREL 2016). Therefore, it is useful for a preliminary assessment of a potential location for a PV system that uses crystalline silicon modules, such as is envisaged in this research.

The PVWatts Calculator uses an hour-by-hour simulation, over a period of a year, to produce estimates of the monthly and yearly electricity production of the PV system, following user inputs of system size, module type, array type, system losses, array tilt and azimuth angles (NREL 2016).

3.3.6 Greenhouse Gas Offsetting

The carbon dioxide emissions offset potential of the renewable energy generated from the rooftops of the inner city core was also determined. At best, this represented a technical offset potential determination because the study only set out to determine technical power capacity and energy production. A more realistic calculation would require a further refinement of the technical potential power capacity and energy production, to include market, economic and social considerations. This would be done by accounting for technology costs, regulatory limits, policy and incentives, investor appetite and access to capital. Therefore, although it is a more realistic approach, it is also beyond the limits of the study.

In assessing the greenhouse gas emissions impact of rooftop PV installation in the CoJ, the Eskom grid emission factor was used. The grid emission factor relates the carbon dioxide emissions to the electricity produced in the grid (Spalding-Fescher 2011; Mukonza & Nhamo 2015). The use of the Eskom grid emission factor for an area of the CoJ that is supplied by City Power was deemed appropriate, not only because City Power does not have a published grid emission factor, but also because it does not have generation and transmission infrastructure of its own. Instead, it purchases electricity in bulk from Eskom, for distribution and supply to its consumers.

The Clean Development Mechanism Executive Board (CDM EB) has published clear guidelines for the calculation of grid emissions factors for grid systems. However, there is a significant variation in the grid emission factors used for local projects, although they are based on the same Eskom grid. This is thought to be due to different interpretation of the guidelines and assumptions contained in the calculation methodology. Available factors range between 0.8 and 1.03 tCO_2e/MWh (Mukonza & Nhamo 2015; Spalding-Fescher 2011; UNIDO GEF 2014; Lotz & Brent 2014). For purposes of this study, the grid emission factor of 0.940 tCO_2e/MWh, which was published by the National Business Initiative, with support from Eskom, was used (National Business Initiative 2013). This grid emission factor was used to relate the rooftop PV electricity production with the carbon dioxide emissions that are avoided in the process.

Chapter 4 – Results and Discussion

4.1 Introduction

The results of the research are presented in this section, together with their analyses and interpretation, with a focus on their implications for the research problem.

4.2 Roof Area Determination

Three different area measurements were extracted from the building rooftops of the 202 buildings in the CBD of the CoJ. These were the total rooftop area per building (gross roof area), the total area occupied by permanent fixtures on the rooftop, including their shadows (obstructions), and, lastly, the shaded area imposed on the subject-building by the neighbouring building (shaded area). Subtracting the shaded area and the obstructions from the gross roof area yielded the usable area; for accommodating PV systems. The data summary is presented in Figure 24, whilst the raw data is included in Appendix A.

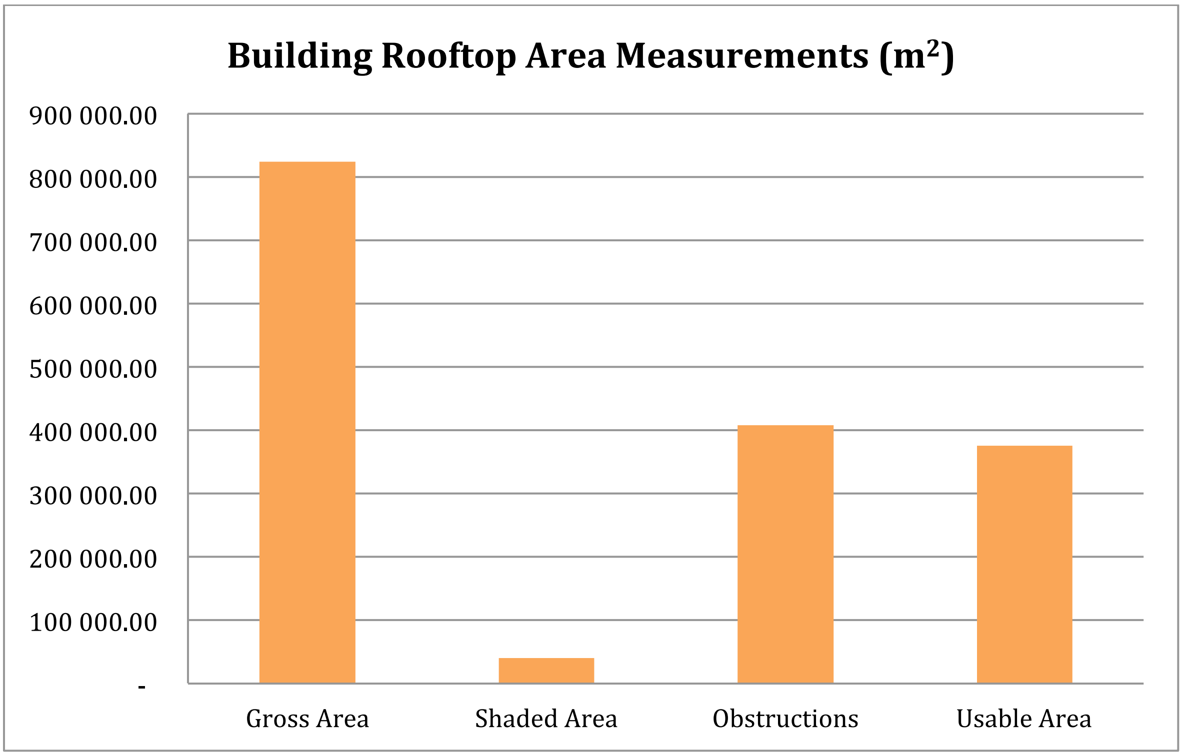

Figure 24: Rooftop Area in the CBD.

As shown in Figure 24, the 202 buildings in the area of the study within the CBD occupied total area of 824 071 m^2. The total roof area covered by obstruction and shades occupied 448 086 m^2 area. As illustrated in Figure 25, the roof obstructions accounted for 49% of the gross rooftop area, whilst the shaded areas accounted for 5% of the gross roof area. The remaining rooftop area, potentially usable for installation of the solar PV array was the remaining 46% of the gross rooftop space of the buildings. Thus, the availability factor for the cumulative building rooftop areas covered in the study was 46%.

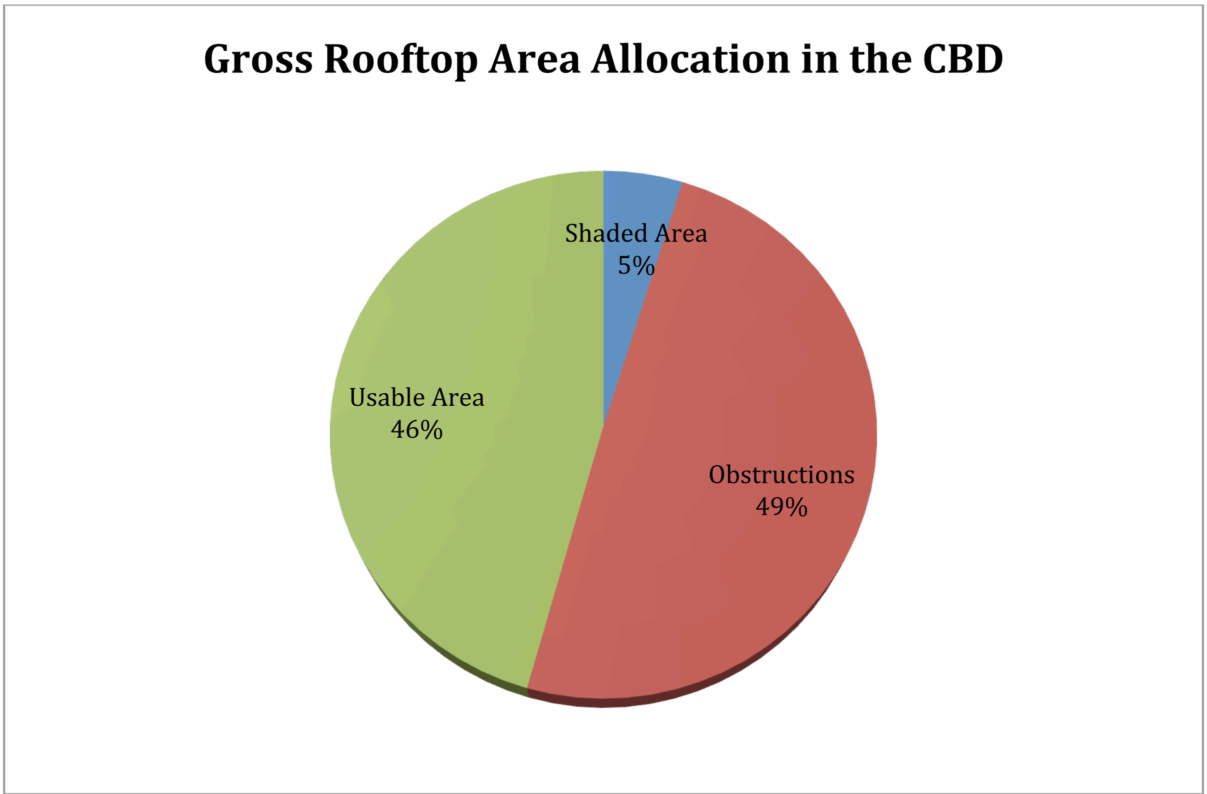

Figure 25: Building Rooftop Availability Factor in the CBD of CoJ.

The shading from adjacent buildings, which is more prevalent in CBD-type building densities, was found to be relatively insignificant, at 5%. Average roof area results were also determined at the level of individual buildings, and presented as shown in Table 4. It would seem from Table 4 results that the rooftop availability factor of 46% for the inner city core is replicated at the level of individual building blocks. This observation is useful when considering inner city areas of other cities within the country, especially if it can be established that they share similar architectural design characteristics.

Table 4: Average roof area utilisation at individual building level in the CoJ.

Gross Rooftop Area	Shaded Area	Obstructed Area	Usable Area
4 100 m^2	198 m^2	2 031 m^2	1 871 m^2

4.2.1 Gross Roof Area

The individual building blocks in the CBD were remarkable in the degree to which they occupied similar gross area. However, this is hardly surprising, as the individual stand sizes would have been carved up at the beginning of the City's establishment, to occupy roughly equal areas. According to Table 4, the average area occupied by these individual building block is about 4 100 square meters. Figure 26 clearly shows the stands on which the individual building blocks in the CBD are situated, which appear to be similar in size. This similarity in stand sizes is also observable from an examination of the raw area data in Appendix A. This observation is useful because it means that we can apply the same rooftop availability factor of 46% to determine the gross roof area of the buildings located north and north-east of the study area boundary, which were excluded from the study. These buildings observably occupy stands of the same size, and, therefore, we merely need to count them to be able to establish the gross area they cover. The same approach can be applied to CBDs of other metros, as long as we can establish the average area factor.

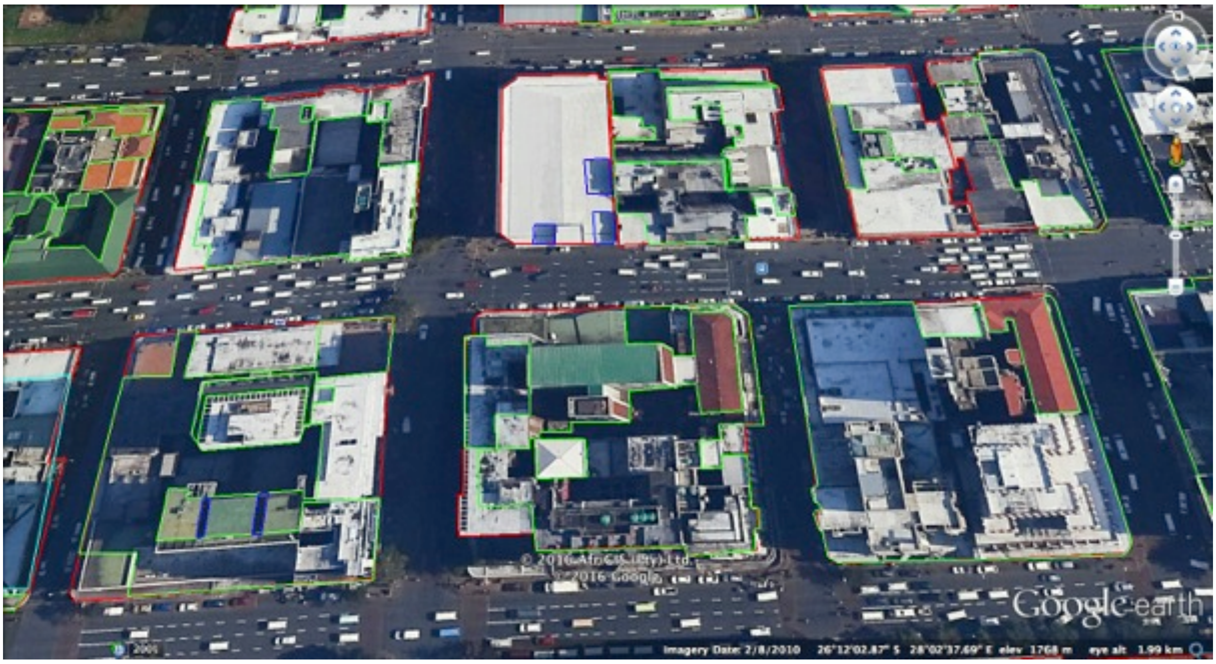

Figure 26: Individual building stands within the CBD.

4.2.2 Usable Roof Area

The usable area for PV system installation purposes was determined by filtering out shading and other obstructions from the building rooftop. Whilst the common competing users of the rooftop, such as lifts shafts, telecommunication equipment and ventilation ducts were encountered, they were relatively insignificant in the rooftop spaces they occupied, when compared to empty spaces between the individual roof surface within the same building block. Although these spaces were not isolated and measured, they were significantly large both in size and number. Figure 27 depicts the typical gaps encountered between the individual rooftops on the same building block.

Figure 27: Aerial image of a building rooftop.

In many instances, on a single building block, the area occupied by the gaps were almost equal in size to that occupied by the roof surface, if not more. Therefore, more than competing uses of building rooftops, these gaps accounted for the most rooftop area reduction.

The rooftops of the buildings were predominantly flat, with only a handful of them incorporating small areas of inclined roofs. These inclined roof sections tended to be lower in elevation, relative to their flat roof counterparts, and therefore more exposed to shading, especially during morning and evening daytime periods. The west-facing surfaces of these inclined rooftops were excluded from the determination of usable roof area. Figure 27 shows an image of a typical inclined roof section part of an entire roof block. In addition to the roofless gaps between continuous rooftop sections, the uneven elevation of sections of roofs on the same building also generated significant shading (see Figure 27). These shaded areas were also excluded from the computation of the usable roof area.

Shades cast upon the subject-building by an adjacent building were expected to account for a significant portion of the total shading on the rooftops. Such significant levels of shading are associated with densely packed high-rise buildings, such as was encountered in the study area. Figure 28 includes a depiction of shading, cast by the building on the right of the image, on the roof of the building on the left, which is indicated in light blue colour. This type of shading was found to account for only 5% of the total available roof area covered in this study.

Figure 28: Adjacent-building overlapping shade, coloured in light blue.

However, this does not mean that such shading is insignificant. It probably has to do with the time during which Google Earth captured the aerial images used for the area measurements. It is a well-known fact that shadows from adjacent buildings will be longer in the early morning and late afternoon, during sunrise and sunset respectively. It is also worth noting that these periods of maximum shading coincide with the morning and evening electricity peak demand periods. The nature of the shadows and their trajectory, as observed from the images used to measure rooftop areas in this study, seems to suggest that the time in the day when the images were captured was approaching mid-day. At mid-day, these types of shadows would be at their minimum, especially in summer. In order to fully characterise the extent of the shadowing and its effect on generating potential, a detailed shadowing analysis would be necessary. However, even without such detailed analysis, real-time shadowing would be expected to be more significant than the 5% suggested by the data in this study.

Treetop shading, which is a feature of residential and industrial buildings, was not a consideration in this study. This is because of the high building elevation in the inner city core, relative to that of treetops.

4.3 Technical Potential

NREL's PVWatts Calculator was used to calculate the estimated system capacity and electricity output. The user inputs utilised in the calculations are detailed below.

4.3.1 Solar Irradiance

In order to run the simulation, the calculator requires solar resource data that describes the solar radiation and meteorological conditions of the system. The calculator derives long-term solar resource estimates from a reading of hourly, typical-year weather data files (NREL 2016). The choice of the data file is automatically determined by the location input from the user. A number of solar radiation databases exist around the world. The nearest solar resource data used in the study was the Kempton Park weather station data, which is located at latitude/longitude 26.130/28.230 (NREL 2016). The irradiance across the expanse of the study area was kept uniform because of the relatively small size of the study area.

4.3.2 Module and Array Type

A locally available polychrystalline silicon module was used as the reference module. The relevant module characteristics are described, in detail, in Table 5 (refer to Appendix B for further details of the module).

Table 5: Reference module characteristics.

Module characteristics	
Module Type	Crystalline silicon PV cells
Model	SD HV 100Wp
Dimensions	length: 1210mm width: 670mm thickness: 35mm surface area: 0.8107 m^2
Maximum Power @ STC	100Wp
Module Efficiency	16%

Although a sun tracking module array would have been ideal for optimising daily and seasonal productivity variation of the CoJ, a fixed module array was used nonetheless. Unlike the tracking array, it has low associated acquisition and maintenance costs. Because the rooftops were flat, an open rack-mount option with the appropriate tilt angle was chosen. Open rack also improves the air-cooling of the array to reduce cell operating temperature and thus improve electricity output of the system (NREL 2016; Dobos 2014; Masters 2013; Boyle 2012).

4.3.3 Array Tilt

The tilt angle is the angle – measured from the horizontal - of the PV modules in the array. An array tilt angle that is greater than the latitude of the location optimises winter energy production whilst one that is less than the latitude of the location optimises summer production (NREL 2016; Dobos 2014). Lower array tilt angles also minimise cost of mounting and racking hardware, as well as wind damage (NREL 2016).

The array tilt angle for the system was chosen to optimise the exposure of the modules to the greatest irradiance, whilst also minimising shading of one module row by another (Boyle 2012; Masters 2013). In line with Masters' (2013, p.195) suggestion of orientating the array towards the equator and tilting it up at an angle equalling the local latitude, and, in order to optimise net annual production, a northerly array orientation with a local latitude of 26° South was chosen. Although the chosen tilt angle does not optimize seasonal irradiance exposure, it delivers a better average annual yield. Our choice of the tilt angle is supported by Boyle (2012, p.30) when he cites Achard & Gicquel (1986), in arguing that the effects of array tilt are not particularly critical as they do not seriously affect system yield. Therefore, in general, for fixed arrays, the location latitude angle is the best guide for optimising tilt.

4.3.4 Array Orientation (Azimuth)

Boyle (2012, p.30) argues that the effects of array orientation away from north are relatively small, and that orientations of as much as 45° either side of northerly orientation produces more than 90% of the production of northerly orientated modules. Therefore modules can be orientated anywhere from north-east to north-west (Southern Hemisphere) without affecting production unduly. Thus, only rooftops with a north, north-east and north-west orientation were included in the usable roof area computation for the CoJ. This way, a large proportion of the available building rooftops were usable.

4.3.5 Roof Coverage Ratio

Roof coverage ratio is the area of the module array to the total usable roof area. The proportion of the total usable roof area that is occupied by the modules is less than the total usable roof area, in order to accommodate a service area (SA) for maintenance and access. There is no industry consensus regarding allowable service area and access in a solar PV array. However, there are guidelines such as those in sections 605.11.3.1 through 605.11.3.3.3 of the International Fire Code 2012 (Byrne et al. 2015). According to these guidelines, and provided there are no other constraints or obstructions on the roof, the average minimum roof space required for access and maintenance pathways ranges from about 11% to 19% (Byrne et al. 2015). But, as indicated, this minimum space applies only if additional access space is not needed for maintenance and servicing of rooftop fixtures and obstructions associated with skylights, air conditioners, lift ducts, etc. In that case the recommended SA allowance increases to about 20% (Byrne et al. 2015).

Avoidance or reduction of wind uplift effect on the module arrays, especially at the roof edges, is another factor, whose consideration ordinarily reduces available suitable roof space. According to City Power (2015b), the effects of wind loading on the module array become more pronounced with module tilt angles of more than 8°, in which case wind stress distribution analysis would be necessary. The module tilt angle in this study would be 26°, thus necessitating wind-loading analysis, whose effect might be a reduction in the suitable roof area. Industry norms suggest that leaving an area of about 30cm from the roof edge reduces wind loading on the module array (TheGreenAge 2014). Closer to home, City Power (2015b), in their rooftop tender documentation, required a module packing factor (term used interchangeably with roof coverage ratio) of 75% to allow for safe installation and maintenance access, meaning that 25% of the suitable roof space in their project would be left unoccupied. This empty gap is commonly left around the edges of the roof, to counter the effects of wind uplift factor.

From the above considerations, roof coverage ratio of 75% was chosen for the rooftops system in this study. Leaving 25% vacant to accommodate maintenance and service pathways as well as allowance for wind loading is consistent with Byrne et al.'s (2015) recommendation, and supported by City Power's own requirements. The implication of this is that the measured available, suitable roof area reduced by 25% from 375 985 m^2 to 281 989 m^2.

4.3.6 Ground Coverage Ratio (GCR)

Inter-row shading, which is caused by one row of tilted modules casting a shadow on the row behind it, reduces system performance and therefore must be accounted for, to arrive at actual technical potential. Inter-row shading is even more relevant to commercial buildings rooftop systems where space is a constraint, and the buildings are in the main flat-roofed, for which tilted modules are preferred. Leaving more space between array rows reduces inter-row module array shading and enhances performance, but accommodates less module array on a given space. Less inter-row spacing accommodates a higher system capacity but amplifies panel-to-panel shading. Between these two extremes, lies an optimal ground cover ratio, which is the outcome of a balance between the module array tilt angle and the SA. Figure 29 is illustrative of module array layup and the phenomenon of inter-row shading.

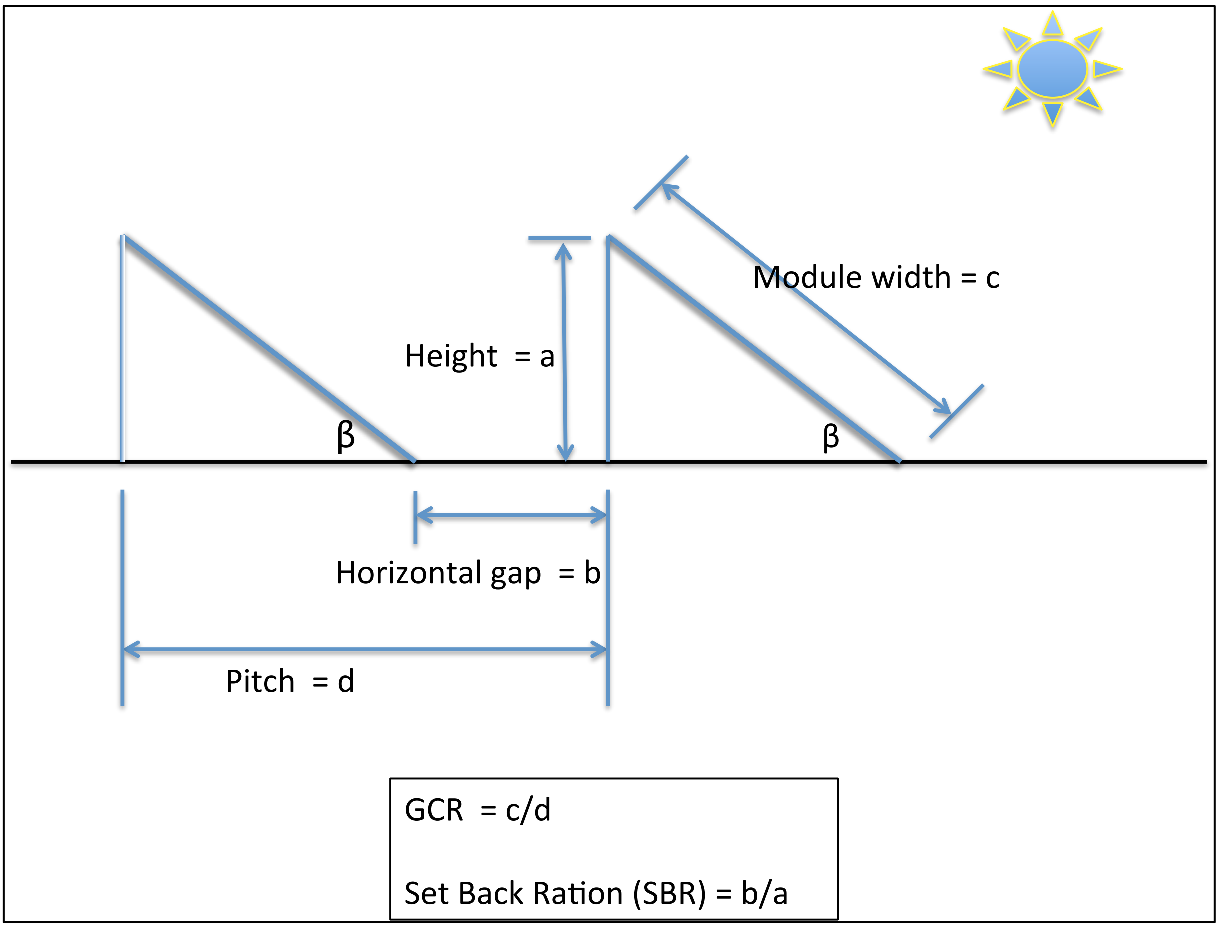

Figure 29: Illustrative module array sketch.

Inter-row shading derate factor can be represented as a function of GCR (the array area to the total usable rooftop area occupied by the array) (NREL 2016; Masters 2013). Figure 30 shows the relationship between GCR and inter-row shading derate factor for various fixed modules tilt angles.

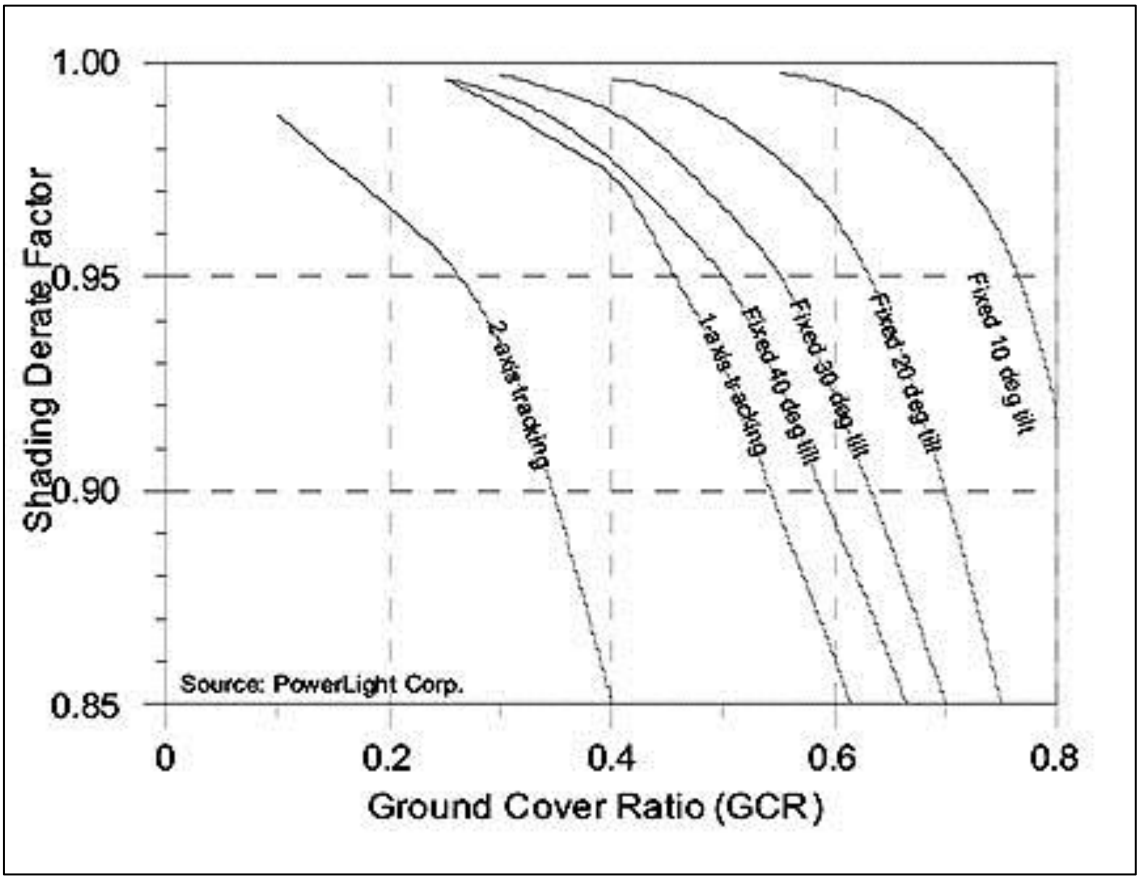

Figure 30: Module-to-Module shading derate factor as function of GCR (Source: PowerLight Corp, cited in NREL 2016).

A reading of Figure 30 reveals that a derate factor that is close to 1 (less shading loss) corresponds to a bigger Horizontal gap between the array rows (smaller GCR) (NREL 2016; Masters 2013). Masters (2013) suggests that common industry practice is to configure the PV system layout to target a GCR that corresponds to a shading derate factor of 0.975 (2.5% loss) (see Figure 30). For purposes of this study, and targeting the recommended shading derate factor of 0.975, and a module array tilt angle of 26° (falling between 20° and 30° on Figure 30), we were able to manually read a GCR of 0.5 off Figure 30. A GCR of 0.5 means that for the chosen module tilt angle of our system, a further reduction of 50% in the available suitable roof space was necessary to accommodate inter-row spacing that minimises shading derate factor. Equation 1 by Masters (2013), where Collector Area is the area occupied by the module array and the Total Ground Area in the total available usable roof area, illustrates the point further.

$$GCR = \frac{Collector\ Area}{Total\ Ground\ Area} = 0.5 \quad \text{(Eq.1)}$$

Although our GCR of 0.5 is an estimate, it appears to be corroborated by Byrne et al. (2015) in their rooftop solar technical potential study for the City of Seoul. They used Equation 1, read with Figure 29, to determine GCR.

$$GCR = \frac{c}{d} = \frac{1}{(\cos \boldsymbol{\beta} + \mathbf{SBR} * \mathbf{\sin} \boldsymbol{\beta})} \quad \text{(Eq. 2)}$$

Using Equation 2, and a module array tilt of 23°, Byrne et al. (2015) was left with only 48% of the roof area for PV installations in their study which was based on the City of Seoul. This space utilisation ratio is comparable to the 50% we arrived at for our system tilt of 26°. Boyle (2012, p.101) corroborates this ratio of space utilisation, when he suggests that spacing the modules to reduce inter-module shading may only leave between 30-50% of space for installation. Further to this, and using Equation 2, Byrne et al. (2015) tabulated the impact of GCR and SA on available rooftop estimates, which are shown in Table 6.

Table 6: Overview of GCR and SA on available rooftop estimates. (Byrne et al. 2015).

Tilt (°)	GCR (%)	SA (%)	Available Roof Space (%)
0	100	20	80
5	80	17	63
10	66	13	53
15	57	10	47
20	51	7	44
25	46	3	43
30	42	0	42

A reading of Table 6, clearly shows that a module tilt angle of 25° corresponds to a GCR of 0.46, which appears to corroborate the GCR of 0.5 which we arrived at from a reading of Figure 30.

Applying a GCR of 50% to our current available and usable roof space of 281 989 m^2, which has been adjusted for module array roof coverage, yields a final available and suitable space for installation of solar PV rooftop system of 140 995 m^2 in the CoJ's inner city core.

4.3.7 System Size

The direct current (DC) system power rating in kilowatts (kW), at standards test conditions (STC), was determined using the following equation (NREL 2016):

System Size = Array Area (m^2) X 1 kW/m^2 X module efficiency (%) (Eq. 3),

Where the total area occupied by the array is the usable roof area measured in m^2, and a reference module efficiency of 16%.

= Usable roof area (m^2) X 1kW/m2 X module efficiency (%),

The usable roof area in the calculation is a culmination of a number of adjustments applied to gross rooftop area as summarised in Figure 31.

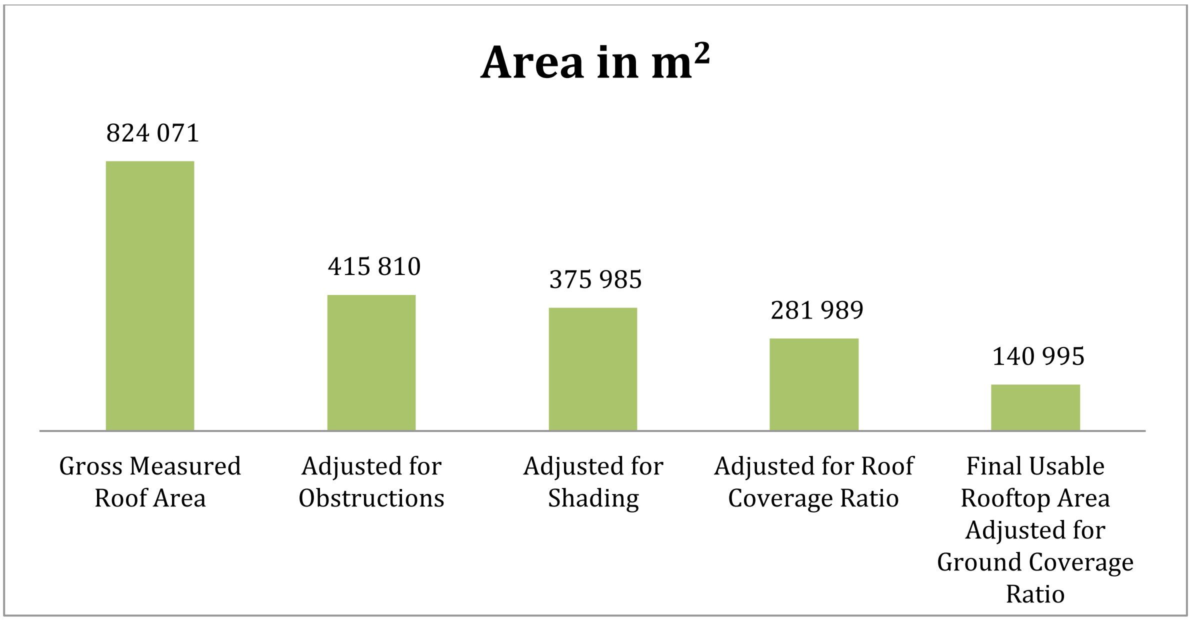

Figure 31: Adjustments to Gross Rooftop Area to arrive at final usable rooftop area.

Using Formula 3, the DC system size = 140 995 m^2 X 1 kW/m^2 X 16%

= 22 559 kW

= 22.6 MW

Thus, the solar PV technical potential for the inner city core of the CoJ was found to be 22.6 MW.

4.3.8 Energy Yield

The power output of PV modules in the field is different from that specified by the manufacturer under standard test conditions. Irradiance is not always 1000W/m^2, nor is module temperature always 25 °C in the field. Modules also get shaded or soiled due to continued usage. A derating factor is used to convert STC module DC Power Rating (PR) to AC PR, as shown below:

$$PR_{AC} = PR_{DC,STC} \text{ X Derate factor} \qquad \text{(Eq. 4)}$$

PVWatts Calculator has built-in estimates of a number of factors that together determine the derate factor (see Table 7 for details of the default derate factors). A few of these can be altered to suit the user-requirements, but the default Derate Factor of 14% was kept unchanged for this study.

Table 7: PVWatts Derate Factors for DC-STC to AC Power Ratings (Source Masters 2013; NREL 2016, Dobos 2014)

Category	Default Values
Soiling	2%
Shading	3%
Snow	0%
Mismatch	2%
Wiring	2%
Connections	0.5%
Light-induced Degradation	1.5%
Nameplate Rating	1%
Age	0%
System Availability	3%
Total System Losses	14%

Inverter's DC-to-AC conversion efficiency is not included in the system losses. The PVWatts Calculator default value of 96% was used.

Using the above model inputs and a system capacity of 22 559 kW, PVWatts Calculator returned a figure of 38 399 915 kWh for the annual average electricity production in the inner city core area of the CoJ. Thus, the inner city core area of the CoJ is able to accommodate 22.6 MW rooftop PV system, which can produce 38 399 915 kWh of electricity per year, on average. This figure is a mere 0.23% of CoJ's current total electricity consumption of 16 344 241 667 kWh (converted 58 839 270 GJ in Table 1 to kWh, using the 1 kWh = 3.6 X 10^6 J conversion factor). Noting that the market potential, which is a more realistic indicator of actual installable capacity, would be much smaller than the technical potential determined in this study, then the inescapable conclusion is that of the startlingly insignificant contribution of the real estate rooftop potential of the inner city core of the CoJ to the energy needs of the CoJ itself. Factoring in the weather-bound variability of solar PV generation, and the dominance of the residential sector demand load, with which the inner city core is not well-matched, serves to weaken the case for rooftop PV in the inner city core, exclusively for energy supply at city wide level.

4.4 Carbon Emissions Impact

The grid emissions factor of 0.940 tCO_2e/MWh was used to relate the rooftop PV electricity generated with the quantity of carbon dioxide emissions that would be offset, as follows:

$$Carbon\ emissions\ Offset = grid\ emission\ factor * Rooftop\ PV\ production \quad \text{(Eq.5)}$$

$$Carbon\ Emissions\ Offset = \frac{0.940\ tCO2e}{MWh} * 38\ 399.92\ MWh == 36\ 096\ tCO2e$$

Thus, the rooftop PV system will potentially offset 36 096 tCO_2e emissions from the CoJ's GHG inventory of emissions. With current, electricity-derived, carbon emissions of 16 834 569 tCO_2e, installation of rooftop PV in the inner city core of CoJ will reduce emissions by a mere 0.2%, to 16 798 473 tCO_2e. The impact is illustrated further in Figure 32.

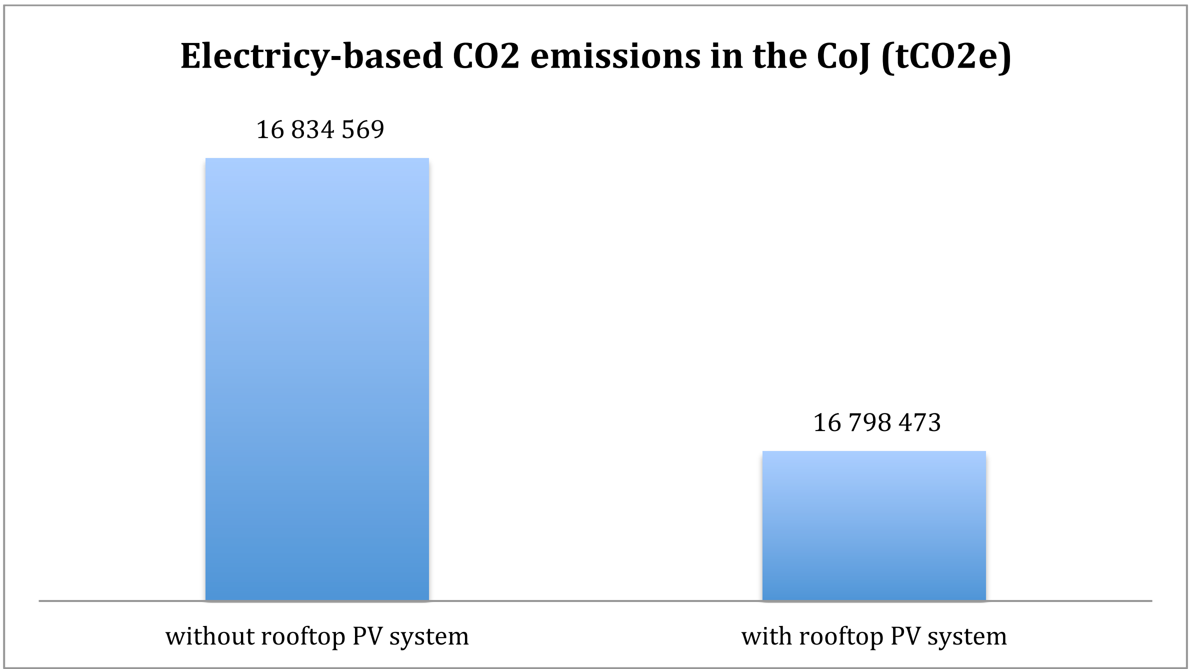

Figure 32: Pre- and Post rooftop PV system installation carbon emissions.

The CoJ targeted a 10% reduction in GHG emissions in 2014/2015 financial year-end (City of Johannesburg 2016a). That this target was not met is perhaps unsurprising as the CoJ only had the planting of trees (19 906 trees) and installation of solar water heaters (19 106 units) as highlight projects for climate change mitigation during the 2014/15 financial year-end (City of Johannesburg 2016a).

Therefore, although a 0.2% reduction in GHG might seem insignificant, it is indicative of the potential of rooftop PV to reduce GHG in the CoJ. What would be needed, to derive meaningful benefit, is wide adoption and scaling up of the city area coverage to all seven regions, and inclusive of residential and industrial rooftops.

4.3.9 Municipal Revenue Impact

Revenue impact of rooftop PV installation within the CoJ was examined from the perspective of the CoJ's financial accounts. This is appropriate because City Power's financial performance is consolidated into the CoJ's financial reporting. For this reason, the electricity services revenue reported by both City Power and the CoJ are practically similar. Electricity services charge of R12.9 billion was the largest contributor to the CoJ's total revenue of R41.6 billion in the 2014/15 financial year-end (City of Johannesburg 2016a). This figure made up 31% of the CoJ's total revenue collection in 2014/15. This figure is also a near-perfect match for City Power's electricity services revenue collection figure of R13.1 billion (See Table 8) for the same reporting period (City Power 2016a, p.48). This figure made up 95% of City Power's total annual revenue collection in 2014/2015. From the foregoing, it is clear that any initiative that reduces electricity services revenue collection is a far more serious threat to City Power (see Table 8), and, less so for the CoJ. This observation perhaps explains the noted subdued regard for rooftop PV and its uncontested positive contribution to climate change both within the CoJ and City Power.

Table 8: Extract of City Power's Financial Statements for 2015 year-end (City Power 2016a)

Figures in Rand thousand	2015	2014
Revenue		
Sales of Electricity	R13 057 501	R12 486 015
Bulk Purchases		
Electricity	R8 933 188	R8 380 255
Gross Profit	R4 124 313	R4 105 760
Gross Profit Margin	32%	33%

In assessing the revenue impact of rooftop PV system in the CoJ, one is confronted with a complex tariff structure that is organised into six categories. Not only is each tariff category disaggregated further into sub-categories, it is also made up of three types of charges, namely; an energy charge, a service charge and a network charge. Some of these tariff plans are not only subject to seasonal and diurnal adjustment, but they also incline with increasing consumption.

Embedded generators with excess energy to feed back into the grid in the CoJ are offered a negotiated tariff which is capped at Eskom Megaflex energy tariff level, as well as a grid connection charge of R0.50 per kW installed per day (City of Johannesburg 2015). For purposes of this study, we assumed that the rooftop PV systems would be designed to match the load requirements in the individual buildings, with no excess power to feed into the grid. Although this is reasonable, considering that suitable rooftop space is quite constrained in the inner city core, and more likely to be just enough to supply own consumption, in the end, it will depend on the level of incentives available to support the commercial case for the installations.

To get around the tariff complexity, and in order to determine the revenue loss associated with installation of 22 669 kW of rooftop PV in the CoJ, we derived the average tariff factor from the bulk electricity demand of 12 435 GWh in 2015 and the associated electricity services revenue collection of R13.1 billion (see Table 8) for the same period (City Power 2016a; City Power 2015a; City of Johannesburg 2015). The average unit price for electricity charged by City Power was found to be R1.05 per kWh. Multiplying this average tariff figure by the rooftop solar PV electricity production yielded R40 322 230, being the potential revenue loss that could be incurred by the CoJ in the event of complete grid defection by its customers in the inner city core of the Coj. Being only 0.31% of the CoJ's electricity revenue for 2015, it is an even smaller proportion of the R41.6 billion total revenue for the CoJ for the same period. Thus, the revenue impact of rooftop PV systems in the inner city core of the CoJ is insignificant.

Chapter 5: Conclusion

The gross rooftop area within the central business district of the City of Johannesburg was found to be 824 071 m^2. Only 46% of this rooftop space was available for consideration in installing a rooftop PV system; the balance of 54% having been discounted by shading, empty gaps between roofs and inappropriate roof orientation. The same roof availability factor of 46% was encountered for each individual building rooftop. For areas of the CoJ and other Cities with similar inner city building typologies and densities, this factor can possibly be useful in determining rooftop spaces available for either rooftop PV or rainwater harvesting project planning and implementation.

Further downward adjustment of the available rooftop space to accommodate the laying up of module arrays resulted in a final, usable rooftop space area of 140 995 m^2, which is 17% of the gross rooftop space in the inner city. This final rooftop space within the inner city of the CoJ was able to accommodate a rooftop PV system with a technical potential of 22.6 MW and an average annual electricity production of 38 399 915 kWh. This level of electricity production in the inner city made up 0.23% of CoJ's current electricity consumption. If fully utilised, the rooftop PV system, would have the negative impact of reducing the CoJ's electricity services revenue collection by 0.31%, whilst positively impacting its emissions inventory through the offsetting of 36 096 tonnes of carbon dioxide equivalent emissions.

As low as the technical potential of rooftop PV in the inner city core the CoJ appears to be, it will decline further when economic and market potential assessment are taken into account, as is the case when consumer decisions are made about realistic installations. Thus, in the context of the CoJ's electricity sales figures, revenue and associated carbon emissions reduction, the inner city rooftop area has an insignificant impact. This is mainly because of the low roof availability factors and high ground (roof) coverage ratio necessary to minimise inter-module shading, both of which are unique features of the inner city rooftop typology.

Thus, roof availability factor (RAF) and roof coverage factor (RCF) are key determinants of rooftop solar PV potential in dense inner city rooftop buildings. This being the case, inclusion of inner city buildings that have been excluded from the study area on account of their degraded display will not alter the outcome of the study significantly because they display similar RAF and RCF. Residential, commercial and industrial rooftops, elsewhere in the CoJ, offer a different rooftop typology, orientation and tilt, all of which render them much more attractive than inner city rooftops. Therefore, we argue that, in the consideration of rooftop PV installations in the CoJ, residential, commercial and industrial buildings should enjoy priority over the inner city real estate. This argument is sustained even if we consider that, specifically for purpose of the

Shadowing effect has a huge impact on rooftop PV systems performance. In this study, no real-time shadowing effect was analysed. Instead, the extent of the shadowing analysis was restricted to the measurement of shadows, which were extracted from a freeze-frame of the GIS photo image of the rooftops. It is our view that real-time analysis of shadowing in the area of the study, both from buildings and other objects on the rooftops, will have resulted in further reduction of the available suitable rooftop area, and with it, rooftop solar PV production in the inner city.

Another limitation of the study was the use of high-level technical potential rooftop PV system production figures to interrogate themes like revenue loss and GHG emissions impact in the CoJ. The results derived are, at best, high-level estimates, whose accuracy would have been enhanced by prior application of market, economic and social potential filters. However, as the results of this study seem to suggest, such refinements in pursuit of a more realistic and accurate impact assessment would be irrelevant if the high level estimate reveals the benign impact of rooftop solar PV in study area. Only in instances where the high level estimates of impact are significant, would such refinements be necessary.

There are three main areas, which this research has revealed to be worthy of further, and deeper scholarly attention. The first relates to widening the study area beyond the boundaries of the inner city core of the CoJ, to include residential and industrial customers in the remaining regions, as well as to the rest of the large metros in the country. The second area of potential research inquiry could focus on progressing the research further up the pyramid of the hierarchy of potential assessments, to account for both economic, social and market potential factors within the CoJ. This line of inquiry would be even more relevant if the technical potential estimates appear to be highly significant. The third and final area of potential scholarly attention is real-time shadowing analysis.

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Appendix A: Rooftop Area Measurement Results

Building No.	Gross Roof Area (m2)	Shaded Area (m2)	Obstruction Area (m2)	Usable Area (m2)
1	10110,00	0,00	1697,00	8413,00
2	4281,00	200,00	1572,00	2509,00
3	5203,00	141,00	3698,00	1364,00
4	4387,00	0,00	3776,00	611,00
5	4009,00	0,00	2018,70	1990,30
6	4505,00	0,00	2743,20	1761,80
7	4401,00	281,00	1351,70	2768,30
8	3990,00	0,00	2413,80	1576,20
9	4117,00	202,00	1896,60	2018,40
10	2778,00	0,00	1041,00	1737,00
11	4675,00	0,00	379,00	4296,00
12	7705,00	0,00	7705,00	0,00
13	1110,00	0,00	595,00	515,00
14	2267,00	0,00	0,00	2267,00
15	3805,00	170,80	2124,70	1509,50
16	1104,00	203,00	274,00	627,00
17	3486,00	0,00	3486,00	0,00
18	5365,00	114,00	2991,08	2259,92
19	5015,00	411,00	1455,00	3149,00
20	3649,00	0,00	2657,00	992,00
21	5136,00	0,00	3542,80	1593,20
22	5050,00	0,00	2427,00	2623,00
23	5318,00	486,40	2243,00	2588,60
24	5909,00	0,00	2992,41	2916,59
25	5340,00	666,00	2780,80	1893,20
26	4233,00	0,00	1971,90	2261,10
27	3962,00	0,00	3962,00	0,00
28	4079,00	200,00	2538,20	1340,80
29	3698,00	566,00	2562,00	570,00
30	5004,00	0,00	3552,48	1451,52
31	5485,00	2216,00	2560,00	709,00

32	9221,00	1938,00	4895,00	2388,00
33	9794,00	0,00	7254,00	2540,00
34	1813,00	0,00	1346,70	466,30
35	1891,00	245,00	956,00	690,00
36	5587,63	1496,00	3969,00	122,63
37	5461,00	0,00	4171,00	1290,00
38	4954,00	0,00	2813,15	2140,85
39	15154,00	0,00	2712,10	12441,90
40	6543,00	0,00	707,00	5836,00
41	351,00	351,00	0,00	0,00
42	578,10	0,00	35,50	542,60
43	1068,00	0,00	258,60	809,40
44	3065,00	0,00	1377,30	1687,70
45	3836,00	0,00	3004,00	832,00
46	1362,00	0,00	178,00	1184,00
47	3721,00	0,00	1325,08	2395,92
48	1220,00	0,00	852,10	367,90
49	4231,00	0,00	2802,06	1428,94
50	4277,00	0,00	1140,20	3136,80
51	4116,00	664,00	496,09	2955,91
52	1284,00	0,00	1142,90	141,10
53	2564,00	222,00	0,00	2342,00
54	4692,00	0,00	1230,33	3461,67
55	1234,00	61,30	205,14	967,56
56	1635,00	0,00	728,00	907,00
57	521,00	0,00	519,63	1,37
58	2032,00	0,00	156,32	1875,68
59	3081,00	0,00	1558,30	1522,70
60	5866,41	0,00	2247,50	3618,91
61	994,00	0,00	373,40	620,60
62	1147,00	0,00	417,89	729,11
63	3019,00	0,00	1489,90	1529,10
64	2807,00	0,00	912,00	1895,00
65	3621,00	0,00	2696,00	925,00
66	4192,00	2536,00	1478,50	177,50

67	4721,00	0,00	4436,00	285,00
68	7582,10	0,00	2950,30	4631,80
69	5324,00	0,00	2599,60	2724,40
70	9301,00	1052,00	2408,40	5840,60
71	12162,00	0,00	5648,40	6513,60
72	945,00	0,00	502,97	442,03
73	1153,00	0,00	913,00	240,00
74	1020,00	139,00	588,00	293,00
75	3050,00	408,00	693,40	1948,60
76	4080,00	0,00	2037,70	2042,30
77	2976,00	0,00	1620,59	1355,41
78	4229,00	334,00	2411,00	1484,00
79	2766,00	605,00	2036,00	125,00
80	2409,00	711,00	1255,00	443,00
81	2921,00	0,00	1193,00	1728,00
82	2259,00	2259,00	0,00	0,00
83	3052,00	856,00	1158,00	1038,00
84	4245,00	0,00	59,40	4185,60
85	4443,00	0,00	2229,70	2213,30
86	270,00	0,00	0,00	270,00
87	7616,00	0,00	652,00	6964,00
88	2401,00	0,00	1138,60	1262,40
89	2554,00	1092,00	168,16	1293,84
90	2938,00	0,00	285,21	2652,79
91	2318,00	0,00	2146,00	172,00
92	1493,00	0,00	675,86	817,14
93	620,00	0,00	97,09	522,91
94	1196,00	0,00	80,20	1115,80
95	2131,00	0,00	1055,80	1075,20
96	3738,00	0,00	468,90	3269,10
97	2501,00	0,00	1962,00	539,00
98	5453,00	374,00	4234,00	845,00
99	4097,00	0,00	1637,00	2460,00
100	4837,00	0,00	2910,80	1926,20
101	5787,00	0,00	3330,25	2456,75

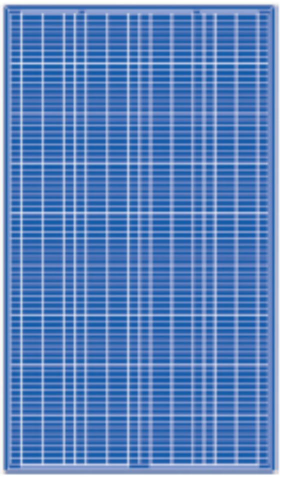
102	797,00	0,00	376,00	421,00
103	2753,00	876,00	926,30	950,70
104	3869,00	0,00	2447,60	1421,40
105	3801,00	0,00	1316,00	2485,00
106	5917,00	0,00	4497,00	1420,00
107	3495,00	0,00	1715,60	1779,40
108	1193,00	128,00	467,30	597,70
109	2934,00	0,00	1382,40	1551,60
110	4197,00	0,00	2608,10	1588,90
111	4972,00	0,00	2973,70	1998,30
112	6950,00	0,00	3206,00	3744,00
113	4023,00	0,00	2831,00	1192,00
114	4343,00	0,00	2259,00	2084,00
115	4253,00	0,00	3595,00	658,00
116	2990,00	0,00	2395,00	595,00
117	2797,00	0,00	1589,80	1207,20
118	2740,00	0,00	1755,80	984,20
119	3968,00	949,00	1821,00	1198,00
120	4776,00	0,00	1904,20	2871,80
121	7794,00	0,00	2883,90	4910,10
122	4161,00	0,00	2757,40	1403,60
123	3827,00	1239,00	736,70	1851,30
124	4908,00	8,00	2181,00	2719,00
125	3387,70	88,40	1426,70	1872,60
126	5199,00	0,00	3138,90	2060,10
127	4981,00	0,00	2095,45	2885,55
128	4511,00	0,00	4133,00	378,00
129	4151,00	0,00	2527,00	1624,00
130	4454,00	0,00	2708,90	1745,10
131	5382,00	1706,00	1666,90	2009,10
132	8476,00	3759,00	1277,30	3439,70
133	7181,00	199,00	3317,50	3664,50
134	5293,00	2243,00	1467,10	1582,90
135	5383,00	314,00	2585,40	2483,60
136	2910,00	0,00	1300,00	1610,00

137	8480,00	0,00	5932,00	2548,00
138	3164,00	856,00	1013,00	1295,00
139	2915,00	603,00	1207,95	1104,05
140	1542,08	327,15	929,00	285,93
141	2218,00	0,00	938,13	1279,87
142	1766,00	0,00	761,00	1005,00
143	2994,00	937,00	272,00	1785,00
144	3025,00	0,00	244,00	2790,00
145	3022,00	0,00	216,00	2952,60
146	8088,00	0,00	235,00	7867,54
147	1988,00	0,00	69,40	1918,60
148	745,00	0,00	220,46	524,54
149	4360,00	0,00	2258,52	2101,48
150	9697,00	0,00	1215,30	8481,70
151	12426,00	0,00	7265,70	5160,30
152	10667,00	0,00	4669,00	5998,00
154	2662,00	0,00	926,30	1735,70
155	9536,00	0,00	4526,78	5009,22
156	1253,00	416,00	182,00	655,00
157	3307,00	0,00	1471,00	1836,00
158	5296,00	857,00	2046,00	2393,00
159	4073,32	960,00	2338,09	775,23
160	4587,00	0,00	2728,00	1859,00
161	4425,00	0,00	3247,00	1178,00
162	5423,00	0,00	3218,40	2204,60
163	2063,00	0,00	2063,00	0,00
164	4698,00	0,00	1801,40	2896,60
165	4504,00	0,00	3882,00	622,00
166	4109,00	0,00	2784,90	1324,10
167	4324,00	0,00	2741,52	1582,48
168	4318,00	0,00	1492,00	2826,00
169	4152,00	200,00	2605,30	1346,70
170	3712,00	136,00	2184,00	1392,00
171	4535,00	0,00	3173,00	1362,00
172	4085,00	0,00	2142,00	1943,00

173	3808,00	0,00	2363,00	1445,00
174	5087,00	0,00	3906,00	1181,00
175	4447,00	0,00	4054,00	393,00
176	4262,00	0,00	3230,00	1032,00
177	4017,00	0,00	2881,70	1135,30
178	4061,00	0,00	1747,00	2314,00
179	5135,00	0,00	2367,00	2768,00
180	4338,00	0,00	3272,10	1065,90
181	5266,00	0,00	1872,00	3394,00
182	4199,00	0,00	2915,00	1284,00
183	4309,00	0,00	2583,20	1725,80
184	4158,00	0,00	1922,30	2235,70
185	4464,00	0,00	3627,00	837,00
186	4313,00	0,00	3278,00	1035,00
187	4428,00	0,00	1834,00	2594,00
188	5638,00	0,00	4672,00	966,00
189	3167,00	0,00	2153,00	1014,00
190	1395,00	150,00	575,50	669,50
191	1624,00	0,00	989,00	635,00
192	1864,00	408,00	642,31	813,69
193	2719,00	0,00	1323,00	1396,00
194	5341,00	0,00	3801,00	1540,00
195	4068,00	1041,00	2332,10	694,90
196	4280,00	0,00	2712,70	1567,30
197	3079,00	0,00	1524,00	1555,00
198	5317,00	139,00	2834,00	2344,00
199	2495,00	0,00	1152,00	1343,00
200	1671,00	85,00	558,00	1028,00
201	6247,00	0,00	4567,00	1680,00
202	3251,00	0,00	1265,50	1985,50
Total (m2)	824071,34	39825,05	408260,90	376155,53
Total (km2)	0,82	0,04	0,41	0,38
Averages	4099,86	198,13	2031,15	1871,42

Appendix B: Typical Crystalline Silicon PV Module

SD HV 100Wp



SDDirectPro

SD HV 100Wp

Specifications	
Cell	polycrystalline solar cell 156mm x 63mm
No. of cells and connections	72(4 x 18)
Dimension of module (mm)	1210 x 670 x 35
Weight	11kg

Characteristics	
Model	SD HV 100Wp
Open circuit voltage (Voc)	44.4V
Optimum operating voltage (Vmp)	36.8V
Short circuit current (Isc)	3.45A
Optimum operating current (Imp)	2.72A
Maximum power at STC (Pm)	100Wp

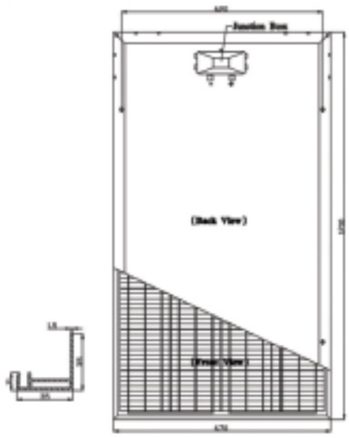
STC: Irrandiance 1000W/m2, Module temperature 25°C, AM=1.5

Limits	
Operating temperature	-40°C to + 85°C
Maximum system voltage	1000V DC

Temperature and Coefficients		
NOCT	48°C ± 2°C	
Current temperature coefficient	%/K	0.035
Voltage temperature coefficient	MV/K	-0.37
Power temperature coefficient	%/K	-0.5

NOCT: Nominal Operation Cell Temperature

5 year warranty



Appendix C: PVWatts Energy Calculation

NREL

Caution: Photovoltaic system performance predictions calculated by PVWatts® include many inherent assumptions and uncertainties and do not reflect variations between PV technologies nor site-specific characteristics except as represented by PVWatts® inputs. For example, PV modules with better performance are not differentiated within PVWatts® from lesser performing modules. Both NREL and private companies provide more sophisticated PV modeling tools (such as the System Advisor Model at http://sam.nrel.gov) that allow for more precise and complex modeling of PV systems.

The expected range is based on 30 years of actual weather data at the given location and is intended to provide an indication of the variation you might see. For more information, please refer to this NREL report: The Error Report.

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The energy output range is based on analysis of 30 years of historical weather data for nearby , and is intended to provide an indication of the possible interannual variability in generation for a Fixed (open rack) PV system at this location.

RESULTS

38,399,912 kWh per Year *

	(kWh / m² / day)	(kWh)	($)
January	6.00	3,158,810	N/A
February	5.88	2,833,743	N/A
March	6.11	3,231,012	N/A
April	5.82	3,083,023	N/A
May	5.83	3,202,888	N/A
June	5.89	3,062,472	N/A
July	5.83	3,295,857	N/A
August	6.28	3,471,055	N/A
September	6.30	3,293,353	N/A
October	6.19	3,385,458	N/A
November	5.81	3,107,409	N/A
December	6.12	3,298,859	N/A
Annual	**6.01**	**38,399,915**	**0**

Location and Station Identification

Requested Location	Johannesburg
Weather Data Source	(INTL) JOHANNESBURG, SOUTH AFRICA 12 mi
Latitude	26.13° S
Longitude	28.23° E

PV System Specifications *(Commercial)*

DC System Size	22569 kW
Module Type	Standard
Array Type	Fixed (open rack)
Array Tilt	26°
Array Azimuth	0°
System Losses	14%
Inverter Efficiency	96%
DC to AC Size Ratio	1.1

Economics

Average Cost of Electricity Purchased from Utility	No utility data available

Performance Metrics

Capacity Factor	19.4%