Assessing potential for net-zero energy building retrofits in commercial buildings using on-site photovoltaic (PV) generation – A case study of Durban- South Africa.

Gareth Davies

1558443

School of Architecture and Planning

University of Witwatersrand

Johannesburg, South Africa

Supervisor: Daniel Irurah

A research proposal submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand in partial fulfilment of the requirements for the degree of Masters of Architecture in Sustainable and Energy Efficient Cities.

29 March 2019

Declaration.

I declare that this research report is my own unaided work. It is being submitted to the Degree of Masters of Architecture in Sustainable and Energy Efficient Cities to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

………………… Date: 29 March 2019

Gareth Davies

ABSTRACT.

Retrofitting existing buildings towards NZEB (net-zero energy building) offers significant benefits in terms of reducing operational electricity consumption and operating costs as well as reducing GHG emissions. The increased efficiency and economic cost competitiveness of renewable energy technologies, as well as the advances in building science and energy modelling, continue to evolve along with the increased demand for energy security, thus allowing for advancement of NZEB. But to what extent is NZEB viable for all existing commercial buildings, and what are the technical and contextual parameters that would influence the potential of NZEB retrofits? The study substantiates on these questions via a simulated performance-based analysis of four existing commercial buildings in Durban, with energy modelling and simulation as the primary data sources. The simulation data were then applied towards the assessment of the potential of retrofitting for NZEB based on passive interventions in conjunction with energy-use optimisation of active/mechanical systems and integrated RE technology in the form of site PV.

The study demonstrated a reduction of 27% - 56% in overall grid-electricity consumption and carbon emissions across the case study samples. Lower FAR buildings achieved greater percentage reductions in grid-electricity consumption due to less site shading combined with larger site-area (for PV) to net floor area ratio. Longer operating schedules were also found to increase annual energy consumption while also being better suited for on-site PV generation due to consistent levels of self-consumption. User-density was found to have less significant impacts on overall electricity consumption. Payback periods for NZEB-targeting interventions were enhanced by the recent introduction of the RE tax allowance, which reduced overall payback periods by 2-3 years with two of the case study buildings achieving 4-6 year yields which is considered to be within an acceptable range based on prevailing efficiency and cost levels of the assessed interventions. The study found that the efficacy and practicality of on-site generation PV is limited by grid constraints for building use-types with a high export balance, and for certain high-density sites due to high shading levels. The study recommends smart-grid integration which would connect buildings that can benefit from either consuming or exporting RE and thus ensure annual energy consumption and GHG-emissions in the sub-sector could be brought into line with the 38% reduction compared to the 2050 Nationally Determined Contribution GHG emission reduction targets.

Key words: NZEB interventions; retrofitting commercial buildings; energy performance simulation; GHG-emissions reduction.

ACKNOWLEGEMENTS

I would first like to thank my research supervisor Professor Daniel Irurah of the School of Architecture and Planning at the University of the Witwatersrand. Your guidance and input steered me in the right direction and your honest feedback forced me to think critically.

To my SEEC colleagues, Lawrence and Ntokozo, I thank you for your friendship you're your uncanny abilities to make me laugh …even when the going was tough. I would also like to thank Trevor, Zayne, Oz, Stephen and leeann for their permission to use their buildings in this study and for their help in inspecting their premises.

Finally I must express my profound gratitude for my family Ken, Barbara and Jonathan for your encouragement and lifts to and from the airport. This dissertation would not have been possible without your support. To my friends and family that are spread across the four corners of the globe, I miss you and thank you for the influence you have had on my life.

Table of contents

APPENDICES

List of figures

List of tables

List of abbreviations and acronyms

ASHRAE	American Society of Heating, Refrigerating and air-conditioning engineers
BAU	Business as usual
CAV	Constant Air Volume
CBECS	Commercial Building Energy Consumption Survey
CDD	Cooling design day
COP	Conference of the people
DBT	Dry bulb temperature
DSM	Demand side management
EE	Energy efficiency
EIA	Energy Information Administration (USA)
EPA	Environmental Protection Agency (USA)
EPC	Energy performance certificate
EPW	Energy plus weather
ESCO	Energy Service company
EUI	Energy use intensity
FAR	Floor area ratio
FV	Future value
GBCSA	Green building Council South Africa
GHG	Greenhouse gas
GUUD	Geographical urban units delimitation model
HDD	Heating design day
HVAC	Heating ventilation and air conditioning
HWS	Hot water services
IEA	International energy agency
kWh	Kilowatt hour
Km^2	kelvin per meter squared

kWp	Kilowatt peak
LED	light emitting diode
NBI	New building institute
NDC	Nationally Determined Contribution
NPV	Net present value
NREL	US National Renewable energy Laboratory
NZEB	Net-zero energy building
PV	Photovoltaic
RE	Renewable energy
REIPPPP	Renewable energy Independent Power Producer Procurement
RH	Relative humidity
ROI	Return on investment
SANS	South African National Standards
SAWS	South African Weather Service
SEA	Sustainable Energy Africa
SHGC	Solar heat gain coefficient
SSEG	Small scale embedded generation
SSM	Supply side management
TRY	Typical reference year
UNDP	United Nations Development Programme
UNFCCC	United Nations Framework Convention on Climate Change
VAV	Variable Air Volume

Chapter 1: Introduction and background.

The world population has more than tripled in the last 60 years, along with increasing production of manufactured goods (including buildings). This places tremendous pressure on the earth's natural capital (due to an unsustainable use of land, water, materials and fossil fuels) and compromises the biosphere's ability to absorb and metabolise all the resultant waste produced in the process of economic development. (Daly 2008)

Possibly the most problematic waste stream for the biosphere comes from the production of energy by combusting fossil fuels, which is also possibly the most difficult to conceptualise, as the waste stream is largely invisible. It has taken decades since the first warnings of the effect of GHG emissions on global warming and climate change for the issue to be internationally recognised as a major threat that requires a co-ordinated and systematic international response. The latest framework for a coordinate response was agreed upon in Paris in 2015 at the 21st Conference of the parties to the United Nations Framework Convention (COP 21) which states:

"The Paris Agreement's central aim is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius. Additionally, the agreement aims to strengthen the ability of countries to deal with the impacts of climate change. To reach these ambitious goals, appropriate financial flows, a new technology framework and an enhanced capacity building framework will be put in place, thus supporting action by developing countries and the most vulnerable countries, in line with their own national objectives. The Agreement also provides for enhanced transparency of action and support through a more robust transparency framework." (UNFCCC 2016)

South Africa's commitment to climate change mitigation was reinforced in 2016 when parliament approved ratification of this international treaty, now commonly referred to as the 'Paris Agreement'. This non-binding accord "sets up an international legal framework for countries to shift toward a zero-carbon and climate-resilient world, and signals a turning point in the international community's commitment to address climate change." (Khambule 2016)

Since the transition to democracy in 1994, there has been a sizeable increase in electrification in households, from 36% to 87% by 2012, with consumption continuing to increase until 2007/8 (Parliamentary Budget Office 2016). This increase in consumption combined with poor management of an aging infrastructure, contributed to a shortfall in electricity supply generation in 2008 which resulted to rolling blackouts in the form of load shedding, and subsequent rapid increases in electricity tariffs. This supply crisis led to overall consumption dropping from 2008-2011, which is largely attributed to the electricity tariff increase that ESKOM implemented in those years. (SEA 2015)

"Between 2007 and 2015, average electricity tariffs increased by over 170% in real terms (nominal: 324%), compared to the period 1999 to 2007 where tariffs only increased by 38 % (nominal: 38.6%). Electricity tariffs are likely to increase further as Eskom moves toward full cost-reflective tariffs." (Parliamentary Budget Office 2016: 7)

The supply and security of SA's historically cheap electricity was thus brought into the spotlight, which has had the effect of driving a growing interest in energy efficiency and RE technology, which has in turn been driven by supply side factors such as decreasing cost and increased efficiency performance (SEA 2015). Along with this, climate change pressures and the need to ensure adequate capacity to drive economic growth saw a host of laudable policy instruments and carbon reduction strategies being created. These include:

- National Climate Change Response White Paper (DEA 2011)
- National Development Plan 2030 (NDP 2012)
- Intended Nationally Determined Contribution (INDC) (DEA 2015)- Illustrates scenarios of BAU, absolute peak and plateau and decline in GHG emissions trajectory range.
- Fifth assessment report (AR5 2014) of the Intergovernmental Panel on Climate Change (IPCC) – identifies cities as major role players.
- IRP – Integrated Resource Plan -"applies the moderate decline annual constraints as an instrument to reduce emissions."

1.1 Problem statement

More than 60% of South Africans now reside in cities (state of cities report 2017), which in turn "account for over a third (37%) of national energy consumption and nearly half (46%) of national electricity consumption." (SEA 2015) Whereas transport dominates SA's energy consumption (60-70%), due to electricity having higher emission levels per unit of energy produced than liquid fuel, emissions from the operation of the built environment constitutes roughly 60% of a typical metro's total emissions.

Despite policy measures being in place, SA's sustainability and carbon reduction commitments are yet to translate into any real impact. On the other hand Eskom and local government electricity distributors are initiating frameworks that would see the integration of small scale embedded generation (SSEG's) grids and systems, even though regulatory guidelines have been slow in coming to effect in order to facilitate the sale of electricity back to the grid. Municipalities rely largely on the profit from the sale of electricity to fulfil their service delivery mandate (SEA 2015) hence creating an inherent conflict of interest surrounding the implementation SSEG's and programs such as REIPPPP, which enables smaller independent power producers to sell 'clean' electricity back to the grid.

In a 2017 assessment by the Climate Action Tracker group (CAT) South Africa's Nationally Determined Contribution (NDC) targets, are noted as being inadequate towards meeting the Paris accord's long-term goal of stabilising temperatures within a 1.5 ºC limit. Furthermore, even in the proactive municipalities of Cape Town and Durban, which are developing low carbon pathways in line with these national long term mitigation strategies, current emission reduction trajectory falls short of the already inadequate 38% (from BAU) carbon reduction target of the cabinet-endorsed peak plateau-decline emissions path for 2050. (SEA 2015)

To ensure that SA's GHG reduction targets improve their alignment with more stringent targets as required by the Paris accord will require "aggressive energy efficiency measures across all sectors," (ibid pp 36) as well as the roll out of SSEG's and other renewable energy resources. The challenge for this energy transition pathway is to provide not only low carbon electricity generation but also a supply that is affordable and secure. (Hammond 2013)

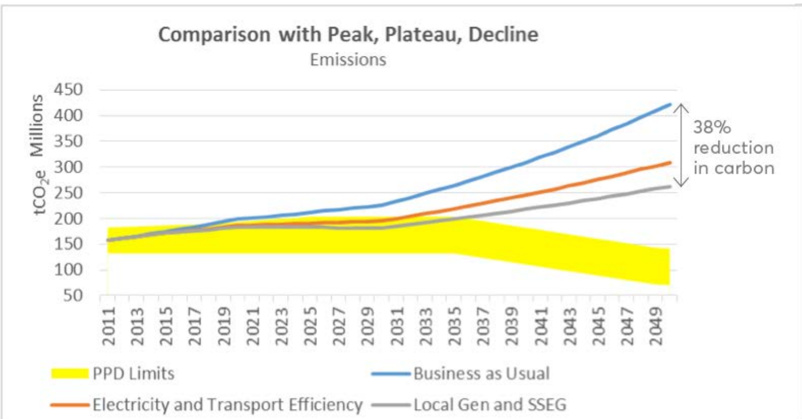


Figure 1.1: Peak, plateau, decline limits (SEA 2015)

1.2 Rationale of the study

As the operation of the built environment in South Africa is the single largest GHG emission contributor amongst the sectors of the economy, it is imperative that this is addressed through multiple initiatives towards sustainable or green building. Green building technologies, products, regulations and rating tools have evolved significantly in the last two decades. During this period, the South African building industry has seen the introduction of mandatory national regulations for energy efficiency in new buildings (SANS 10 400 – XA) and its reference standard (SANS 204) as well as the formation of the country's Green Building Council of South Africa (GBCSA) in 2007.

Given that these programs are relatively in their infancy, the bulk of the country's existing building stock was designed and built without considering the necessary practices and interventions. Furthermore, due to the lifespan of modern buildings (which are estimated to stay in use for 50-100 years after completion especially for commercial buildings) and the fact that, typically older buildings are likely to be less energy efficient, it is essential that existing stock is renovated, preserved and improved on in order to mitigate the environmental impacts related to their operation.

Even though energy efficiency codes and regulations for existing buildings are yet to be implemented in South Africa, the adoption and implementation of energy efficiency practices is gaining momentum. This is due, to some extent, to market forces which include on the demand side, rapidly escalating conventional electricity tariffs, and on the supply side, increased public/corporate awareness, advances in building science performance simulation as well as the cost and efficiency of renewable energy technologies such as photovoltaic generation and battery storage. This is creating favourable conditions in the socio-technical landscape where the opportunity for introducing aggressive cost effective carbon reduction strategies at a building scale is gradually emerging.

South Africa's 12B renewable energy tax allowance

In an effort to reduce emissions, broaden energy sources, ease pressure on the national electricity-grid and stimulate investment in renewable energy projects, SA's national treasury has amended Section 12B of the Income Tax Act No. 58 of 1962. The act "provides for a capital allowance for moveable assets used in the production of renewable energy"

(Steenkamp 2016) This is provided that the generation capacity is less than 1MW, thus the act benefits small scale embedded generation (SSEG) with “solar PV being favoured because of its low environmental and water consumption impact, economies of scale and job creation components (ibid) The current amendment, which came into effect on 1 January 2016 and applies to wind, biomass, hydropower and PV “allows for a deduction on a 50/30/20 basis over three years in respect of any machinery, plant, implement utensil or article owned by the tax payer” (ibid) The cost of installation is also deductible under sub-section 12B(3) of the act. This has greatly improved the affordability of PV and hence improved the overall potential for NZEB retrofits.

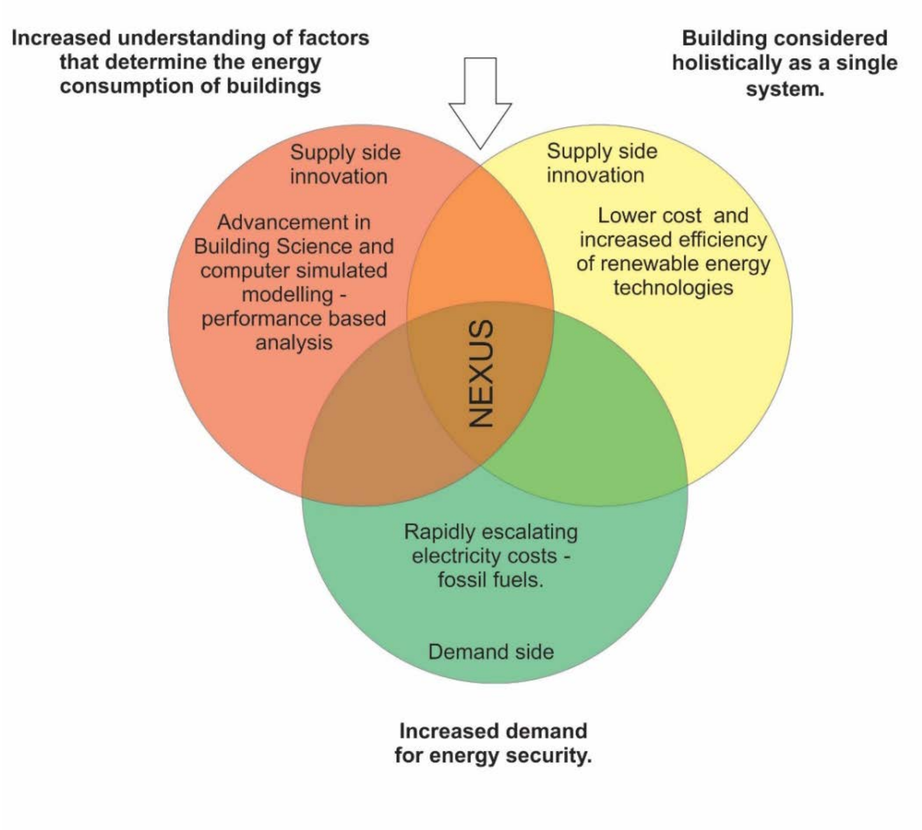


Figure 1.2: Convergence of technological innovation and increased demand for economical energy security allowing for advancement of NZEB.

1.3 The need to address existing building stock

“While case studies have clearly shown that net-zero energy buildings could be created using existing technologies and practices, most experts agree that a broad scale shift towards net-zero energy buildings will require clear policy frameworks and significant adjustments to prevailing market structures” (Marzal 2010: 5)

Given that the energy efficiency and carbon neutral paradigms have only become prominent since 2006 (Mazria 2017), The adoption of regulations and mandatory energy codes for new buildings, in many countries has only been implemented over the last 10 years, which means that the majority of buildings globally have been built with minimal consideration for energy efficiency and carbon reduction strategies. It is therefore essential that existing stock is renovated, preserved and improved in order to mitigate the environmental impacts related to their ongoing operation.

1.4 Net zero energy retrofits of commercial buildings

On average commercial buildings undergo major renovations every ten to fifteen years (UNDP 2013) and there is a direct correlation between the benefits of energy efficiency measures as cost effective ways to achieve significant reductions in consumption without negatively affecting economic growth. It should therefore be noted that costs of interventions associated with major renovation should include “only the supplementary costs caused by the actual efficiency improvements and not the total renovation cost” (Griffith et al 2007: 184)

1.5 Integrated design and front loaded sustainable design

Integrated sustainable design requires a cross-disciplinary approach to design, construction, financing, commissioning, operation and maintenance. Referring to the approach as whole building design, Griffith et al (2007) noted that the method takes advantage of interactions between different building systems and components as well as impacts on occupants, with the main purpose of “maximising environmental versus cost benefits of the project through informed choices” (Ceranic et al 2015: 435)

Dekay and Brown (2014) refer to ‘front- loaded sustainable design’, as an approach where great emphasis is placed on a hierarchical approach to design interventions. The practice is based on the imperative of pursuing maximum benefits in terms of overall building performance by implementing strategies that would enhance overall performance early on in the design phase, when the cost to benefit ratio can be kept very low. At the base of the hierarchy would be the fundamental responses to site conditions such as orientation, form, massing and height-to-volume ratio. This is followed by ensuring that appropriate technologies are integrated with the passive solar or bioclimatic design responses with the goal of improving building performance and user comfort. This minimises the need for costly and energy intensive HVAC and lighting systems and thus affords a building the best chance of achieving net-zero energy. NZEB retrofit design follows the same process even though it would be constrained by existing structure, which limits early design interventions such as orientation, form and surface to volume ratio.

1.6 The net-zero energy building strategy

Zero energy or carbon neutral building began gaining impetus as an architectural paradigm near the turn of the millennium, primarily informed by the theme of carbon neutrality as promulgated by the 1997 Kyoto Protocol (Attia 2016). British architect Bill Dunster and American architect Ed Mazira were instrumental in highlighting the massive impact that the construction and operation of the built environment has on fossil fuel energy use and the associated GHG emissions. Along with partner organisation, Bioregional, Dunster prototyped the design response in BedZED, a sustainable housing development in London, where, amongst other ambitious goals, set a target of achieving zero carbon or net-zero energy building. The initial construction was completed in 2002 and it continues to be a valuable demonstration of the importance of zero carbon building within the larger sustainable living paradigm. Mazria's 2030 Challenge or Architecture2030 is a research and education organisation committed to reducing GHG levels in the built environment through passive design and renewable energy along with resilient and adaptive regional responses where the built environment can positively contribute to climate-change mitigation (Mazria 2017).
Zero Energy Building or Net Zero Energy Building as it is now more commonly referred to, continues to grow as a key proponent of green or sustainable design, not only due to its effects on reducing GHG emissions through mitigation of fossil fuel based energy consumption (the generation of which is also highly water intensive) but due to the sustainable economic benefit of reducing the overall lifecycle cost of buildings.

1.7 NZEB in South Africa

Without well adapted regulatory codes for existing buildings in South Africa as well as under-developed policy that would enable buildings to feed electricity back into the grid, the decision on implementation of energy efficiency retrofits is voluntary, with economic factors such as high capital costs and lack of financial resources and incentives being other commonly cited barriers. Whereas research suggests that regulation to make energy efficiency retrofits mandatory is critical, its absence means that the decreasing cost of RE technology, increased professional team know-how/integration, increased corporate image and stakeholder awareness and responsibility as well as improvements in financial tools are likely to play significant roles in the successful expediting of up-take of NZEB projects (UNDP 2013).

1.8 Problem statement and overall objective

The study aims at identifying NZEB potential in existing commercial buildings through examining and identification of: technical limitations to commercial NZEB retrofits in terms of building floor area ratio (FAR) in high and medium and low density urban typologies; the effect of differing urban densities and zoning regulations on solar access and shading and hence the effect on NZEB retrofit potential (on-site PV); the effect of occupancy classification/density and building use type on NZEB retrofit potential.

Technical limitations of NZEB retrofits often relate to the size of the building and its site constraints. As the number of floors increase, so too does its bulk which thus makes adequate on-site micro-generation more difficult to achieve because of the relatively smaller ratio of roof space in relation to useable floor area. However, the potential for achieving NZEB retrofits is also affected by a number of variables that would ultimately impact on the building's overall energy requirements and related feasibility (cost effectiveness of related interventions). These variables include the existing climatic conditions on site, building orientation, design components and materials of the building envelope, building systems and user activities.

Furthermore, user adaption, which allows for flexibility in internal set-point temperatures, can be used in conjunction with HVAC optimisation and passive design techniques thus enabling reductions in EUI whilst maintaining adequate levels of thermal comfort. The level of energy efficiency achievable through application of passive interventions to the building envelope and optimisation of electrical systems such as lighting and HVAC will also vary from building to building and would require different approaches under varying climatic zones which also effects the nature and size of the required RE intervention.

Identifying the critical influencing factors for the retrofit of existing commercial buildings with reference to their potential to achieve NZEB when complimented with on-site micro-generation therefore constitutes the primary focus of this research. The study therefore aims at assessing the potential for NZEB retrofits in commercial buildings using on-site PV, in Durban, based on prevailing (status quo) efficiency opportunities and cost levels of the assessed interventions.

1.9 Main research question

The main research question which guided the study was stated as follows:

> What are the contextual and technical parameters that would influence performance optimisation outcomes of NZEB retrofits for existing commercial buildings based on EE and on-site PV generation interventions?

The sub-questions of the study were conceptualised as follows:

- What is the effect of urban density and zoning regulations on solar resource on specific sites and stands and how does this affect NZEB potential and how can insights gained guide subsequent densification regulations and development rights?
- What is the significance of building FAR on EUI and NZEB potential?
- What is the significance of occupancy density and building use-type on EUI and NZEB potential?

To substantiate on these questions, the process of the study entailed simulating NZEB interventions in purposely selected case-study buildings in order to determine:

- The portion of overall building EUI which can be achieved through implementing energy efficiency interventions in the form of passive design and building operation system optimisation. This would translate into energy reduction through energy efficiency interventions

- The extent to which rooftop PV generation can meet the optimised energy requirements. This would translate into energy reduction through renewable energy interventions

- The overall viability of NZEB interventions in the form of simple payback period calculations
- The extent to which carbon emissions can be reduced through the simulated interventions.

1.10 Expected findings (working hypothesis)

The initial expectation of the study was that the technical potential to achieve NZEB retrofits using on-site PV generation intervention would be positively affected by:

- Lower zoning densities which translate to lower levels of site shading from the surrounding urban fabric.
- A larger availability of effective site area available for the installation of solar PV in relation to the number of floors and associated FAR.
- Shorter payback periods which is dependent on the extent of reduction in consumption levels through cost-optimal passive design interventions and active system optimisation.
- Lower occupancy densities and shorter periods of operation, which would contribute to lower EUI's and greater NZEB potential.

It was therefore expected that buildings with greater FAR and more floors would not have adequate roof space for PV to take them to net-zero. Buildings with higher energy use intensities like hotels may also equally struggle to reach adequate levels of cost optimal efficiency and optimisation techniques. The energy use intensity of a building is influenced by both technical service systems related to the building operation (cooling, heating, lighting, ventilation, pumps etc.) as well as by user activities (DHW, cooking, appliance plug loads and lighting) (Marszal 2011). The study thus allowed for evaluation of the critical aspects/factors towards achieving NZEB performance.

1.11 Research approach and delimitation of scope

The research employs a comparative analysis of four case study buildings in Durban, based on their potential to achieve NZEB as influenced by critical factors related to the efficacy and financial viability of retrofitting EE and RE interventions. The study is delimited to technical analysis, through technical simulation of reductions in energy consumption achievable through passive and active EE interventions before introducing solar PV. Simulated energy savings were used to calculate simple payback periods based on budgetary order of magnitude estimates for capital costs as well as discount rates to allow for derivation of net present value. A shadow study on individual sites was conducted in order to understand the effect of urban density and FAR on solar availability. The study is delimited to NZEB that uses on-site PV generation, and assumes a grid tied connection as the accounting framework to assess each individual case study building's overall energy balance. Finally the study considers the viability of micro-grids in relation to NZEB using on-site PV generation.

1.12 Definition of key terms

Grid tied PV

PV array connected to the central utility grid, thus mitigating the need for storage systems and the high costs associated. If the array is able to generate electricity in excess of average consumption, or during low load periods, the surplus can be exported to the grid using a 'net metering system'. During periods where PV cannot meet consumption demands, electricity is drawn from the central grid. In South Africa, RE energy can be used effectively to reduce dependence on conventional grid electricity, but the provision/option to export excess 'net positive' electricity back into the central grid is not permitted/facilitated. To overcome such limitations and improve the quality and reliability of decentralised power generation, small scale embedded generation (SSEG's) can be interconnected create microgrids.

SSEG's and microgrids

Buildings can be connected to a micro-grid in a series of cellular networks, whilst still remaining connected to the centralised distribution network, thus allowing buildings or neighbourhoods to trade low-carbon electricity in a power pool. This allows buildings with excess generation to export clean electricity to other buildings in the micro-grid that are experiencing high loads or generally have a higher EUI. Microgrids essentially transform the building into its own localised electricity generation-system that raises "the reliability, resilience, security, efficiency and quality of the electrical services and supply." (Massoud 2016: 49)

EUI

"Energy use intensity (EUI) is a metric that many rating tools and international studies use to compare building energy efficiency" (Bannister et al 2012: 15). It is calculated by dividing annual energy consumption by "the gross lettable area of the whole building in m^2" (ibid). In this way it allows for buildings of different sizes and use-types to be compared using a common metric.

EE intervention – passive and active

Energy efficiency interventions can be categorised as passive and active. Passive EE interventions for existing buildings include modifications to the building envelope, materials and construction systems that would improve building energy efficiency and lower EUI. Active EE interventions include optimisations made to energy consuming electrical and mechanical building systems and equipment, such as HVAC and lighting.

RE interventions

Renewable energy interventions include technology and equipment that are capable of generating power from renewable resources such as solar, wind, hydro and bio-fuels. In the context of NZEB, it is essential that RE interventions are applied after electricity loads have been optimised through EE interventions.

Room electricity

Room electricity is the default Design builder terminology for appliance/plug loads. For simulation purposes, the lift motors have been included in room electricity consumption values. However lift motors and plug load reduction is not included in optimisation techniques, and beyond the scope of the study.

1.13 Chapter outline and overview

The document is structured into 7 chapters as follows:

Chapter 1 gives insight into South Africa's climate change mitigation policies energy usage with focus on the built environment. This is followed by the research problem, the rationale of the study, research objectives, expected findings (working hypothesis), conceptual approach, delimitation and scope, definition of key terms before lastly providing an outline of chapters of the report.

Chapter 2 reviews relevant literature relating to theoretical and practical understanding of NZEB, EE and RE as well as related local regulations and standards. Studies on the effect of FAR, building use-type and urban density are reviewed in relation to EUI and/or PV generation potential. An overview of 7 commercial building retrofits displaying varying degrees of NZEB success is presented at the end of chapter 2, with individual precedent examples presented in appendix 1.

Chapter 3 presents the research method of the study, the data required, and how the data were represented and analysed. This includes the overall framework for the implementation of NZEB interventions as applied in the study.

Chapter 4 presents results from a solar shadow study on all four case study buildings and their immediate urban context and ends with a summary of the results and findings. The significance of the findings is summarised at the end of the chapter.

Chapter 5 substantiates on the second sub-question through a comparative analysis of two office buildings which were simulated towards NZEB. Quantitative results from the simulations provided primary data on which insights of sub- question 1 were distilled. The chapter concludes with a summary of findings from the two buildings in which EE interventions and RE interventions are appraised in terms of electricity reductions, financial viability and carbon emission reductions.

Chapter 6 addresses sub-question 3 through a comparative analysis of a hotel and an educational facility, which were simulated towards NZEB and analysed in terms of this potential. The chapter concludes with a summary of results from the two buildings in which EE and RE interventions are appraised in terms of electricity reductions, financial viability and carbon emission reductions.

Chapter 7 synthesises the sub-findings from chapters 4-6 and substantiates on the overall research question, before providing recommendations.

Chapter 2: Literature review

2.1 Overview

This chapter presents an analysis of pertinent academic studies, technical reports and policy documents regarding NZEB, and particularly NZEB retrofit of existing commercial buildings, beginning with a brief outline of the NZEB paradigm. Building energy use intensity is internationally employed as the key metric used for assessing and comparing building energy performance, and subsequently NZEB potential amongst various commercial buildings. Identifying the various factors that influence EUI has been the focus of numerous academic studies and technical reports, some of which have been reviewed in the following sections of the chapter, with particular focus on the relationship to floor area ratio, operating hours and occupant density. The importance and advantages of NZEB's connection to the grid is explored along with methods for reducing energy consumption whilst increasing generation. As the study focuses on on-site solar generation as the renewable energy technology, studies on the influence of solar availability for on-site PV generation are also discussed, as well as studies on impacts of EUI and overall NZEB potential.

2.2 Fundamental NZEB principles

Even though definitions and metrics of NZEB vary, it can be fundamentally characterised by optimised energy efficiency being combined with renewable energy. In this sense, The zero-energy building paradigm is characterised by its energy balancing protocol which includes demand side management strategies (DSM) and supply side strategies (SSM). DSM include those interventions that save energy (energy efficiency) while SSM involves the effective introduction and configuration of RE resources to maximise their adoption.

The "Net" in NZEB is defined within a specific period in time (usually one year) in which energy use values are to be balanced by RE generation. The NZEB methodology/approach does not necessarily require that a building generate all its own needs on-site, but rather NZEB is an annual balancing perspective. Although the basic calculation method for achieving NZEB involves this balance, there are variations in energy supply options, calculation methodologies and definitions that are followed in various parts of the world (Griffith et al 2007). These illustrate differing ways and means of measuring energy usage, costs and environmental implications in order to assess a building's potential to achieve a zero-energy balance by using the grid for net-use accounting.

2.3 International NZEB practices - calculation methodology and balancing

Accounting for the various end-use demands of commercial building systems is a complex task, often made more difficult when various forms of primary and secondary energy are consumed on-site, as is common in more temperate northern climates. In South Africa, the predominant fuel consumed in commercial buildings is electricity, which is a secondary energy source as the primary fuel product is mainly coal which is converted to electricity off-site. "A unit of primary energy and a unit of secondary energy consumed at the site are not directly comparable because one represents a raw fuel while the other represents a converted fuel." For example, in the USA, grid purchased electricity has a source to site ratio of 3.14 (Energy Star 2018) meaning it takes 3.14 units of energy to get 1 unit of energy to site. Canada has a more efficient generation process and has a site source ratio of 1.94 whilst Europe has an average of 2.5 (EPBD 2013ecofys). Inefficiency and losses in conversion and transmission account for this inefficient energy-transformation and provide a strong argument for using source energy to account for actual energy consumption as well as corresponding CO_2 emissions.

In this vein, America rates the quality of NZEB by the boundary definition in relation to RE generation. Italy, Denmark, Norway and Switzerland have developed building codes that are 'in-line' with NZEB calculation methodologies (Marszal – undated) whilst Germany uses energy delivered to the building and energy fed back to the grid for balancing energy of NZEBs, even though this is not reflected in their national regulations. Although there is a wide and nuanced range of differences amongst NZEB accounting methodologies, the most notable is the variation in approach towards supply options i.e., a NZEBs relationship to the grid. (Marzal - undated)

The US National Renewable Energy Laboratory (NREL) has developed a framework for energy supply options available for NZEB which is used to classify and rank NZEB efficacy (Pless & Torcellini 2010), and four energy supply options have been identified as relevant to NZEB. These are:

- RE generation within the building footprint as characterised by all RE being generated within the building footprint and being directly connected to the buildings electricity system, thereby reducing transmission and distribution losses. The advantage of this type of generation is that the surface area required for collection/generation is guaranteed over the lifetime of a building.

- RE generation within the site boundary is similar to footprint generation, but related to the full site boundary for RE generation which may include properties that are “geographically contiguous” within a given site. This is more typically inclusive of the utilisation of external site space (such as PV installations on parking structures) for such generation.

- Off-site RE resource used to generate energy– This option would apply for buildings which cannot sufficiently reduce their already high EUI, and involves importing primary RE energy resource onto the site where it is converted to required energy services. Examples include woodchips, ethanol and biofuels. Although valuable when appropriate levels of RE cannot be generated on-site, the energy required to transport such fuels to site and convert them would negatively impact NZEB potential.

- Purchase or install RE off-site – Renewable energy credits or ‘green’ credits can be purchased from a certified source in order to offset carbon emissions, or an organisation might contribute to the financing of off-site RE generation plant which it will use to offset its non-renewable energy consumption. This supply option is regarded as the least optimal, as it does not incentivise buildings to reduce EUI. (Pless & Torcellini 2010)

It is possible for a NZEB to be off-grid, although this is not regarded as the optimal option due to the additional need for energy storage, which is expensive as well as having environmental drawbacks related to their disposal. The key advantage of net-balance of the energy supply (input) and the grid-export (output) is that it allows for a transition from energy-negative to energy positive buildings. Self-consumption of RE generation varies between building types, which means that buildings with higher energy demands use their own consumption to reduce demand whilst buildings with lower energy demands will feed more energy into the grid.

2.4 Interaction with the grid

Energy efficiency measures such as passive solar heating, daylighting or natural ventilation that save energy but cannot be directly commoditised are not included in the supply side equation of NZEB accounting and are examples of demand side RE (ibid). Supply side RE generation options available for NZEB includes PV, solar hot water heaters, wind, hydro-electricity and biofuels. In order to guide on the option which could be most beneficial, these supply side energy generation options should be considered in terms of which option reduces "transportation, transmission and conversion losses, will be available over the lifetime of the building, and [sic] are highly scalable, widely available and have high replication potential for future NZEBs." (Pless & Torcellini 2010: 3) Along with these guidelines, RE supply options have been weighted to favour those technologies that can be readily applied within the building footprint or site boundary, as this is regarded to be the most effective approach to NZEB (ibid)

Micro-grids and smart-grids provide substantial potential for networking NZEB optimised buildings. According to Massoud (2016) energy conservation is one of the fastest ways to achieve payback on micro-grids. EE measures also help to manage excessive loads while RE generation essentially transforms the building into its own localised electricity generator that raises "the reliability, resilience, security, efficiency and quality of the electrical services and supply." (Massoud 2016: 49)

The smart-grid concept would essentially see buildings connected in a series of cellular networks, whilst still remaining connected to the centralised distribution network, where buildings or neighbourhoods can begin to trade low carbon electricity in a power pool, thus allowing buildings with excess generation to export clean electricity to other buildings in the micro-grid that are experiencing high loads or generally have a higher EUI. The smart micro-grid model is beneficial in that energy consumption is nearest to the generation point (Amado 2016). Networking certain buildings in the commercial sector has the ability to provide a "positive business case for micro-grid adoption by cutting energy costs while potentially providing a demand response opportunity for the local utility" (Massoud 2016: 50)

2.4.1 Consumption versus export to the grid

With the exception of certain commercial buildings such as hospitals and hotels, which operate on a 24hr/7 day/week basis, most commercial buildings (such as offices and retail that have been optimised towards NZEB), will at some point generate more electricity than is required by the building operation. The most obvious example of this is during weekends, when the building is essentially closed and consuming far less than when operating normally during week-days. Ideally, RE could be sold back into the grid during these periods and during times when RE is insufficient for meeting building loads, conventional energy can be drawn from the grid "using the utility to account for the energy balance" (Griffith et al: 2). Drivers of DG have been identified as "feed in tariffs, net metering, net billing, self-consumption and generation export tariffs" (Sewchurran et al 2016: 68).

2.5 Drawbacks to on-site generation

Small scale distributed generation (SSDG) does however present challenges, especially in South Africa's context, where technical, regulatory and administrative aspects of all power from the central utility to the end-user are structured to support a one way flow electrical power (Sewchurran et. al 2016). SSDG's require a bi-directional flow of electricity within the grid system which can negatively impact on the quality and supply of power flow (ibid). One such problem of using the grid as a battery is the export of electricity during the off-peak period in daytime day when demand is low. Municipalities in SA currently do not offer feed-in tariffs, even though in certain instances some of them have allowed a fixed monthly grid connection fee with very low feed in tariffs. (ibid) Thus the feasibility of PV SSDG's is largely dependent on higher levels of self-consumption to avoid grid costs (ibid).

2.5 Baseload, peak demand and load shifting

"Where electrical meter estimates are made, no valid data exist for electrical demand." (US DOE 2002) The baseload of a building, that is the minimum continuous consumption over un-occupied periods, is very difficult to estimate using whole building simulation and annual consumption values. To accurately measure peak demand and baseline consumption requires record data measured on-site using specialised meter logging equipment, and is beyond the scope of this study. Baseload can be attributed to the influence of resistive loads from the HWS as well as lighting systems which may remain running during unoccupied periods.

Larger inductive loads from elevators are also suspected to contribute to baseload demand. Reducing baseload consumption through installing power factor correction equipment is recommended to ensure the current flowing in the system is not larger than it needs to be. This option in energy-consumption optimisation is also beyond the scope of this study.

Peak loads occur when energy demand and consumption is at its highest (within a given monitoring domain), generally due to simultaneous demand for power by diverse loads/consumers at specific times (eg: when all HVAC systems are working at their maximum capability on the hottest period of the year, or daily loads related to user patterns of home-work cycle). Peak daily demand is usually limited to a short period (which in the majority of commercial buildings in warm climates, occurs in the afternoon due to cooling loads). This is beneficial to NZEB as electricity generated via on-site PV can be immediately utilized to reduce consumption over the peak demand period. This eliminates the need for battery storage unless the building's generation capacity exceeds its peak loads. Although more rare, in these instances excess electricity can be stored in on-site battery units which can be used to further reduce consumption after the PV system has stopped generating electricity. Load shifting is a DSM strategy aimed at reducing consumption during peak periods, when electricity tariffs are at their highest. An example of this method is the use of ice chillers to supplement an HVAC cooling capacity by creating ice using electricity purchased during off-peak periods, thus enabling the system to reduce consumption during peak times.

2.6 Benchmarking commercial buildings

Building EUI is the common indicator in the assessment of a building's energy consumption, as well as the level of energy efficiency which would then guide the formulation of performance -based benchmarks, thus allowing for a comparison of energy consumption across buildings with different characteristics (Bannister 2012). Over the last decade, various studies have been conducted in different countries/regions that benchmark electricity consumption in commercial buildings.

The EU has set the target "nearly zero energy" in all new buildings by 2025 which is outlined under the Energy Performance of Buildings Directive (SHCP task 40 - ECBCS Annex 52 2012). (Hermelink et al 2013).The US Department of Energy's Building Technologies program has strategic targets of zero energy residential new-buildings by 2020 and commercial buildings by 2025. California targets show 100% of new buildings and 50% of existing buildings being net zero by 2030. Most central and northern European countries favour the basic NZEB accounting framework of conventional energy use balanced by RE generation but do stipulate a preference to on-site or off-site generation.

Even though there is limited statistical data for existing commercial buildings in South Africa, in the last decade, various studies have started to report on benchmark standards for existing commercial buildings. These include a 2008 survey of 20 commercial buildings in Cape Town and the GBCSA Greenstar survey of 155 office buildings throughout the country. Whereas this allows the sampled buildings to be monitored annually with regard to industry averages, it is not without its limitations. Martin (2013: 27) argues that "… it does not allow buildings to be compared against each other between years, and the buildings used to generate benchmarks will not necessarily provide a representational sample of national building stock."

Performance data on South Africa's other building use-types such as hotels and retail have not yet been captured or reported. In the absence of comprehensive baseline consumption data, various performance based benchmarks have been developed to analyse survey results, such as the 'Enerkey' performance certificates, which use targets set in the SANS 10400-XA (national building regulations) for new buildings as the comparative benchmark. (ibid 2013). This is the method used in the current study to compare case study building performance to national benchmarks, as explored further in a subsequent sub-section. The results from simulations are presented for each case-study building in Chapters 4 and 5. This is done by "identifying the underlying relationship between resource input and productive output." (Bannister 2012 p 8.) Common criteria for evaluating or estimating energy performance in commercial buildings in SA are monthly electricity billing data, building use-type (user activity), EUI, age, size, operating schedules and environmental /climatic zone data.

In a GBCSA energy and water benchmark report published in 2012, it was found that building size, location, age , % of active cooling (% of building serviced by HVAC) and energy intensive services did not significantly affect the EUI of the survey sample of 350 buildings significantly.

A 2017 study of non-residential buildings in Bavaria indicated that the highest absolute demand reductions in the specific non-renewable primary energy demand were achieved by those reference designs that had high demand (often buildings with a high degree of technical installations such as hospitals and research facilities) and large volumes.

In the US, the 2003 commercial buildings energy consumption survey (CBECS) compiled a report containing critical statistical data from a survey of over 4 500 commercial buildings which enabled numerous studies to be undertaken, including the assessment of the technical potential for achieving net-zero energy buildings in the commercial sector. (Griffith, et al 2007) The report found that, energy efficiency improvements using the best available technology combined with a whole- building design approach can on average reduce overall electricity consumption by 43%.

If this was applied to all commercial buildings in conjunction with solar PV, these buildings could on average decrease annual energy consumption by 86%. (ibid) One of the key findings was that those that could not reach net zero had insufficient roof area for PV installation and generation. On average, commercial buildings needed to reduce consumption by roughly 60%, with single story unrefrigerated industrial warehousing having the most potential for NZEB, only requiring a reduction of 6% whilst offices required on average a 67% reduction. The most common energy efficiency interventions in existing commercial buildings are: advanced thermal insulation of the building envelope, sun shielding, advanced daylighting, passive ventilation and cooling, solar thermal HWS, efficient HVAC, heat recovery and LED lighting. According to the US Energy Information Administration (EIA) Commercial Building Energy Consumption Study (CBECS), energy efficiency measures are generally required in order to reduce energy consumption by at least 60% in individual buildings before RE can effectively balance the consumption/demand of fossil fuel generated energy.

Even with the increasing affordability due to decreasing costs, renewable energy technolgies such as PV, still entail a large portion of the upgrading cost thus making it paramount to reduce EUI before introducing such RE technologies. Reducing EUI through passive and active interventions also requires a balancing of energy saving potential versus cost effectiveness such that the benefits in terms of energy reduction correlates with the cost of the intervention. In South Africa, acceptable payback periods for the sector may vary between projects, however, as the cost of conventional electricity continues to rise while the cost-competitiveness and technical efficiency of PV continue to increase, payback periods are estimated to be shortening to between 5 and 7 years (Du Plessis 2017) and (Sewenchurran et al 2016). However this does not take into account reduction in generation capability that shading of PV can cause.

2.7 Precedent for NZEB retrofits- case studies

In a sample of seven US NZEB office retrofits reviewed (see Appendix 1, pages 133-139) , the selected buildings were able to reduce their EUI by more than 30% from the CBECS national average and thus demonstrate what can be learned from the deep energy retrofit process in terms of barriers, market forces, business rationale, technology and common practices. Buildings were selected on the basis of their improved energy performance (in relation to CBECS national average for building type) through integrated energy efficiency retrofits.

The appraised case studies exhibit many common technologies and practices required for deep energy savings. Lighting, ventilation and HVAC interventions generally provide the highest potential to reduce a building's EUI, especially when combined with digital smart sensors and differenciated energy metering devices (Higgins et al 2011).The monitoring equipment constitutes an integral part of assessing the performance of efficiency upgrades and getting building users to actively be involved in energy saving techniques especially towards facilitating behaviour change. This is beyond the scope of the simulated studies. The influence of the building user on EUI is well demonstrated in the California Lottery Building (see appendix 1 page 135) where plug loads are greatly reduced through smart automated systems that turn off workstations when not in use. Other simple user-behaviour changes (such as window cleaning during daylight hours reduce the need for lights to be turned on for night cleaning) were found to further reduce EUI.

The motivation for deep energy saving retrofits is constant across the case study samples. Building owners seek to improve rental returns and corporate image through increasing building performance whilst improving user comfort. Achieving various international, national and regional goals and targets for CO_2 emmission reduction is increasingly being persued in order to unlock related subsidies and rebates(ibid). This was demonstrated in the retrofit of The Alliance Building (see appendix 1 page 136) which was able to achieve a $ 50 000 reduction in project costs and making cost effective savings possible.

In the majority of retrofit cases, another key concern was to mitigate disruption of existing building tenants during the rennovation process. Much of the retrofit of The Aventine offices in California (see appendix 1, page 135) was completed after hours to avoid disruption during business hours. Commissioning and user training was also viewed as an essential part of any major retrofit as it allows for fault finding and rectification, system optimisation and the creation of benchmark/baseline data. (ibid)

Of the 7 precedent study buildings, only one was able to achieve a net positive balance when accounted for at site. This is most likely due to its extremely small floor area, which at 418 m^2, demonstrates the relative ease with which a single story office structure such as 1955 Bacon Street, (see appendix 1 page 137) can achieve a positive NZEB balance through passive design techniques and on-site PV.

2.8 Electricity consumption in commercial buildings

Studies of EUI in office buildings indicates that a large portion of annual energy consumption goes towards satisfying cooling loads, followed by lighting and plug or process loads. The extent to which these loads fluctuate from the baseload demand is affected by multiple factors including weather cycles, operation hours, and occupant and/or computer density.

The GBCSA energy benchmark report for office buildings explored the relationship between variations in EUI in response to certain potential consumption drivers. These included climate, occupancy hours, computer density, occupant density, % of lettable space, vacancy rate and car park density.

Computer density was found to be a reliable driver of building EUI whilst operating hours were found to be a less significant driver. The study also found that “locations with high annual cooling design days (CDD) usually signify cooling-dominated climates where additional cooling loads and decreased HVAC cooling efficiency could lead to higher EUI” (Bannister et al 2015: 32). Diversity in the CDD and HDD range was found to increase energy consumption in both cool and warm climates, however small inefficiencies in HVAC systems (which they are prone to) were found to negate climate effects (Bannister el al 2015). The study concluded that there was very little empirical evidence to support the impact of climate on building EUI.

2.9 Factors influencing EUI

“A large number of factors could potentially drive building energy use and energy efficiency” (Bannister 2017: 19) These include characteristic and operational aspects such as climate, building use-type (which relates to operating hours and occupancy density) and building size as well as other ‘demographic’ factors such as the age and location of the building, the % active cooling it uses and the concentration of energy intensive services. Li et al (2015) prioritise improvement of equipment efficiency, and in particular lighting, HVAC and building envelope performance (Insulation and shading, glazing improvements)

The following sub-sections review what recent academic studies and reports on the impact of these drivers. Building size and annual energy consumption are the two key data requirements for calculating building EUI. “Building size is a key variable in the benchmarking methodology as it is one of the few metrics that can be measured and validated for any given building. The equation used to calculate EUI is as follows:

$$\text{Energy Use Intensity} = EUI = \frac{\text{Annual Energy Consumption(kWh)}}{\text{Building Area (m}^2\text{)}}$$

2.10 The effect of occupancy and operation times on EUI

Kontocosta (2012) reported a significant correlation between operating times and user density, and argued that user density has a more substantial effect on influencing EUI. This highlights the importance of understanding building usage and operational characteristics when attempting peer to peer efficiency comparisons.

Accurate operational data for commercial buildings from logged occupancy times is in most instances not available. The common measurement for a building’s occupancy density is normally specified by the number of assigned occupants and is regulated in most building codes as a maximum number of people per unit area. Occupants interact both passively and actively with the building, through metabolic output that contributes to heat gains, and by their use of appliances, lifts, lights hot water etc. Whereas these interactions influence building system electricity consumption actual occupancy as well as behaviour is subject to random variations and drivers.

With reference to this study for example, hotels are generally energy intensive due to guest comfort being prioritised, varied activities (catering, laundry, shopping) as well as operating 24/7, 365 days a year (Rotimi et al 2017). The same research revealed that the correlation between guest occupancy levels and EUI was weak, while it was unexpectedly found that there was a stronger correlation between increased staff and increased EUI (ibid). In a study of hotel energy use in China, Lang et al (2016) report correlations between hotel star rating, number of guest rooms, room revenue and the number of staff to building EUI. “Based on statistical analyses, two significant indicators represented a standardised distribution of EUI: hotel star rating and yearly occupancy rate.”

Selvacanabady and Judd (2017) studied the effect of occupancy on energy use of office building energy use and concluded that while measurable, the impact was ‘relatively minor’ even when taking into account the effect of occupancy on plug loads, weather-dependant loads such as HVAC and non-weather-dependant loads such as lighting.

A GBCSA office building study by Bannister and Cheng (2012) viewed occupancy as analogous with computer density, which was found to be a significant consumption driver when accounting for residual EUI. Although the survey did not identify a strong correlation between operating hours and building performance, there is a theoretical connection from building simulation outcomes suggesting a clear correlation between operating hours and EUI. A simulation of two different buildings in different climatic zones under various operating schedules revealed that there is a linear link between increased operational hours and increased EUI to the scale of 1.14% per hour. Furthermore, there was a weak link between vacancy rate and energy use variability across the sample, which is contradictory to the Chinese study (2005)

2.11 The effect of building size and FAR on building EUI

Building size (m^2) is the key variable in the energy benchmarking methodology as it is can be measured and validated (hence making an EUI calculation possible) as well as correlating strongly with other factors such as occupancy. (Bannister 2017: 14).

Various studies benchmarking energy efficiency in commercial buildings have not been able to find a significant empirical evidence of the links between building size and EUI despite the theoretical notion that the complexity and level of building systems increases with building size (ibid). In a South African study conducted by the country’s Green Building Council, it was concluded that there is a linear link between EUI and office building’s size in terms of gross lettable area, indicating that buildings will generally consume more electricity per m^2 as they get larger.

In the CBECS study, overall building size and FAR were identified as inadequate indicators of NZEB potential. This however should be understood in the context of the study, where out of the 4 500 commercial buildings simulated, 75% were less than 1 000 m² and significant portions of the stock were large single story buildings. This illustrates that the majority of the buildings studied have a very low FAR and therefore are not representative of buildings in the higher FAR range.

Li et al (2015) tested the effect of building size and climatic zone on a building's EUI for office buildings. They found a wide variation in EUI across the sample, and despite a general trend where EUI did increase with increased floor area, the findings were not significant towards confirming such a relationship, with enough of the smaller buildings displaying higher EUI's and visa-versa. It was concluded that there was no conclusive evidence that smaller buildings under 5 000 m² will result in lower EUI's, although it was noted that many smaller buildings are assumed to have a larger relative perimeter area than larger buildings with deep floor plans, and as such if correctly designed can utilise natural lighting and natural ventilation more effectively, thus lowering EUI.

Kontocosta (2012) conducted a study of over 20 000 buildings in NY City with a floor area larger than 5 000 m² and established that there was a positive correlation between EUI and building size in office buildings, although it was also noted that buildings with a larger amount of non-office spaces had higher EUI and that buildings located on an 'inside' lot, where there is a large amount of adjacent buildings, were found to have lower EUI.

From the literature reviewed, it is evident that the correlation between FAR and EUI does not provide a clear indication of energy efficiency especially across different building use-types. However, FAR could be used as a rational indicator for overall energy consumption, in a theoretical/ design scenario where two identical buildings with equal site coverage are likely to experience constant EUI with increasing floors, but overall energy consumption is likely to increase with an increase in FAR or number of floors.

Despite a weak correlation between building size and FAR with EUI at the individual building/site level, it may still be a useful indicator for assessing NZEB potential when using on-site PV, as it is in essence a marker of site density, which can be used to explore the link between urban density (site density on a larger scale) and zoning regulations which in turn influence solar resource available for on-site PV generation, and thus affects NZEB potential.

2.12 Urban density, passive solar design, and solar access for PV

The fundamental passive solar design strategy is orientating a building in relation to the sun. In the northern hemisphere, this translates to buildings primarily facing south, whilst southern hemisphere buildings would primarily face north. “Passive solar design involves arranging the form, fabric and systems of a building to increase the benefits of ambient energy for heating, lighting and ventilation, to reduce the consumption of conventional fuels” (Littlefair 1998: 303) Conventional urban layouts, based predominantly on the modernist town planning grid layout, have been designed and built with very little emphasis placed on orientation and form in relation to solar resource. Instead, modern development models for commercial buildings are based on a simple premise that increased floor area on a given site equates to an increase in usable/lettable space which leads to an increase in profits. Town planning regulations aim to limit the impact of density on traffic, waste and sewage disposal as well as excessive shading at high densities, which can lead to inadequate lighting levels on ground and lower floors. It can be argued that cheap fossil fuel based energy has been a key driver for modern commercial property development, as the impact on the operating cost of energy intensive HVAC and lighting systems which have been used to offset the poor performance of buildings, has up until recently been limited. As the cost of fossil fuel based electricity generation increases, so too do building operation costs both financially and environmentally, thus highlighting the inadequacies of inefficient building systems and the limitations of conventional urban planning and zoning layouts.

In a study to ascertain the effect of diverse influences of urban form on daylight access and solar potential, Cheng et al (2006) simulated high, medium and low density scenarios with reference to three design criteria of openness at ground level, daylight availability on façade and PV potential on the building envelope. An analysis of 18 generic models that represent a range of built forms and densities allowed researchers to investigate the interrelation between FAR, site coverage and randomness (in both vertical and horizontal layouts). The best performing models in terms of solar PV potential were those with high site coverage and uniform vertical and horizontal layouts. FAR appeared to have very little effect on solar potential under these conditions, as the top three performers were high medium and low FAR.

Despite advantages to solar potential, high site coverage has the converse effect on the amounts of daylighting available at ground level and on the building façade, thus making high coverage uniform urban layouts unsatisfactory. To reduce coverage whilst maintaining constant FAR results in an increase in building height which is also disadvantageous to daylighting potential. However it was found that this can be offset by employing a random horizontal urban layout with more open space (ibid 2015). The model found that horizontal randomness is preferred at high density as opposed to uniform building height. Vertical randomness was also attributed to improvements to solar potential and daylighting. Ammado et al (2013) argue that priority should be given to lowering site coverage as it is complimentary to increasing the average distance between buildings.

A Bavarian study (Keltch et al 2017) of non-residential buildings, found that case studies that performed well generally had large flat roof surfaces that were clear of technical installations. They were mainly 2-3 floors in height with one of them being 4 floors. The study revealed that the production of RE is highly dependent on the amount of available roof area for solar energy use. As such solar energy use potential can be estimated by the correlation between available roof area and gross floor area (GFA). "Buildings with several usable floors have limited proportions of usable roof area per square meter of the total floor area" (ibid: 14). Buildings with high levels of technical installations on their roofs reduced available roof space for PV installation.

Conclusion

From the literature reviewed it is evident that achieving optimal density (which can have environmental and economic benefits) whilst ensuring adequate solar access for lighting and PV generation is a complex task with multiple variables. Solar access and shading of specific sites vary due to orientation, urban density, location and form especially in terms of number of floors and site coverage. In the context of the current NZEB retrofit study in hot humid climates, shading from surrounding buildings may decrease direct solar gains and hence cooling loads, but may adversely affect PV generation potential and daylighting levels. The study is primarily focused on assessing the effect of shading on generation potential of on-site PV and hence on overall NZEB retrofit potential.

2.13 Theoretical framework

The extent to which FAR and urban density effect NZEB potential is directly related to the generation potential of on-site PV, which is primarily influenced by the amount of available site area for PV and the amount of shading that this area receives from the surrounding urban fabric. On the other hand, building user population and the duration of operating times has been found to have a varied effect across different building use-types, with certain studies on office buildings finding a relatively minor influence on EUI whilst hotel studies have found that occupancy rate and operating hours have a more noticeable effect on building EUI. Figure 2.3 presents the conceptual framework of the study which reflects both sides of the NZEB accounting framework in terms of SSM and DSM, as represented by on-site PV generation and energy efficiency measures respectively. As both types of intervention will affect NZEB potential, the effect of building use type, FAR and urban density are appraised in relation to their effect on EUI and PV respectively.

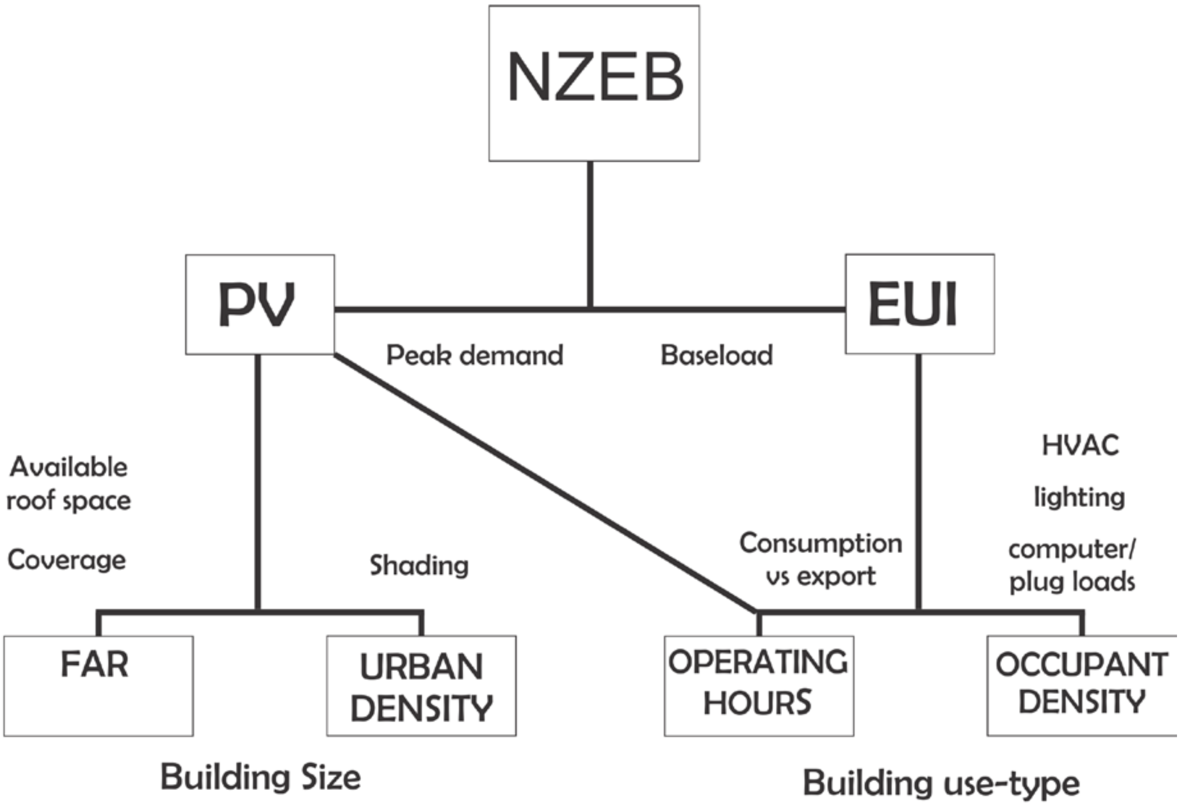


Figure 2.3: Theoretical/ conceptual framework of the study

Chapter 3: Research method of the study

3.1 Research methods

This chapter explains how qualitative findings in response to the research sub-questions were derived through detailed building performance simulations under various scenarios and guided by the overall research question on whether every existing building can achieve a net-zero balance, and the technical and contextual parameters that would influence the potential of NZEB retrofits, and what would be the effect of retrofitting all existing commercial building stock for NZEB

The study takes the form of a performance-based analysis of four existing commercial buildings in Durban, with energy modelling and simulation as the primary data approach. The simulation data were applied towards the assessment of the potential effect of retrofitting for NZEB, based on passive interventions in conjunction with energy-use optimisation of active/mechanical systems and integrated RE technology in the form of on-site PV. Primary quantitative data for each building's annual energy consumption were also collected and applied towards assessment of the baseline condition, from which subsequent cost benefit assessments were referenced.

Calculating energy use in the design phase is a complex task that requires detailed energy performance simulations. Simulation tools are also needed in order to model interactions between building systems, components, occupant activity and weather. (Griffith et al 2008) Dynamic simulations were required towards the modelling of continually changing building loads and energy use which vary constantly with time of day and year. The process of introducing interventions becomes a complex design exercise in experimenting with heuristic 'what if' scenarios where various iterations/combinations were required in order to achieve optimal results from complex relationships between building systems and elements. Each component as well as cross-influences among the components were iteratively simulated for the assessment.

3.2 Data needed and data collection method

Given that the study involves the assessment of technical potential, a variety of quantitative data sets relating to a building's physical characteristics (including location) and energy use profile were required. These were collected by the researcher in order to serve as primary data required for modelling the baseline conditions. Each building was modelled and simulated as it currently is (as-built state) ensuring that size, scale, proportion, materials, building systems and actual annual energy consumption were used to create a series of baseline perspectives which were needed as a reference to "cast results for the metric of percentage savings" (Griffith et al 2007)

In the US, these type of data are available through the 2003 Commercial Buildings Energy Consumption Survey (CBECS) which thus enabled subsequent studies of NZEB technical potential nationally, by subsector, as well as across different climatic zones which has proven to be greatly beneficial towards informing policy and building codes as well as setting carbon reduction targets and monitoring their impact. Analysis of preliminary data from South Africa's benchmark surveys indicate that KZN's commercial building sector is less energy intensive than that of other prominent regions of Gauteng and the Western Cape (Bannister et al 2013). It is speculated that this is due to a lower incidence of energy intensive building types such as data and call centres. For the purpose of this study, the maximum energy consumption per building use type and climatic zone as laid out in SANS 204 and SANS 10400-XA energy efficiency in buildings, were used as the benchmark reference to assess building energy performance both before and after NZEB interventions.

3.3 Energy efficiency regulations- The SANS documents

Prescriptive (design) codes focus on individual building components to ensure they are built or perform to a certain performance standard such as, the R-value for walls. Given that they do not factor in the interaction between design elements and building systems, they miss the opportunity to guide optimisation of the benefits of retrofits. (UNDP 2013) Significantly more energy can be saved through a whole building retrofit than through piece-meal application or replacement of building components. (Aksamji et al 2016)

A draft of SANS 1544 has been in circulation since 2014 and it is expected to be implemented initially in public-sector buildings, and subsequently in private-sector commercial buildings by 2020. (Ngwenya 2016) The document uses SANS 10400-XA 'energy efficiency in buildings' as a normative reference and "specifies the requirements for producing energy performance certificates (EPC's) for buildings that compare the energy performance of the building to a reference energy consumption" (SANS 1544 2014: 3) The standard addresses " the energy performance of buildings based on a) measured energy consumption, b) existing buildings that have been in operation to meet a particular need associated with the use of the building for two years or longer, and that have not been subjected to a major renovation or change of occupancy within the year before the assessment period, c) building occupancy classes considered in SANS 10400-XA for which the maximum energy consumption is specified in SANS 10400-XA, and d) maximum energy consumption values contained in SANS 10 400-XA" (ibid).

Table 2 — Maximum annual consumption per building classification for each climatic zone

1	2	3	4	5	6	7	8
Classification of occupancy of building	Description of building	Maximum energy consumption[ab] kWh/m^2					
		Climatic zone[c]					
		1	2	3	4	5	6
A1	Entertainment and public assembly	420	400	440	390	400	420
A2	Theatrical and indoor sport	420	400	440	390	400	420
A3	Places of instruction	420	400	440	390	400	420
A4	Worship	120	115	125	110	115	120
F1	Large shop	240	245	260	240	260	255
G1	Offices	200	190	210	185	190	200
H1	Hotel	650	600	585	600	620	630

[a] The annual consumption per square metre shall be based on the sum of the monthly consumption of 12 consecutive months.

[b] Non-electrical consumption, such as fossil fuels, shall be accounted for on a non-renewable primary energy thermal equivalence basis by converting mega joules to kilowatt hours.

[c] The climatic zones are given in annex A.

Figure 3.1: Maximum annual consumption per building classification for each climatic zone – SANS 10400-XA. (SAB standards division 2011: 8)

Reference energy consumption levels are based on occupancy classification and climatic zone as well as SANS 10 400-XA as a normative reference. "Internationally, EPCs are used to focus energy efficiency and provide a straightforward way to benchmark a building's energy performance against industry benchmarks or national standards. It also establishes a register of information on buildings' energy performance, which government can use to support policy development; and informs retrofitting programmes by building owners and operators." (Hayes 2016) Thus SANS 1544 and EPC's could be seen as a necessary and important first step in defining a baseline condition in existing stock but not necessarily for achieving energy consumption and CO_2 emissions reduction ."EPCs are considered as drivers of energy efficiency for buildings because they can provide information on the energy performance of buildings and be used as tools to track the energy efficiency of buildings over time." (Ngwenya 2016)

3.4 Weather data – Durban

Based on SANS 10400-XA classification, Durban falls within a sub-tropical coastal climate which is coded as zone 5. The fine summer weather is associated with north-easterly winds, high temperatures and high levels of humidity. This is interrupted by the eastward progression of coastal low pressure systems and occasional cold fronts, which are accompanied by a switch to south-westerly winds, increased rainfall and a decrease in air temperature. In winter, prolonged periods of calm weather can be experienced when high pressure cells dominate the interior. During these periods of calm, cold but light north-north-westerly winds prevail in the early mornings with low levels of humidity, swinging to light north-easterly winds by midday. In addition, highly urbanised areas such as Durban's CBD have a significant amount of concrete buildings that act as heat sinks, thus leading to higher temperatures than would otherwise be experienced. (Bellingham et al 2010)

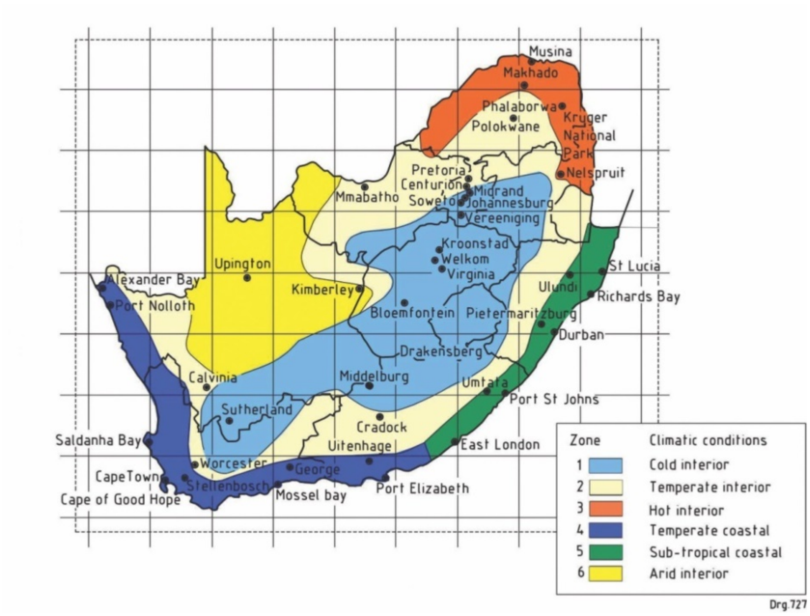


Figure 3.2: SA climatic zones as per SANS 204/10400-XA. (SABS standards division, 2011: 15)

With regard to simulation inputs, weather data for a typical reference year (TRY) are now available for key cities globally. Aggregated Weather Data for six of South Africa's main cities have been converted to 'energy plus weather' EPW files that contain average yearly weather statistics, which in the case of Durban, were collected from a weather station at the old international airport. The simulation software uses the exact site location combined with comprehensive climate data in order to accurately create specific contextual conditions.

Site Data - DURBAN

Weather Data	Hourly									
Time/Date										
Outside Dry-Bulb Temperature (°C)	31.70	23.30	21.10	25.60	24.40	20.60	23.90	27.80	21.70	22.20
Outside Dew-Point Temperature (°C)	19.90	21.70	20.30	17.30	18.80	18.90	19.00	22.40	17.50	20.60
Wind Speed (m/s)	5.10	4.10	5.70	8.20	1.50	3.10	7.20	4.60	1.50	7.20
Wind Direction (°)	90.00	22.00	45.00	22.00	202.00	90.00	45.00	157.00	90.00	22.00
Solar Altitude (°)	24.47	60.94	-23.39	-11.17	75.56	8.18	-36.91	37.63	45.27	-35.31
Solar Azimuth (°)	256.85	82.46	136.18	236.63	304.02	109.27	200.78	267.33	87.23	148.34
Atmospheric Pressure (Pa)x10^3	101.25	101.25	101.25	101.25	101.25	101.25	101.25	101.25	101.25	101.25
Direct Normal Solar (kW)	0.73	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.64	0.00
Diffuse Horizontal Solar (kW)	0.11	0.11	0.00	0.00	0.47	0.02	0.00	0.17	0.15	0.00

Figure 3.2: Example/sample of E+ output - hourly climatic data used in the simulations.

3.5 Method for designing appropriate passive strategies based on climatic zone

The influence of climate and location on responsive high performance buildings is important as it guides the passive design responses appropriate for a particular climatic zone while also influencing the intensity and availability of solar radiation as well as wind resources.

The primary aim of passive design interventions is to obtain desired internal comfort and daylighting levels using the surrounding ambient environment and site conditions while minimising the need for active (energy consuming) interventions. However passive design interventions are a little more difficult to retrofit to an existing building as they are better integrated in to overall design strategies such as building orientation, envelope design, materials and construction techniques. In the context of the study, passive design techniques were explored first in order to ascertain whether their implementation would be feasible.

The visual interpretation of these climatic data in relation to building level design inputs can be presented in the format of 'Bio-climatic Chart' which depicts the major thermal comfort factors which are temperature, humidity, radiation and air movement. The bio-climatic chart for a certain location entails plotting of the relative humidity 'high' against the corresponding dry bulb temperature 'low' for each month. Conversely, the RH 'low' and the DBT 'high' for the month form another point to plot. Once these two points have been plotted they are joined with a straight line. This process is then repeated every second month over a period of one year (translates to six lines) in order to get a chart plotted as shown in Figure 3.3. The straight lines are then used to guide on the relevant zones which can in turn guide on passive strategy options for pursuing thermal comfort for the site being evaluated.

Based on this approach, natural ventilation and shading are deemed to be the most suitable passive design strategy options for a humid sub-tropical climate such as the one for Durban.

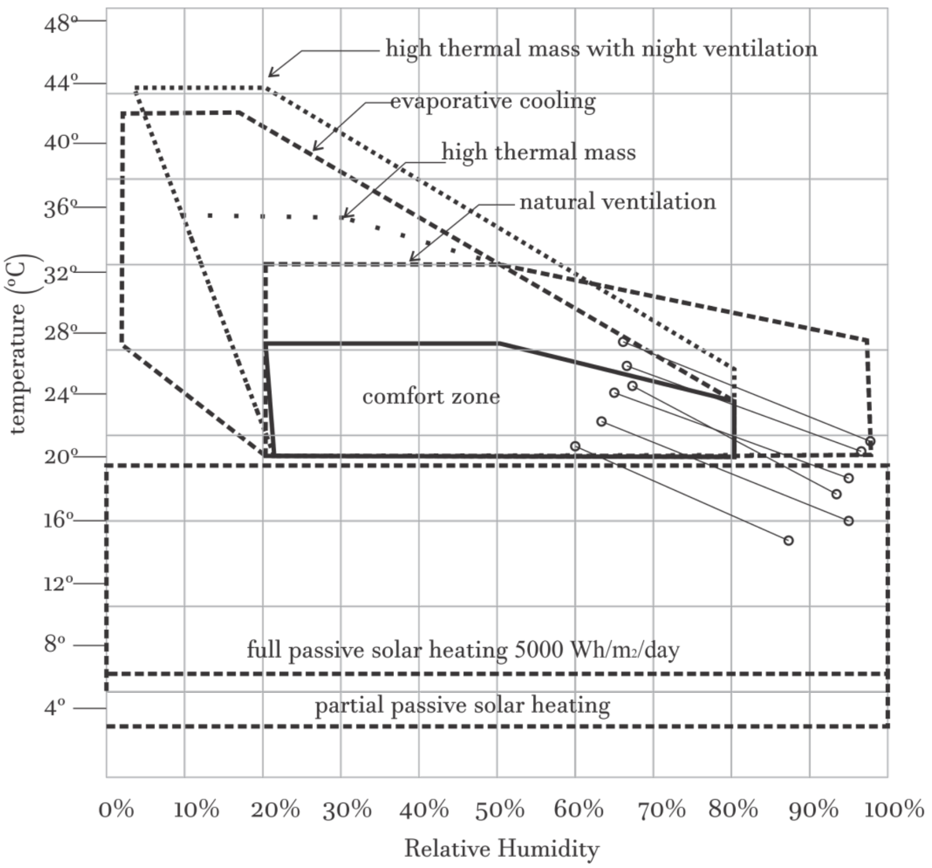


Figure 3.3: Bioclimatic chart analysis – Durban 29◦51’37”S 31◦01’29”E (Adapted from Olgyay’s 1963)

3.6 Tools used for the simulation analysis

EnergyPlus™ is a whole building energy simulation program used by engineers, architects, and researchers to model energy consumption in buildings. Its development was funded by the U.S. Department of Energy’s (DOE) Building Technologies Office (BTO). It was chosen as the software for the 2003 US CBECS study due to its attribute as a “tool that accounts for the complicated interactions between climate, internal gains, building form and fabric, HVAC systems and renewable energy systems” (Griffith et al 2007: 11) Design Builder™ was used as the graphic/architectural interface program through which EnergyPlus data are simulated.

3.7 Data processes and presentation

Sub-question 1

Substantiation on this question entailed a solar study on purposely selected sites, where the effect of shadowing was simulated on an hourly basis over a period of 28 weeks (6 months) in order to assess the effect of the surrounding urban fabric with regard to casting shadows on space that would otherwise be suitable for PV.

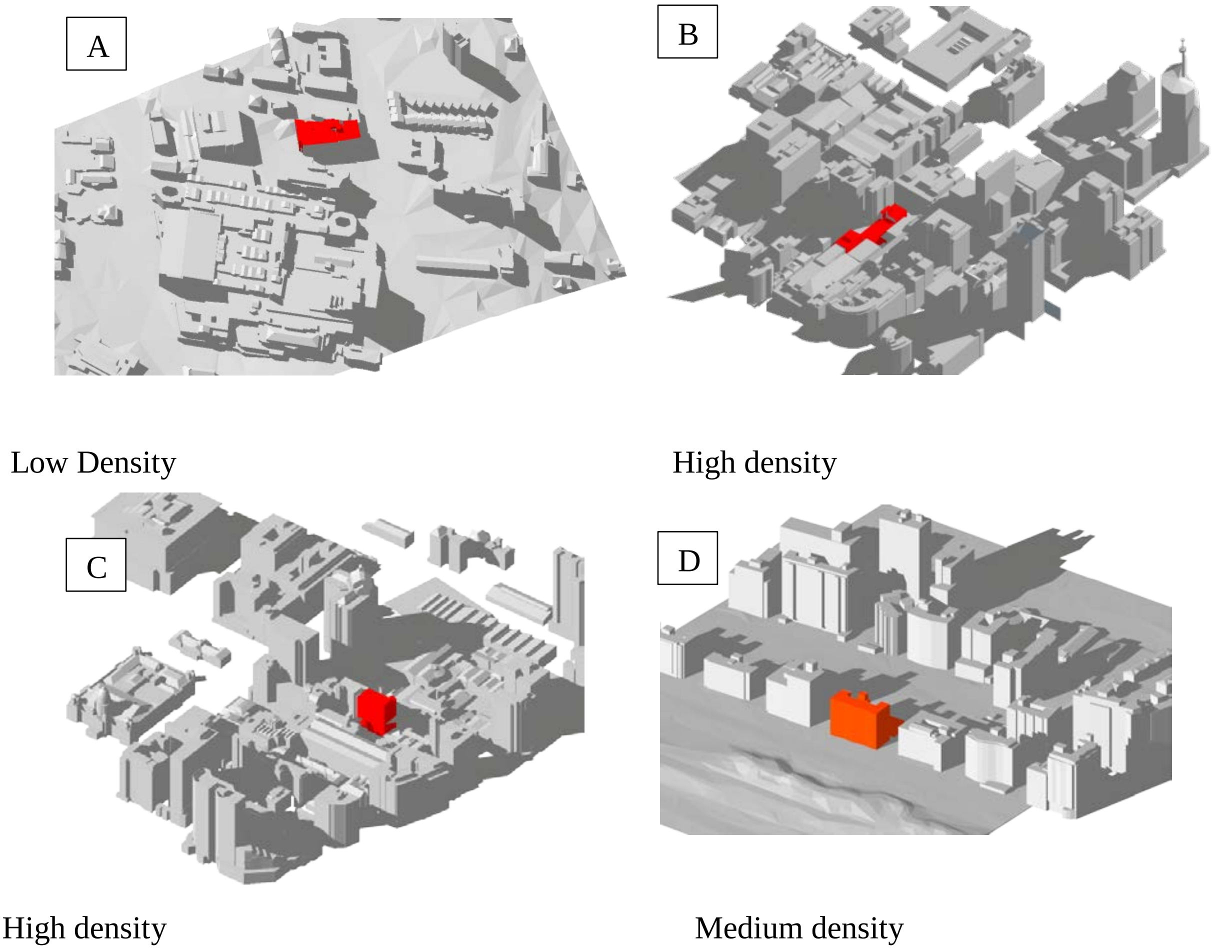


Figure 3.4: Sample images of 3D models tracking the effect of shadows cast by surrounding urban fabric on the case study buildings.

The solar shading analysis of the purposely selected case-study buildings started with creating urban-scale block models of each building and their surrounding context. This was based on capturing 3D data from Google Earth models and importing them into the Sketch-up software platform which is capable of running solar simulations. The scaled models were then orientated and geo-located to the co-ordinates of the actual site which then allowed for an accurate analysis of the effect of urban density and zoning regulations on solar resource access on the selected stands.

The total area available for the installation of PV includes ground level open parking lots, flat roofs and north facing portions of roof, falling between NE and NW. This is particularly pertinent in pitched roof scenarios, where south facing pitches between SW and SE are not considered suitable for the installation of PV. In order to derive the available roof area for PV, SW and SE facing roofs as well as significant obstructions were subtracted from the overall site area. The resulting area formed the baseline from which subsequent shading calculations were based. The shading calculations involved simulating shadows for a particular time on a specific date using the 3D model orientated to plan view. A 2D graphic representation was then exported to software where the portion of the site available for PV that was shaded was measured. This was repeated at hourly intervals over a period of 7 hours to get a daily shadow co-efficient. This was calculated by dividing the total area shaded over a 7 hour period, by the total site area available for PV multiplied by 7. This process was repeated for each case study building at weekly intervals over a period of 28 weeks (6 months). These calculations have been tabulated in two separate 3 month periods for each building. Results from simulations and substantiations on sub-question 1 are presented in Chapter 6. Graphic results from simulations can be found in Appendix 3 (see page x)

Sub question 2

In order to substantiate on the effect of FAR on NZEB potential, a comparison of two commercial buildings of the same building use-type but of different FAR's in low and high density zones were required for which two office buildings were purposely selected based on the criteria that one office has a low FAR (>1.5) in an area that is zoned as such, whilst the other has a high FAR (4>) in a high density zone (FAR 8). Electricity bills for a 1 year period and architects-drawings were the secondary data sources. A building inspection allowed for the identification of building system types such as HVAC, lighting and lifts as well as user activities that may influence energy consumption as well as operating schedules. Population density was simulated to maximum levels as laid out in the SANS regulations. These data allowed for each building to be modelled in its baseline condition to which subsequent reductions in energy consumption were referenced. Simulations and substantiation on sub-question 2 are presented in Chapter 4.

Sub-question 3

The effect of building use-types (which influences occupancy density and operation times) on NZEB potential is investigated by sampling a further 2 buildings from commercial building sub-sectors, namely: Hotels and Place of instruction. These were selected on the basis of variation in operation schedules, occupancy density, use, and efficiency targets. Different building classes also have varying energy performance benchmarks and regulations as in SANS 10 400-XA and SANS 1544 (draft). Secondary quantitative data outlined in the previous paragraph were used to model buildings in their baseline condition to which subsequent simulations energy efficiency interventions were made. This allowed for an analysis of the influence of occupancy density/building use-type as well as the effect of FAR on NZEB retrofit potential using on-site PV. Simulations and substantiation on sub-question 3 are presented in Chapter 5.

3.8 Framework for implementing NZEB interventions

3.8.1 Overview

Dekay and Brown (2014) recommend that the process of achieving net zero energy building retrofits should follow a hierarchical method, where an integrated design approach would be applied starting at the site 'macro-level'. This first area of consideration relates to building layout, form, massing and orientation which would be designed to suit a particular site, location and climate in order to take advantage of the existing microclimatic conditions. In existing buildings, most of the 'macro-design' elements are already fixed, thus limiting cost-effective interventions related to site or site-level modifications.

The first step in the hierarchy of interventions was therefore to reduce a building's EUI by implementing passive design strategies aimed at improving user comfort and thermal performance with the least energy input. Passive design interventions in existing buildings focused on modifications of the building envelope. They can be implimented singularly or in bundles as it is often advantageous to combine interventions which maximise efficiency. Conversely, a modification may consist of a single intervention such as introducing solar shielding to reduce heat gains.

Subsequent to passive efficiency measures, building system optimisation of the electrical/ mechanical systems (HVAC, lighting, HWS) was undertaken. With annual energy consumption reduced, renewable energy technologies were integrated in order to test the generation potential, and the extent to which the building's optimised energy requirements could be met through on-site PV generation. Finally, a cost benefit analysis was conducted in order to calculate simple payback periods, based on discount rates, inflation adjusted electricity tariffs as well as degradation and maintenance costs. Results were analysed using the following framework:

- The extent to which current energy efficiency codes align /integrate with NZEB principles.
- The combination of passive and active design interventions necessary to achieve maximised, cost effective reductions in EUI.
- Percentage of overall energy usage achieved through retrofits of efficiency interventions in passive design and systems optimisation with a breakdown of savings.
- The extent to which PV (on-site) can meet the remainder of the building's energy requirements.
- Determining cost benefit analysis based on payback period calculations.
- Possible CO_2 emissions reductions achievable from the cost-effective interventions.

3.8.2 Baseline model

In order to create the required baseline model of an existing building for NZEB analysis, the existing buildings were replicated as accurately as possible, orientated correctly and assigned the appropriate operating schedule, occupancy density, user activity construction and material types and properties, lighting, HWS and cooling systems. Each model was built in a manner that when simulated, the annual electricity consumption was matched to that of the actual building based on the electrical bill accessed from the respective building owner.

Despite baseline models being simulated to reflect the exact annual metered consumption with 99% accuracy, monthly correlations between the simulated consumption and billed data are far harder to draw. This is because electricity data that is derived from utility meters/invoices contains estimated data which makes inaccuracies in monthly consumption and demand. By averaging out the consumption difference between estimated and metered readings it is possible to estimate monthly values. When comparing monthly data between simulated and metered consumption, the simulated results display a greater variation between the highest and lowest monthly consumption values. Known as a 'performance gap' (Rotimi et al 2017) the differences between simulated data and utility readings can have margins where the prediction of energy use on a monthly basis is satisfactory when the difference is within 5% for non-variable loads such as lighting and plug loads but that this can increase to 15-25% for the simulation of HVAC systems. (Rahman et al 2008)

3.8.3 Passive interventions

In order to test the percentage of the overall energy consumption and EUI that can be reduced, each baseline model was subjected to a combination of passive design and active system optimisation techniques. These design interventions are coded as passive or active. Passive interventions in existing buildings were implemented as modifications to the building envelope, considering that issues of orientation, form, massing and area to volume ratio become more difficult and expensive to implement in an existing building. In terms of Durban's bio-climatic chart analysis, the optimum passive design strategy for the particular climatic zone involves natural cross ventilation and the shading of exposed fenestration and thermal mass.

Due to a multitude of reasons such as noise and air pollution, users requiring cellular office space for rental purposes, as well as buildings being enclosed on three sides by adjacent buildings, cross ventilation was excluded as a suitable passive design technique primarily because performance could very easily be compromised. The primary passive design technique implemented across all the case study buildings was solar shielding of exposed fenestration which influences solar absorption, reflection and transmission.

3.8.4 Active interventions

Active interventions include assumed modifications made to mechanical and electrical systems such as HVAC and lighting systems, building management systems as well as energy efficient appliances that reduce plug loads. As HVAC and lighting are the largest energy consumers in commercial buildings, the systems were prioritised as the focus for active interventions towards performance optimisation. Lighting systems retrofits were simulated first due to the effect of internal heat gains being significantly lowered through the use of LED. Lower internal heat gains enabled HVAC systems to be subsequently optimised in line with the lowered cooling loads, which in turn enabled reductions in the size and capacity of the HVAC systems.

3.8.5 Specifying PV systems

The size of the PV system required to bring an optimised building to net zero, is conventionally calculated based on the highest monthly electricity consumption average. This is to ensure that the system will be able to cater for periods of peak demand. Grid tied systems ensure that excess generation capacity can be fed back into the grid. However, based on case studies reviewed as well as the buildings simulated in this study, it is evident that very few existing commercial buildings that are larger than one or two floors have enough space for the size of a PV system required to meet NZEB. Thus the available area for PV is in most instances, the defining driver/parameter for specifying PV. Once the available site area for PV has been defined a simple calculation based on solar panel specification data can be used to estimate what portion of the optimised load could be met by PV. Calculating the system size based on peak consumption is however a useful exercise to demonstrate differences in required versus available generation capacity.

Due to panels being orientated at 30 degrees, care had to be taken to ensure that shading of panels by other panels was mitigated. This was achieved by simulating shadows cast on the winter solstice at 3 pm, when the shading angle would be at its greatest due to the low solar altitude.

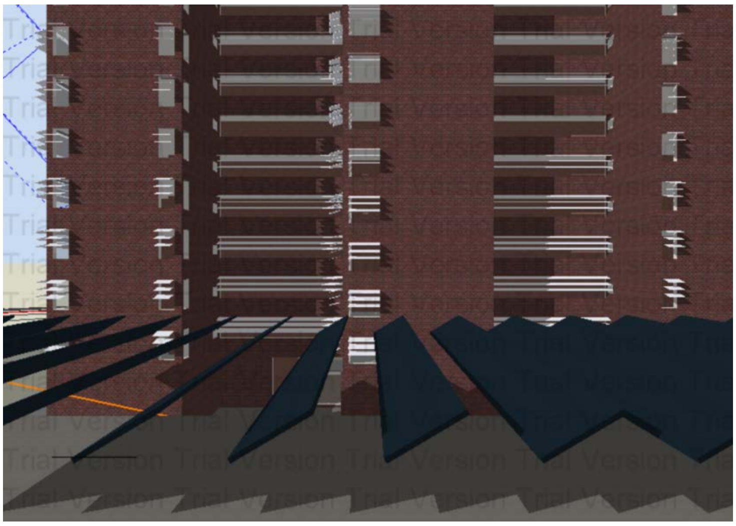


Figure 3.5: Shadowing of panels by other panels – winter solstice 3pm.

From the shadow test on the winter equinox (June 22) it was found that a 1 meter spacing between panels led to negligible shading of panels by panels and allowed for the maximum coverage and hence maximum generation potential. With as much of the available area for PV covered without shading, PV arrays were simulated so that the generation potential could be derived.

3.8.6 Cost and feasibility evaluation

A preliminary cost evaluation for each individual building intervention was used to guide the feasibility evaluation. This was necessary in order to ascertain whether the technical performance and related environmental benefits acquired through an intervention were viable under current cost/returns scenarios. This is based on the premise that it makes little sense to spend vast amounts of money if the benefits and returns do not adequately align with an acceptable payback period, which would vary amongst projects. According to Hay (2016) discounts rates for solar PV vary across projects but in general lower discount rates (0-4 percent) indicate greater risk tolerance while higher discount rates (4-12%) indicate the opposite. Based on this, a discount rate of 5% was applied to calculate the net present value (NPV) of the investment. This was calculated using the following formula: (PV= $\frac{FV}{(1+i^y}$) where Fv represents future value (After tariff increases) í = discount rate and y = the number of years. (Investopedia 2018)

The discounted payback period model was used to derive the time period within which interventions would 'break even' with the initial capital expenditure, such that a shorter payback period is preferable compared to a longer period. Along with the discount rate, an electricity tariff increase of 8% per year was assumed, as well as maintenance costs, which were factored into the calculations. According to du Plessis (2017) solar PV systems in South Africa have the potential to pay themselves off within a five year period, while Sewchurran et al (2016) estimate a payback period of closer to 7 years for residential PV, depending on the quality of the installation and its maintenance. However, this does not take into account the effect of shading, which can have a dramatic effect on the generation potential, which in-turn can increase payback periods. However, South African companies are now entitled to a tax incentive that allows deductions of the cost of RE systems and equipment for up to three years after installation (ibid 2017). This allowance is defined in section B of the amended income Tax Act No. 58 of 1962 which "provides for a capital allowance for moveable assets used in the production of renewable energy. More specifically, it allows for a deduction on a 50/30/20 basis over three years in respect of any machinery, plant, implement utensil or article (referred to as a qualifying asset) owned by the taxpayer" (Steenkamp 2016: 1) The Act essentially allows for the full cost of the PV system to be recovered in the first three years of operation (provided that the property is operating at a profit, which is discussed further in Section 3. 7.7). Thus electricity generated after year three can be used to offset longer payback periods of EE interventions. This was the approach that was applied to the case-study building simulations presented in Chapter 4 and 5. Initially, the payback period for EE and PV interventions were calculated without applying the allowance, to ascertain a baseline payback period from which savings through the tax allowance could be calculated. After applying the tax allowance to the PV installations, subsequent savings and revenue from generation from year four onwards, were used to effectively pay-off EE interventions, which are not included in the 12B allowance. The effect of the tax adjustments are reflected in Chapters 4 and 5 in the consolidation of simulation results (Sections 4.5.3 and 5.4.3) and again in chapter 7.

Cost estimates for the various NZEB interventions were based on 'rough order of magnitude' estimates, which is an estimation technique that is commonly used in the early phases of a project appraisal and which can based on a per m² basis. (Manfredonia 2016)Even though Design Builder's software includes a cost estimate of building systems and architectural elements per m², the estimates were cross referenced with product specific estimates obtained from online searches and through conversations with local consultants in order to ensure that estimations by the software were in alignment with prevailing local practices. A local HVAC company, CoolAir, provided rough estimates for HVAC systems, whilst Solar Beam and Mustek provided approximations of lighting and PV costs. The eThekwini municipality has developed an online solar PV calculator specifically for Durban, which was used to verify budgetary rough order magnitude estimates for PV. (eThekwini Municipal Solar Map Viewer)

3.8.7 CO_2 emission reductions

CO_2 emission reductions were simulated using a grid emission factor of 0.7 $kgCO_2/kWh$, which was the simulation software's suggested default value for the region. This indicates that for every 1000 kWh of grid electricity consumed, emissions would be 700 $kgCO_2$ (Spalding-Fecher 2011). However, SA's grid emission factor has been estimated to be as high as 0.95$kgCO_2/kWh$ (ibid) and 1.0 $kgCO_2/kWh$ (Brander et al 2011). Despite variations in estimated emission factors, the percentage reduction in CO_2 emissions remains consistent and hence valid to this study.

3.8.8 Limitations of the study

Due to the estimation billing method employed by the eThekwini municipality, whereby monthly consumption periods of up to six months are estimated before a meter reading is taken, actual monthly estimations do not accurately reflect real-time monthly consumption figures. Although this does not impact the study significantly as the overall annual consumption figure is what was used to simulate baseline consumption, it does explain for the disparity between actual and simulated annual consumption figures. Given that the case study buildings do not have separate metering for their various loads, the proportions of overall electricity consumed by each system are estimated through system values within the building performance software data-base.

'Rough order of magnitude' estimates are used in the early phases of project-costing and are not as accurate as detailed costing assessments. To mitigate discrepancies in cost analysis, all the interventions were applied using the same costing mechanism and rates. It is also not possible to determine the exact composition and original materials used in the building envelope in the absence of detailed annotated construction drawings, which were not available to the researcher within a reasonable time for the study. Limitations on cross-ventilation were taken as a given rather than simulating for its feasibility and using that to motivate the case.

It is also important to note that the '12B' RE tax allowance (described in Section 3.7.6) will only be effective for firms/businesses in which the overall profitability of the property is net-positive. Properties operating at a net- loss would not have tax-liability, thus negating deductions under the allowance. In the context of this study, the purposely selected properties have been assumed to be operating at a net-profit, thus qualifying them for deductions under the 12B tax allowance for RE equipment. It is also expected that prevailing prices (especially for PV) versus the rapidly declining market prices could change feasibility in the next 5 to 10 years (most likely in a positive direction). The risk of changing urban form in a manner that undermines solar access and possible loss of suitable area for PV installation constitutes further limitations of the study.

3.9 Summary of research methods

The research table presents a summary of each sub-question of the study, the data needed for that aspect of the study, tools needed for the data collection as well as the data analysis methods which allow in turn for derivation of sub-findings for sub-questions which are then systematically synthesised towards resolution of the main research question.

<table>
<tr><th colspan="2">Research sub-question 1: Substantiated upon in chapter 4</th></tr>
<tr><td colspan="2">What is the effect of urban density and zoning regulations on solar resource on specific sites and stands and how can insights gained guide subsequent densification regulations and development rights?</td></tr>
<tr><td>Primary data collected :
• GIS data relating to property plot sizes. Zoning regulation data were obtained from the eThekwini GIS database.
• 3D google earth data of the building and its surrounding urban fabric.
• Available site area for the installation of PV.

Secondary data collected :
• Journals, academic reports.

Data collection tools:
• Collection of data required the use of a series of software. DX-Ripper was used to capture 3D GIS data from Google Earth Pro. This was then converted in 3D Studio Max to a format that could be imported into Google Sketch-up, which was used to simulate the final shadow study. Archicad was used to measure the shadow areas.</td>
<td>Data analysis and coding:

Each site was simulated for shadows over a period of 28 weeks (6 months).
Obstructions and South facing roofs were excluded from the available site area.
The available site area for PV installation was used as the baseline area (m^2)

Each site was orientated and geo-located.
The first day was simulated for shadows, starting at 9am
Shadows cast at this hour were measured in m^2
The time was changed to 10 am and re-simulated with shadows cast on available site area measured in m^2
This was repeated on the hour over the day until 3pm.
A series of 7 plans with varying degrees of shadowing thus formed 1 day analysis
The area of shadows for each hour was measured in m^2
The total site area available for PV was multiplied by 7 hours to represent the 7 hours that were simulated.
The shading on available roof area obtained from each simulation for each hour were added together.
This total was divided by the site area for PV to attain a metric percentage of site shading over the period of that day.
This process was repeated at weekly intervals over a period of 6 months and used to calculate the overall percentage metric of site shading.</td></tr>
</table>

<table>
<tr><th colspan="2">Research sub-question 2: Substantiated upon in chapter 5</th></tr>
<tr><th colspan="2">What is the significance of building FAR on EUI and NZEB potential?</th></tr>
<tr><td>Primary data collected :

• Basic building audit including inspection of 2 office premises for the purpose of identifying electrical services such as lighting systems, HVAC, appliance usage, elevators.
• Basic building audit including inspection of premises for the purpose of identifying site conditions, operating schedules, internal spaces, building fabric including materials and parking.
Secondary data collected :

• Building drawings and 12 months electricity bills.
• SANS maximum energy consumption data, journals, academic reports.

Data collection tools:

• Site inspection and discussions with building representatives, photographs and notes were taken.</td><td>Data analysis and coding :

Data were coded by combining a thematic and descriptive approach as presented in Chapter 5.

Field notes and photographs were referenced against available building drawings (which were limited to basic plans, sections and elevations) and actual annual energy consumption figures to simulate a 3D baseline energy model.

Models were simulated with an identical series of NZEB retrofits. Results from these simulations were used to cast metric savings in terms electricity consumption and CO_2 reductions.

These data were used to calculate a simple payback period based on prevailing cost estimates for EE and RE technology, a discount rate of 5% to attain NPV, and electricity tariff starting at 2017 rates with an 8% inflation adjustment per annum.</td></tr>
</table>

<table>
<tr><th colspan="2">Research sub-question 3: Substantiated upon in chapter 6</th></tr>
<tr><th colspan="2">What is the significance of occupancy density and building use-type on EUI and NZEB potential?</th></tr>
<tr><td>Primary data collected :

• Basic building audit including inspection of 2 premises, one being a hotel and the other a college, for the purpose of identifying electrical services such as lighting systems, HVAC, appliance usage, elevators.
• Basic building audit including inspection of premises for the purpose of identifying site conditions, operating schedules, internal spaces, building fabric including materials and parking.
• Building drawings and 12 months electricity bills.

Secondary data collected :

• SANS maximum energy consumption data, journals, academic reports.

Data collection tools:

• Site inspection and discussions with building representatives, photographs and notes were taken.</td><td>Data analysis and coding:

Data was coded by combining a thematic and descriptive approach and can be found in Chapter 6.

Field notes and photographs were referenced against building drawings and actual annual energy consumption figures to simulate a 3D baseline energy model.

Models were simulated with an identical series of NZEB retrofits. Results from these simulations were used to cast metric savings in terms electricity consumption and CO_2 reductions.

These data were used to calculate a simple payback period based on prevailing cost estimates for EE and RE technology, a discount rate of 5% to attain NPV, and electricity tariff’s starting at 2017 rates with an 8% inflation adjustment per annum.</td></tr>
</table>

Overall research question : Substantiated in Chapter 7
What are the contextual and technical parameters that would influence performance optimisation outcomes of NZEB retrofits for existing commercial buildings based on EE and on-site PV generation interventions?
The resolution to the overall research question follows on the consolidation of sub-findings on the sub-questions in order to substantiate on overall findings and provide recommendations for future studies.

Chapter 4: The effect of urban density on NZEB (site-PV) potential

RE generation within the site boundary uses the full site grounds for generation which is typically observed to include the utilisation of outdoor space within the site (such as PV installations on parking structures) for such generation. The method for calculating site shading has been outlined in Chapter 3. The calculations for each specific site and stand are presented in Appendix 2 (see pages 139 to 146). The summary of the shading calculations and derivation of annual shading percentage for a period of 6 months for each site have been tabulated below (calculations have been split into two, 3 month periods)

4.1 Shadow study 1: Building A. Low density zoning > 1.5 FAR; coverage = 50% Overall site shading = 6%

Date/time	9am	10am	11am	12pm	13pm	14pm	15pm	Total/m²
Total Available Space on site for pv (m²)								198 940
22-Jun	620	160	40	40	40	220	750	1870
29-Jun	600	100	35	50	40	200	740	1765
05-Jul	580	200	95	35	35	180	710	1835
12-Jul	550	180	50	35	50	140	650	1655
19-Jul	510	170	90	30	30	120	590	1540
26-Jul	480	150	35	30	23	110	550	1378
02-Aug	450	120	34	31	50	90	470	1245
09-Aug	430	110	33	31	30	70	430	1134
16-Aug	400	100	30	28	0	40	400	998
23-Aug	380	90	0	0	0	30	380	880
30-Aug	370	80	0	0	0	0	360	810
07-Sep	350	80	0	0	0	0	350	780
14-Sep	310	70	0	0	0	0	320	700
21-Sep	280	70	0	0	0	0	310	660
Total area (m²) of available site for pv that is shaded								17250
% of available site area for pv that is shaded								9%

Table 4.1: Results of daily shadowing measured in (m²) at weekly intervals from 22 June to 21 September indicates an 8% shadowing of available area for PV.

Date/time	9am	10am	11am	12pm	13pm	14pm	15pm	Total/m²
Total Available Space on site for pv (m²)								184 730
28-Sep	260	85	0	0	0	0	400	745
05 Oct	250	50	0	0	0	0	310	610
12-Oct	240	80	0	0	0	0	300	620
19-Oct	230	80	0	0	0	90	270	670
26-Oct	230	110	0	0	0	60	180	580
02-Nov	180	100	0	0	0	40	200	520
09-Nov	210	85	0	0	0	70	220	585
16-Nov	210	75	0	0	0	70	235	590
23-Nov	210	90	0	0	0	0	155	455
30-Nov	250	70	0	0	0	0	140	460
07-Dec	200	95	0	0	0	0	135	430
14-Dec	200	90	0	0	0	0	115	405
21-Dec	200	90	0	0	0	0	140	430
Total area (m²) of available site for pv that is shaded								7100
% of available site area for pv that is shaded								4%

Table 4.2: Results of daily shadowing measured in (m²) at weekly intervals from 28 September to 21 December indicates a 3.8% shadowing of available area for PV.

4.2 Shadow study 2 – Building B. High density zoning 4 > 8 FAR; coverage =100%
Overall site shading = 27%

Date/time	9am	10am	11am	12pm	13pm	14pm	15pm	Total/m²
Total available site area for PV in m²								93100
22-Jun	515	403	80	125	455	624	795	2997
29-Jun	544	386	68	113	452	620	770	2953
05-Jul	507	445	172	117	430	608	803	3082
12-Jul	464	352	85	105	430	590	790	2816
19-Jul	453	268	93	72	572	400	783	2641
26-Jul	437	200	65	95	384	584	814	2579
02-Aug	397	114	60	90	376	594	821	2452
09-Aug	386	56	54	85	348	557	751	2237
16-Aug	290	51	52	78	330	550	742	2093
23-Aug	222	48	64	54	320	540	700	1948
30-Aug	163	50	54	70	328	523	678	1866
07-Sep	90	20	20	30	500	300	649	1609
14-Sep	40	25	20	20	330	500	615	1550
21-Sep	25	15	15	20	335	485	600	1495
Total available site area for PV that is shaded in m²								32316
% of available site area for pv shaded								35%

Table 4.3: Results of daily shadowing measured in (m²) at weekly intervals from 22 June to 21 September indicates a 35% shadowing of available area for PV.

Date/time	9am	10am	11am	12pm	13pm	14pm	15pm	Total/m²
Total Available Space on site for pv (m²)								86 450
28-Sep	20	20	0	0	320	490	560	1410
05 Oct	20	20	0	0	320	450	560	1370
12-Oct	20	0	0	0	330	440	530	1320
19-Oct	0	0	0	0	330	440	530	1300
26-Oct	0	0	0	0	320	450	500	1270
02-Nov	0	0	0	0	330	440	480	1250
09-Nov	0	0	0	0	320	430	460	1210
16-Nov	0	0	0	0	310	420	450	1180
23-Nov	0	0	0	0	290	400	430	1120
30-Nov	0	0	0	0	280	410	410	1100
07-Dec	0	0	0	0	260	400	410	1070
14-Dec	0	0	0	0	250	410	390	1050
21-Dec	0	0	0	0	230	390	390	1010
Total area (m²) of available site for pv that is shaded								15660
% of available site area for pv that is shaded								18%

Table 4.4: Results of daily shadowing measured in (m²) at weekly intervals from 28 September to 21 December indicates a 18% shadowing of available area for PV.

4.3 Shadow study 3 – Building C. High density zoning 4>8 FAR. Coverage 42%
Overall site shading = 37%

Date/time	9am	10am	11am	12pm	13pm	14pm	15pm	Total/m²
Total available site area for PV in m²								**117600**
22-Dec	350	290	190	0	25	130	230	1215
29-Dec	370	385	195	0	40	120	400	1510
05-Jan	400	400	220	0	40	115	400	1575
12-Jan	420	390	220	20	30	115	370	1565
19-Jan	450	410	260	40	50	130	390	1730
26-Jan	450	430	280	75	40	140	390	1805
02-Feb	450	450	280	90	45	140	440	1895
09-Feb	460	450	300	100	60	175	420	1965
16-Feb	500	470	320	140	70	200	470	2170
23-Feb	500	480	330	140	100	215	500	2265
02-Mar	550	490	350	120	160	240	540	2450
09-Mar	580	390	165	130	280	575	500	2620
16-Mar	550	530	390	180	150	300	580	2680
23-Mar	530	490	400	220	190	360	550	2740
Total available site area for PV that is shaded								**28185**
% of available site area for PV that is shaded								**24%**

Table 4.5: Results of daily shadowing measured in (m²) at weekly intervals from 22 December to 23 March indicates a 24% shadowing of available area for PV.

Date/time	9am	10am	11am	12pm	13pm	14pm	15pm	Total/m²
Total Available Space on site for pv (m²)								**109 200**
					1200M2			
30-Mar	570	520	440	200	180	360	580	2850
06-Apr	580	540	450	200	180	370	590	2910
13-Apr	600	560	460	220	200	380	600	3020
20-Apr	660	610	500	230	220	400	640	3260
27-Apr	720	650	520	250	240	480	700	3560
04-May	780	680	580	280	270	540	730	3860
11-May	810	740	650	330	300	570	760	4160
18-May	870	760	700	400	360	610	790	4490
25-May	900	810	740	480	440	640	820	4830
01-Jun	930	860	800	560	500	680	850	5180
08-Jun	990	910	860	590	580	700	880	5510
15-Jun	1040	960	900	640	630	720	910	5800
22-Jun	1080	1030	950	710	680	800	920	6170
Total area (m²) of available site for pv that is shaded								55600
% of available site area for pv that is shaded								**50%**

Table 4.6: Results of daily shadowing measured in (m²) at weekly intervals from 30 March to 22 June indicates a 50% shadowing of available area for PV.

4.4 Shadow Study 4 – Building D. Medium density zoning 1.5>4 FAR coverage 36%
Overall site shading = 6%

Date/time	9am	10am	11am	12pm	13pm	14pm	15pm	Total/m²
Total Available Space on site for pv (m²)						**1785**		**173 210**
22-Jun	560	400	110	50	0	20	60	1200
29-Jun	550	420	140	50	0	20	60	1240
05-Jul	540	410	120	40	20	20	60	1210
12-Jul	520	380	110	30	20	20	60	1140
19-Jul	500	350	110	30	20	20	60	1090
26-Jul	480	320	20	0	0	0	50	870
02-Aug	480	300	50	0	0	0	40	870
09-Aug	450	280	40	0	0	0	40	810
16-Aug	440	250	40	0	0	0	40	770
23-Aug	430	230	30	0	0	0	40	730
30-Aug	420	210	20	0	0	0	30	680
07-Sep	420	200	20	0	0	0	30	670
14-Sep	430	180	0	0	0	0	30	640
21-Sep	430	170	0	0	0	0	30	630
Total area (m²) of available site for pv that is shaded								12550
% of available site area for pv that is shaded								**7%**

Table 4.7: Results of daily shadowing measured in (m²) at weekly intervals from 22 June to 21 September indicates a 7% shadowing of available area for PV.

Date/time	9am	10am	11am	12pm	13pm	14pm	15pm	Total/m2
Total available site area for PV in m²								**175 000**
23-Sep	430	175	0	0	0	15	30	650
30-Sep	410	160	0	0	0	15	30	615
07-Oct	400	145	0	0	0	5	30	580
14-Oct	400	145	0	0	0	5	30	580
21-Oct	380	105	0	0	0	5	25	515
28-Oct	360	100	0	0	0	5	20	485
04-Nov	345	90	0	0	0	5	20	460
11-Nov	335	85	0	0	0	5	25	450
18-Nov	325	80	0	0	0	5	20	430
25-Nov	330	85	0	0	0	5	20	440
02-Dec	330	80	0	0	0	0	20	430
09-Dec	350	80	0	0	0	0	20	450
16-Dec	350	80	0	0	0	0	15	445
23-Dec	365	90	0	0	0	0	20	475
Total available site area for PV that is shaded in m²								**7005**
% of available site area for PV that is shaded								**4%**

Table 4.8: Results of daily shadowing measured in (m²) at weekly intervals from 23 September to 23 December indicates a 4% shadowing of available area for PV.

4.5 Summary of sub-findings

The four sample buildings have been analysed to assess the effect of urban density on PV generation and in-turn, NZEB potential. Despite shading being recognised as having an effect on lighting levels and EUI, particularly in warm climates, the simulated case study buildings are limited in their ability to determine the effect of shading from surrounding buildings on heat gains, internal lighting levels and EUI. The case study sites have been analysed in terms of low, medium and high density (FAR) and site coverage in relation to shading experienced on surfaces that are suitable for PV.

Low density zoned Building A experienced 6% site shading over the simulated period of 6 months from 22 June to 21 December. The low percentage of shading can be attributed to the low rise nature of the surrounding urban fabric. Building B which is located in high density CBD was simulated for shadows over the same period and was found to experience 27% annual site shading. Building C is also located in the CBD and experiences approximately 37% site shading. Medium density hotel building D experiences 6% annual shading.

From the results it can be seen that high density urban environments cause an increase in overall site shading. It is speculated that the difference of 10% in shading between the two buildings in the CBD can partially be attributed to the difference in site coverage, where building B with lower shading, has 100% site coverage, thus offsetting any shading caused by the building itself. Building C has a much lower site coverage of 42%, which is suspected to increase the shading factor of the building itself on the remainder of the site footprint, which is suitable for PV installation.

Building A and D, both experience far lower shading, despite building D being located in medium density zoning. Building A has 50% site coverage whilst building D has a 36% coverage. In this comparison, it is less clear what effect coverage has on shading, although it is suspected that lower coverage in the medium density zones has the effect of reducing on-site shading from surrounding buildings.

It can be concluded that high density urban environments increases the incidence of shading on site and thus reduces roof area available for PV. Given the focus of this study on the impact of various factors on NZEB using on-site PV generation, increased shading amounts to decreased generation potential. The decrease is assumed to be by the same factor as the proportion of shading the site experiences. At medium and low density, the impact of surrounding buildings on shading is less significant. Although PV potential is improved, buildings that receive more direct solar radiation will inevitably have increased heat gains through the building fabric.

Chapter 5: The effect of FAR on NZEB potential

In order to substantiate the effect of FAR on NZEB potential, two office buildings with varying FAR's were modelled to reflect actual baseline conditions as closely as possible. The buildings were then simulated with passive design interventions and active building system optimisations in order to reduce energy consumption before simulating for on-site PV generation.

5.1 Baseline conditions –Building A (Offices)

Figure 5.1: Aerial photograph showing urban context and location of building A. (Google maps)

Office building A is a five storey office-building situated in a predominantly residential zoned suburb of Durban and has a maximum bulk zoning regulation of a floor area ratio of 1.5 (FAR 1.5). The building has a net floor area of 3 980 m², with key uses such as banking and retail on the ground floor, a parking garage on the first floor and offices on floors two, three and four. Walls of the masonry structure are predominantly 220 mm clay brick and are simulated at a thermal resistance (R-value) of 0.5 m²·K/W. Standard tinted glass and aluminium frames have been simulated with a total solar transmission co-efficient (SHGC) of 0.427 and U-value of 6.066 K.m²/W. Slabs (including roof-slab) and columns are cast from reinforced concrete and thus entail significant thermal-mass effect.

The occupancy density was simulated at SANS standards of 1 person per 15 m² for the office component of building A. The ground floor occupancy density was specified for retail as per

SANS 204 at 1 person per 10m². The building operation time was simulated at 5 days a week from 7am to 6pm. The initial baseline simulation indicates that the major electricity consuming systems are the HVAC, lighting, plug loads and process loads which mainly entail the electricity consumed by the two lifts. The analysis of utility bills reveals that the building consumes in the region 859 344kWh of electricity per year, which forms the baseline figure from which subsequent reductions in energy consumption have been calculated.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
kWh	82 520	81 494	75 330	72 490	68 490	65 140	61 280	64 270	68 820	70 430	72 040	77 040	859 344

Table 5.1: Monthly electricity consumption for building A. (Source: Adapted from actual monthly electricity bills)

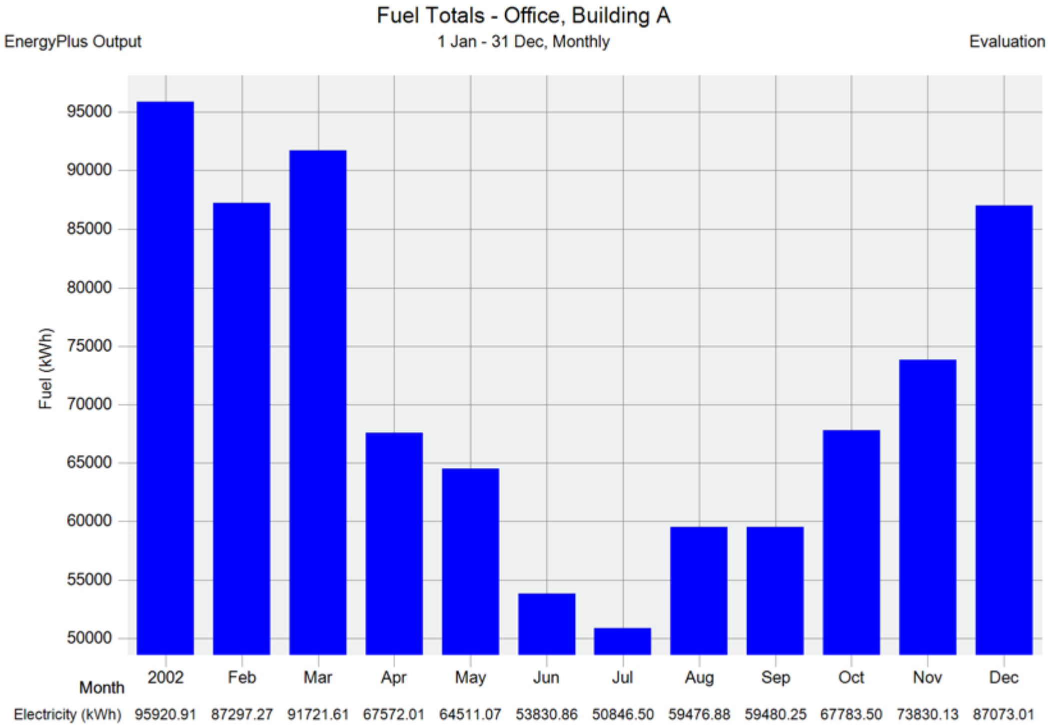


Figure 5.2: Simulated monthly electricity consumption.

Despite the simulated baseline model reflecting the exact annual metered consumption at 99% accuracy, monthly correlations between the simulated consumption and billed data are far harder to draw. This is because electricity data derived from utility bills/invoices contains estimated data which makes inaccuracies in monthly consumption and demand. By averaging out the consumption difference between estimated and metered readings it is possible to estimate monthly values. When comparing monthly data between simulated and metered consumption, the simulated results display a greater variation between the highest and lowest monthly consumption values. In building A, simulated annual peak demand, which occurs in January, is approximately 15% higher than billed data for the same period. Similarly, the lowest consumption simulated occurs in July and is approximately 15% lower than billed data averages for the same period. It is suspected that the majority of this 'performance gap' can be attributed to the cooling and ventilation. This can be attributed to the influence of weather on the HVAC system, as occupancy density, operating times and lighting remain constant. Rahman et al (2008) citing Kaplan (1992) suggest that the prediction of energy use on a monthly basis is satisfactory when the difference is within 5% for non-variable loads such as lighting and plug loads but that this can increase to 15-25% for the simulation of HVAC systems.

Annual simulated electricity breakdown by building system within Durban's climatic conditions shows HVAC as the largest consumer at 40% followed by plug and lighting loads at 35%. Despite the performance gap experienced in monthly data which is attributed to HVAC, on an annual basis, the higher summer consumption balances the lower winter consumption value.

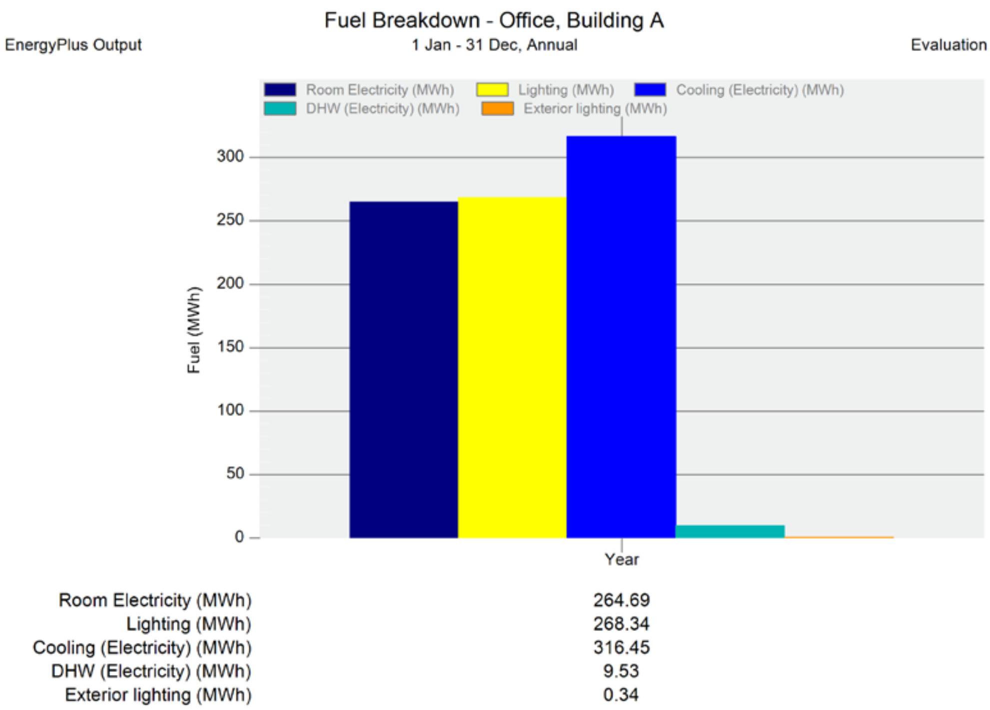


Figure 5.3: Annual electricity consumption by building system (plug loads and lift motors are represented under 'room electricity').

5.2 NZEB interventions - Building A

5.2.1 Passive interventions

Passive design strategies for a warm humid zone such as Durban are predominantly solar shading and natural cross ventilation. Due to the relatively deep plan concept and conventional cellular layout of the floor plans (which is in response to the lessee's requirements), the opportunity for natural cross ventilation was severely constrained.

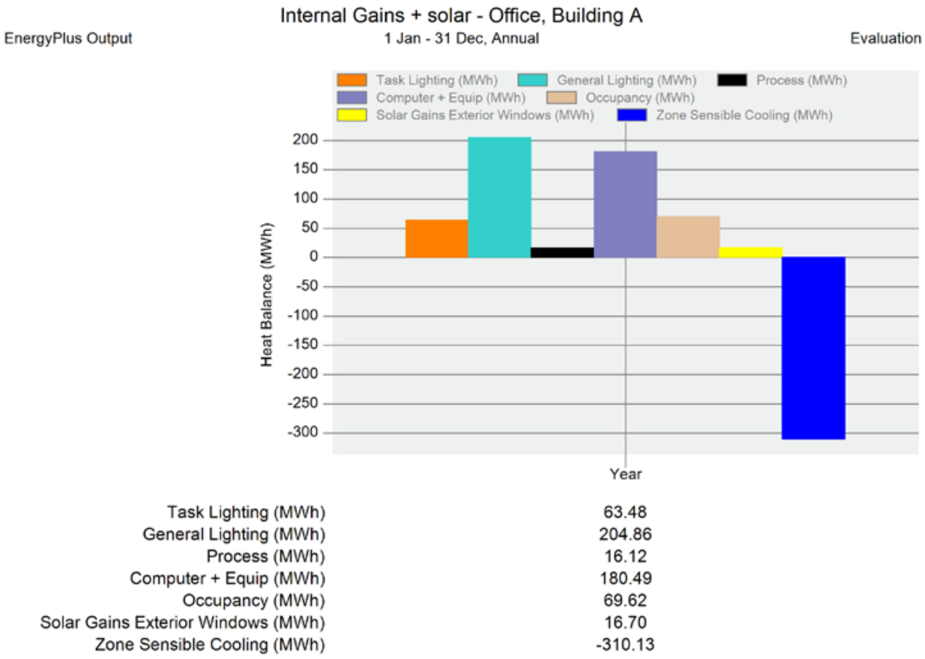


Figure 5.4: Baseline breakdown of internal gains.

As reflected in Figure 5.4 lighting and office equipment contribute the highest proportions of internal gains. Even though solar gains through fenestration are responsible for only a small portion of the overall internal gains, solar shading of north facing fenestration from summer sun was the first passive intervention tested for the building. Aluminium solar shielding was introduced to north, west and east facing fenestration with the intention of reducing solar gains and unwanted heating of internal thermal mass. Annual solar gains decreased from 16 698 kWh/yr to 14 235 kWh/yr. This reflects a total reduction of 2 463 kWh/yr, which led to a decrease of 11 460 kWh in the cooling load, which is in turn reflected in the net reduction in annual electricity-consumption.

A payback period for solar shielding was calculated using a rough order of magnitude estimate of R900 per m² of glazing. A total of 180 m² fenestration was shielded at a capital cost of R162 000, with professional fees and installation adding a further 10%. The estimated capital cost was R 180 000 and the derived payback period was 8 years, the benefit of a 1.3% reduction in annual electricity consumption was therefore deemed to be unviable at this stage.

	Savings per year kWh			8% tariff increase		NPV (5%)	
						Discount rate	
year 1		11 460		1.5728	18 024	18 024	
year 2		11 460		1.6986	19 466	17 656	
year 3		11 460		1.8345	21 023	18 160	
year 4		11 460		1.9812	22 705	18 679	
year 5		11 460		2.1397	24 521	19 213	
year 6		11 460		2.3109	26 483	19 762	
year 7		11 460		2.4951	28 594	20 321	
year 8		11 460		2.6947	30 881	20 901	
					191 697	152 716	

Table 5.2: Payback period for solar louvers is just over 8 years.

5.2.2 Active interventions

Lighting

Inspection of the premises revealed a combination of T5 and T8 florescent lighting tubes. When simulated, they contribute the largest proportion of the building's 268 304 kWh/yr baseline lighting consumption (see Fig 4.2) After retrofitting these with energy efficient LEDs, electrical consumption for lighting was reduced by 125 048 kWh to 143 256 kWh which is 15% of overall consumption.

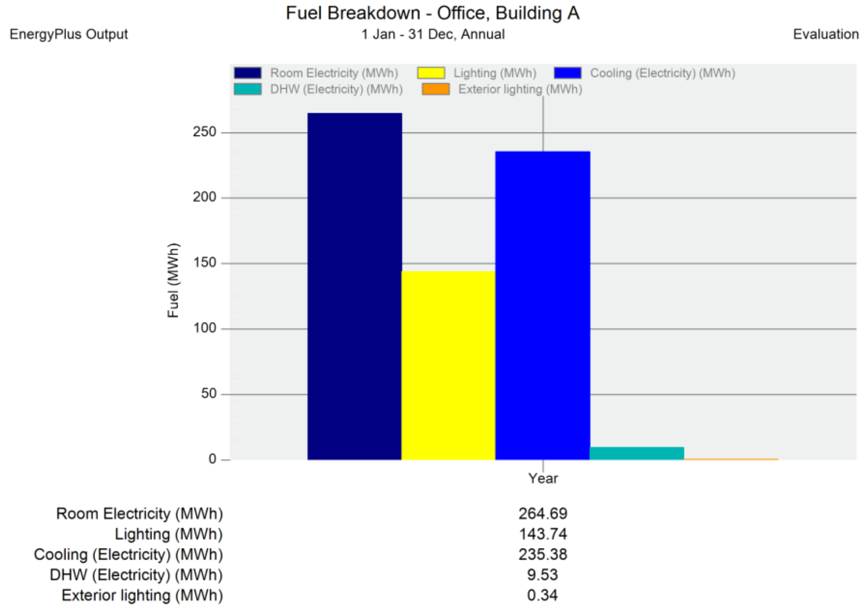


Figure 5.5: Reduction in lighting and HVAC consumption as a result of retrofitting fluorescent lighting with LED.

Internal heat gains were also decreased by retrofitting with energy efficient LED. Normalised power density decreases from 4.4 W/m² to 2.5W/m² which led internal heat gains from lighting to decrease from 208 485 kWh to 115 916 kWh/yr. This led to further reductions in zone sensible cooling load which was reduced by 101 647 kWh.

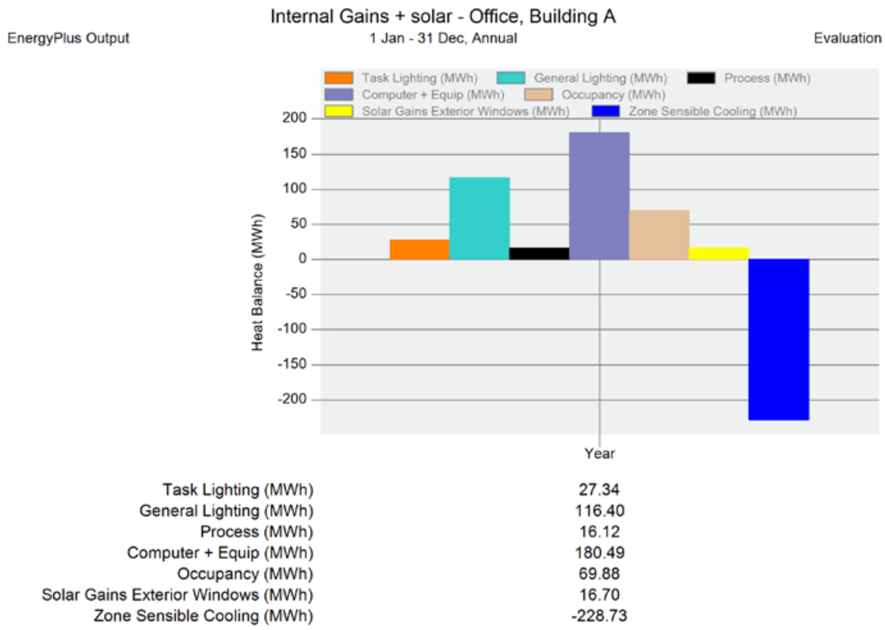


Figure 5.6: Reduction of cooling loads and heat gains due to general lighting replacement with LED.

The effect of retrofitting a smart LED lighting system led to overall annual electricity consumption being reduced from 859 344 kWh/yr to 652 958 kWh/yr which translates to a 24% reduction. Due to extremely high light density of building A, LED retrofitting has an estimated cost of R 900 000 based on a budgetary order of magnitude estimation of R225/m² with a 10% installation cost which yields an overall cost of R990 000. A discount rate of 5% and an 8% electricity tariff increase were used to calculate the payback period.

	Savings / yr(kWh)	8% tariff increase	savings ZAR	NPV (5%) discount rate
year 1	206 386	1.5728	324 604	324 604
year2	206 386	1.6986	350 567	302 833
year3	206 386	1.8345	378 615	327 062
year 4	206 386	1.9812	408 892	336 396
				1 290 895

Table 5.3: Calculations for LED lighting replacement at a 3.2 year payback period.

HVAC

Building A uses a centralised constant air volume (CAV) HVAC system with water cooling, which employs a simple on-off switch. This negates the principle of differentiated zone control requirements especially prioritised by user-needs. The system is controlled by an on-off switch and runs from 7am to 6pm at a constant set temperature at 24ºC. For simulation purposes, this was modified and replaced by a VAV closed loop system which incorporates a small building management system, thus allowing for autonomous control of each compressor station (on each floor) in order to provide for more control according to the various needs and therefore for a more efficient system. The new HVAC system reduced the overall simulated HVAC consumption from 316 445 kWh/yr to 161 760 kWh thus yielding a saving of 154 685 kWh/yr which amounts to 18 % of the total annual electricity consumption.

The capital cost based on a rough order of budgetary magnitude of R300/m² with 10% installation and professional fees is roughly R1.3 million. A simple payback period calculation based on an 8% tariff increase and a 5% discount rate reveals that the system will pay itself off in the 6th year of operation.

	Saving/yr (kWh)		tariff +8%pa		NPV (5%)		
year 1		154 685	1.5728	243 289	243 289		
year2		154 685	1.6986	262 748	238 320		
year3		154 685	1.8345	283 770	245 131		
year 4		154 685	1.9812	306 462	252 127		
year 5		154 685	2.1397	330 979	259 331		
year6		154 685	2.3109	357 462	266 744		
					1 504 942		

Table 5.4: HVAC replacement showing 5.4 year payback period.

5.2.3 PV grid tie proposal

Baseline yearly electricity consumption was reduced by 33 % from 859 344 kWh to 579 573 kWh/yr through the retrofitting of lighting and HVAC systems. A PV array on the available site area was simulated to test how close the building could get towards achieving net zero energy balance. This was pursued through the following process (as outlined in the methods section in chapter 3 (see Section 3.7.5)

Based on PV specification product data, a 250W mono-crystalline panel has a 1.6 m² surface area which indicates 6.4 m² is required to generate 1 kWp. The available area on the rooftop and the ground level car park, the building's total available space for PV is 1 790 m². However, when designing the system, the spacing required to ensure panels do not shade one another makes it unviable to cover the full area.

At this point the building energy model was used to simulate the following PV system using the full extent of site area available:

Peak power: 174 kWp

Number of modules: 696 - 250 W monocrystalline panel

Total area of array: 1 114 m²

Electricity generation potential: 212 870 kWh/yr

Angle to the horizontal: 30º

Figure 5.7: Axonometric of building model showing PV array.

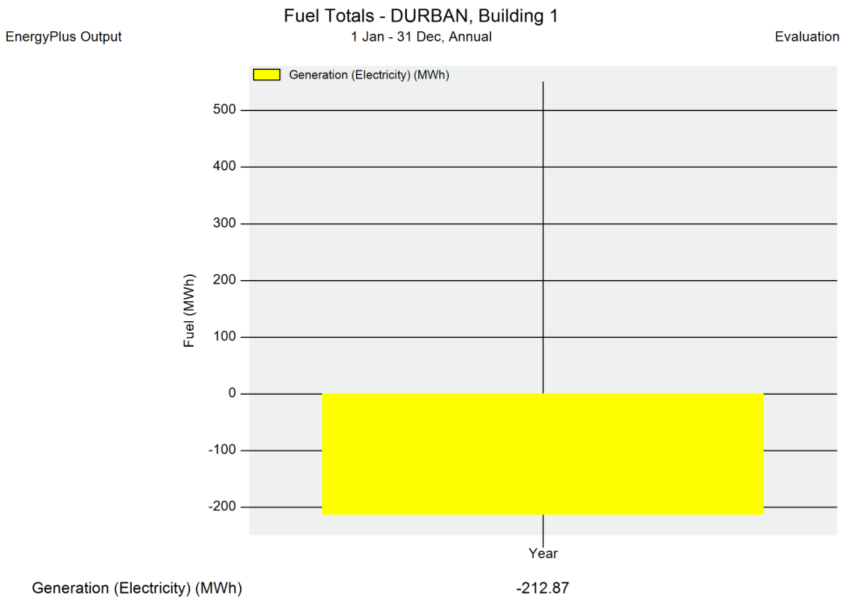


Figure 5.8: Simulated on-site electricity generated - kWh.

The total electricity generated by the array, was simulated at 212 870 kWh/yr. This is however without any form of shading from surrounding buildings. From a solar shadow study carried out on the specific site it was found that building A experiences approximately 6% annual shading on surfaces that are suitable for PV installation which is accounted for as a 6% loss in annual generation capacity bringing annual generation to approximately 200 00 kWh.

Consumption-export balance

During a regular weekday when office building A is operating, its peak loads occur in the late afternoon as the building heats up and more cooling is required. The simulations indicate that during a regular working day peak PV generation, represented by the green bars in Figure 5.9 below, occur slightly earlier than do peak loads, but remain below consumption levels , indicating that all generated electricity is accounted for by the building itself. This pattern was congruent with warmer and cooler months. On a weekend day PV generation exceeds the baseload consumption as its electricity consumption is much lower over these periods, whilst PV generation remains unchanged, leading to the building having excess capacity which either needs to be fed back into the grid or stored in batteries. Assuming an ideal scenario where net metering is available building A's energy balance would see it consuming roughly 70% of its own electricity generated on-site, whilst exporting the remaining 30%.

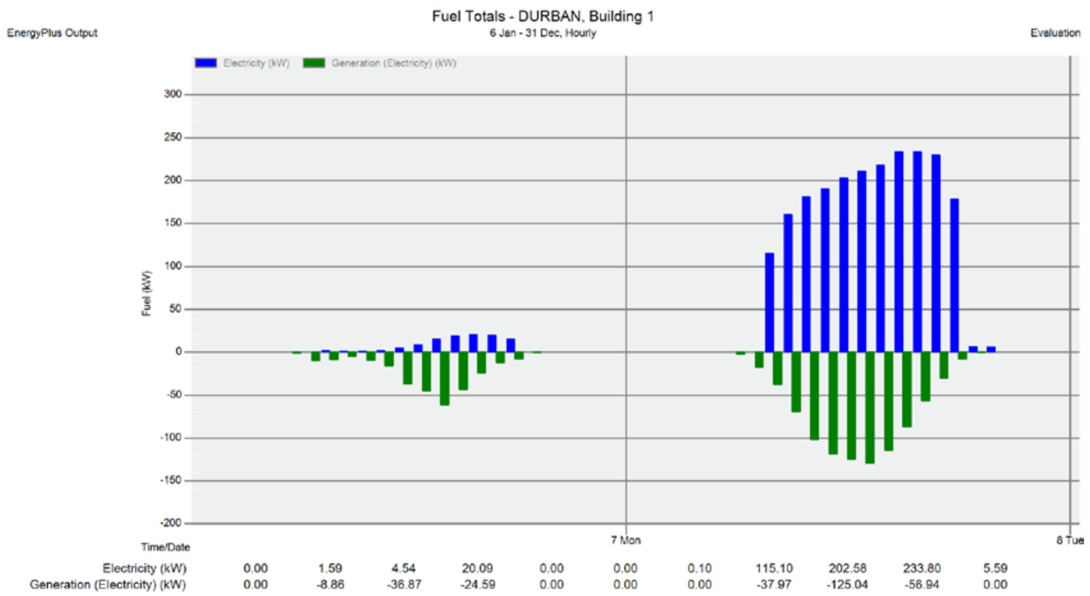


Figure 5.9: The graph on the left represents electricity consumption and generation on an hourly basis over the course of a Sunday, when the building is closed. On the right, when the building is open on a Monday.

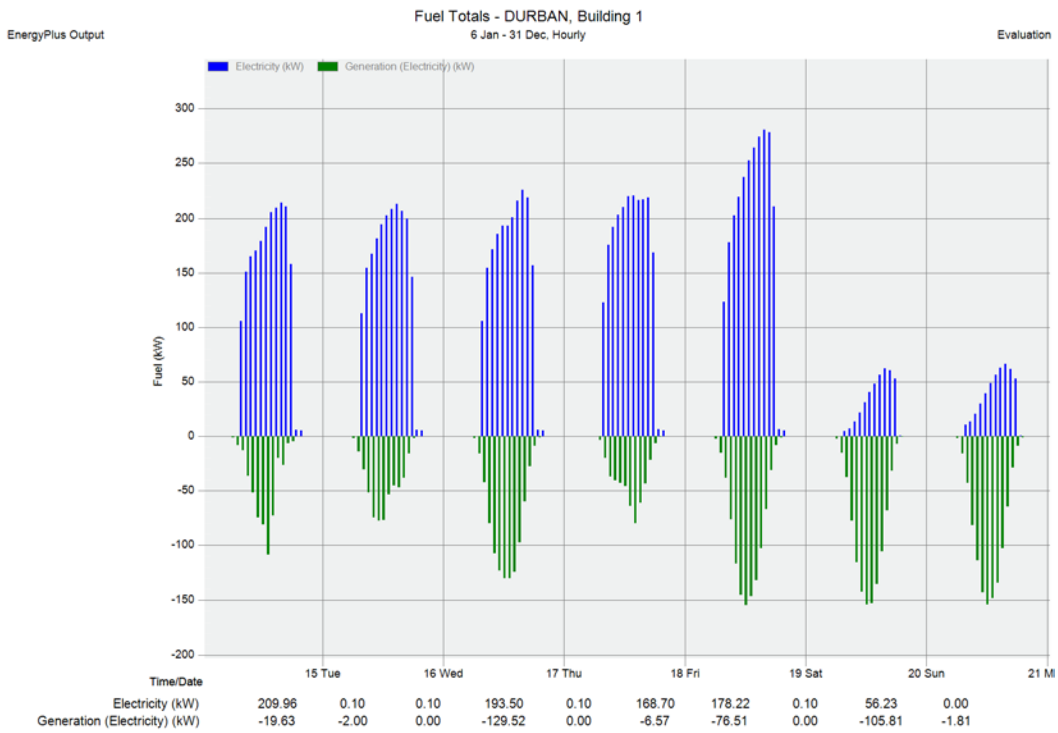


Figure 5.10: Hourly electricity consumption and generation for a period of 1 week.

Payback period

Overall reduction in electricity consumption from the baseline condition of 859 797 kWh/yr to 551 250 kWh/yr was achieved by optimising the HVAC and lighting systems. After simulating the PV array, this was decreased further to 514 460 kwh/yr, due to the shading effect of the array on the concrete roof-slab, which prevents the thermal mass from over-exposure to direct solar radiation and has the effect of lowering the building's cooling load. This saving was accounted for in the payback period calculation, where annual savings of 36 790 kWh/yr were added to the PV generation figure (see Table 5.5)

Yr of op	pv gen - shading kWh/yr	Self- Consmp.	Shading Savings kWh/yr	Total Savings kWh/yr	Inflation adjusted tariff (8%)	Savings ZAR	Discount Rate 5% (NPV)	Maintain-ence cost - inflation	Savings total(ZAR)
Yr1	200 100	140 000	36 790	176 790	1.5728	278 055	278 055	R 7 000	271 055
Yr2	200 100	140 000	36 790	176 790	1.6986	300 295	272 376	R 7 350	265 026
Yr3	200 100	140 000	36 790	176 790	1.8345	324 321	280 160	R 7 718	272 442
Yr4	200 100	140 000	36 790	176 790	1.9812	350 256	288 156	R 8 104	280 052
Yr5	200 100	140 000	36 790	176 790	2.1397	378 278	296 390	R 8 509	287 881
Yr6	200 100	140 000	36 790	176 790	2.3109	408 544	304 862	R 8 934	295 928
Yr7	200 100	140 000	36 790	176 790	2.4951	441 109	313 488	R 9 381	304 107
Yr8	200 100	140 000	36 790	176 790	2.6955	476 537	322 444	R 9 850	312 594
Yr9	200 100	140 000	36 790	176 790	2.9942	529 345	331 659	R 10 343	321 316
Yr10	200 100	140 000	36 790	176 790	3.2337	571 686	341 133	R 10 860	330 273
Yr11	200 100	140000	36790	176 790	3.4924	617 421	350 874	11 403	339 471
Yr12	200 100	140 000	36 790	176 790	3.7718	666 817	371 309	R 11 930	359 379
									3 639 524

Table 5.5: From the payback calculations, the PV system will pay itself off within 12 years however this is reduced to three years by the ‘12B’ RE tax allowance.

According to the eThekwini Municipality’s solar map viewer for Durban, the total system cost of a 174 kWp PV array is in the region of R3.5 million when applying a budgetary rough order of magnitude formula of R20 000 / kWp. Installation is estimated to be in the region 10% of the system cost (Maehlum 2014) thus bringing the total capital cost of the PV system to R3.85 million.

To calculate the payback period, the following method was used: The shadow coefficient (as calculated for the specific site in Chapter 5) was applied to the simulated overall annual generation from on-site PV of 212 870 kWh, indicating an approximately 6% reduction in overall generation potential due to shading from surrounding buildings. The consumption value of electricity consumed by the building itself was then derived from the modified generation potential and the proportion of weekend days to week days i.e. days that the building is closed versus open. Savings through shading of the roof slab by the PV panels, which accounted for 36 790 kWh reduction in overall annual consumption, was then added to the self- consumption value of 154 500 kWh to arrive at a total savings value. This value was used to calculate the payback period. An electricity tariff inflation level of 8% per annum was used and the net present value (NPV) was calculated using a conservative 5% discount rate. Further to this, maintenance costs were factored at 2% of the price of the installation with a 5% inflation increase per annum. The amount of electricity exported is estimated to be 60 000 kWh/yr but cannot currently be used in the payback calculations, and is therefore accounted for as a loss in the PV payback period. However, the option to trade in carbon credits or certificates is discussed further in Chapter 7.

Summary - Case study 1 – Building A (Office)	
Baseline conditions	
Date of construction	1992
Max bulk zoning regulations (FAR)	general business – FAR 1.5
Site area	2 656 m²
Net floor area	3 980 m²
Coverage	50%
FAR	1.5
Occupancy classification	Office
Design population	1 person/15m²
Operation schedule	7am-6pm/5days/week
SANS max energy consmp. (place of instruction)	190 kWh/m²
Annual electricity consmp. (actual)	859 344 kWh or 216kWh/m²
Simulated results of NZEB interventions.	
% site shading	6%
% reduction in overall consmp. From baseline (passive)	1.3%
% reduction in overall consmp. From baseline (active)	33%
Overall reduction from passive and active optimisation	279 771 kWh/yr
Reduction through shading by PV array	36 790 kWh/yr
PV generation (optimised) without shading effect	212 871 kWh/yr 41%
PV generation (optimised) with shading	200 100 kWh/yr 38%
RE consumed on-site	140 000 kWh/yr 70%
RE available for export	60 100 kWh/yr 30%
% Overall electricity reduction	859 344 – 579 573 +176 790 = 456 561 kWh/yr 56%
Annual electricity consmp. After NZEB retrofit	402 783 kWh/yr or 101 kWh/m²/yr
Overall cost	R 6 032 500
Estimated total payback period	5 years
Overall CO_2 reduction	338 (Kg) x 10^3

5.3 Baseline conditions –Building B (offices)

Figure 5.11: Aerial photograph showing urban context and location of Building B. (Source: Adapted from Google Maps)

Building B is a six storey office block in the CBD which is predominantly zoned for general business and has a maximum bulk zoning regulation of 8 (plot area ratio). The building has a plot area or floor area ratio of 4.7. Site area is 1 232 m² whilst the 6 storey office building has a net floor area of 5 760 m², with retail on the ground floor, and offices on floors 1-6. Walls are mainly of masonry structure and predominantly 220 mm clay brick and are simulated with a thermal resistance of (R-value of 0.5 m²·K/W). Standard tinted glass and aluminium frames have been simulated with a total solar transmission co-efficient (SHGC) of 0.427 and U-value of 6.066 K.m²/W. Slabs (including roof-slab) and columns are cast from reinforced concrete. (Generic/default values based on ASHRAE standards which Design Builder applies) The analysis of 12-months utility bills reveals that the building consumes in the region 840 000 kWh of electricity per year, which forms the baseline consumption from which subsequent reductions in energy consumption have been calculated.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
81 520	75 494	71 330	70 490	69 440	59 140	57 280	62 268	68 820	68 935	76 040	79 040	839 797

Table 5.6: Monthly energy consumption of building B. (kWh) (Source: adapted from actual monthly electricity bills)

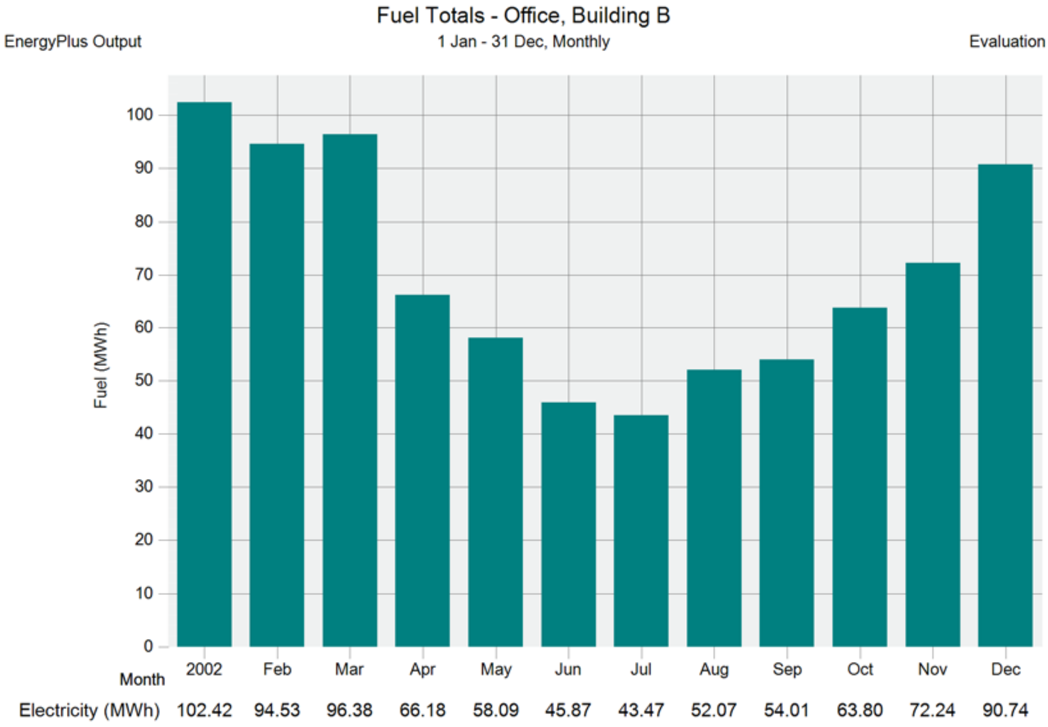


Figure 5.12: Simulated monthly electricity consumption

In Building B, simulated annual peak demand, which occurs in January, is approximately 20% higher than metered data for the same period. Similarly, the lowest simulated consumption occurs in July and is approximately 25% lower than metered data averages for the same period. It is suspected that the majority of this 'performance gap' can be attributed to the cooling and ventilation, and specifically to the influence of weather on the HVAC system, as occupancy density, operating times and lighting remain constant. Annual simulated electricity breakdown by building system shows HVAC as the largest consumer at 45% followed by lighting and plug loads at 33% and 20% respectively. Despite the performance gap experienced in monthly data which is attributed to HVAC, on an annual basis, the higher summer consumption balances the lower winter consumption values.

The initial baseline analysis indicates that the major electricity consuming systems are HVAC, lighting, plug loads, and process loads which mainly entail the electricity consumed by the three lifts. Lighting contributes the largest portion of internal heat gains followed by computers and office equipment.

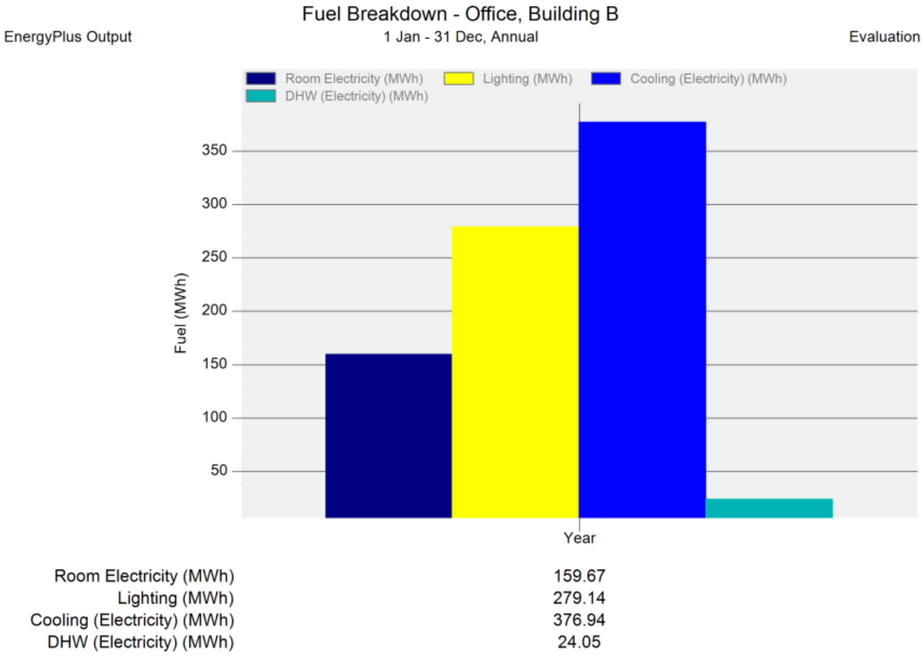


Figure 5.13: Electricity consumption of major building systems for Building B.

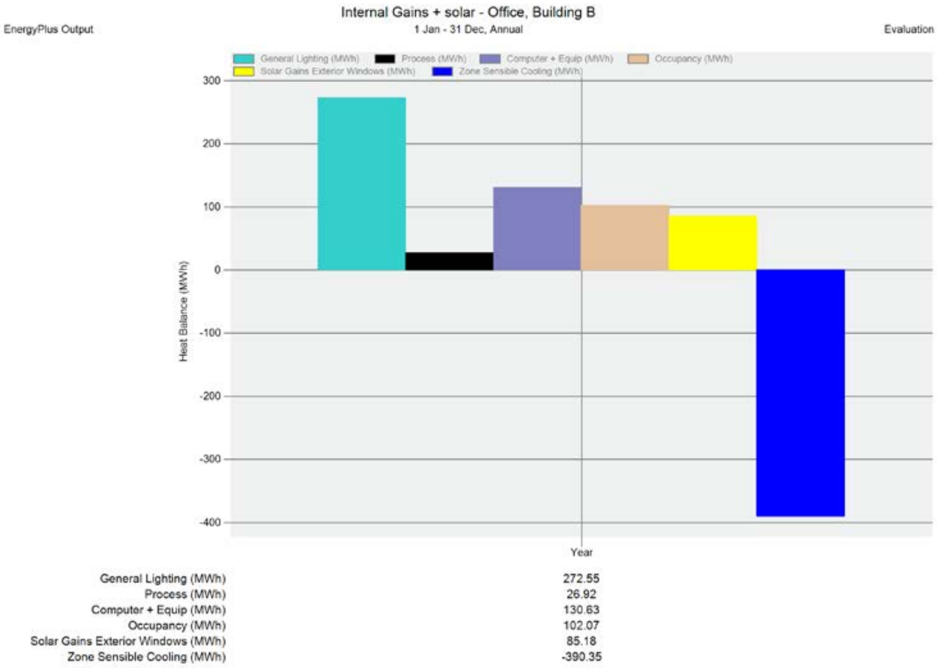


Figure 5.14: Baseline internal gains.

5.3.1 NZEB interventions – Building B (offices)

5.3.2 Passive design strategies

Due to the building being closely surrounded by adjacent buildings, combined with the prevalence of cellular office spaces, potential passive design techniques for sub-tropical coastal zone 5 (includes natural ventilation and shading) is limited. To test the effect of solar shading on east and north facing fenestration, aluminium solar shielding of the windows was simulated which resulted in reduction of overall electricity consumption of 31 190 kWh, or 4% of total baseline consumption. The estimated cost of retrofitting the intervention is estimated at R 900 per m² of fenestration. With 670m² being shaded and a 10% installation fee, the capital cost of the intervention is estimated at R 660 000. A discount rate of 5% was also applied to calculate NPV, and the resultant payback period is 12 years. (see Table 5.7)

		Savings /yr		8% tariff	total savings	NPV 5%	
		kWh		increase	ZAR	Discount rate	
Yr1		31 190		1.5728	49 056	49056	
Yr2		31 190		1.6986	52979	48 054	
Yr3		31 190		1.8345	57218	49 427	
Yr4		31 190		1.9812	61794	50 838	
Yr5		31 190		2.1397	66737	52 290	
Yr6		31 190		2.3109	72077	53 785	
Yr7		31 190		2.4958	77844	55 322	
Yr8		31 190		2.6955	84073	56 904	
Yr9		31 190		2.9942	93389	60 199	
Yr10		31 190		3.2337	100859	61 919	
Yr11		31 190		3.4924	108928	63 688	
yr12		31 190		3.7718	117642	65 507	
						666 989	

Table 5.7: Derivation of payback period for solar shielding.

5.3.3 Active interventions

Lighting

Inspection of the premises revealed that T8 florescent lighting tubes contributed to the majority of the building's general lighting consumption which when simulated was found to consume 279 140 kWh/yr. After retrofitting these with energy efficient LEDs, electrical consumption for lighting was reduced by 123 420kWh to 155 720kWh which is 15% of overall usage.

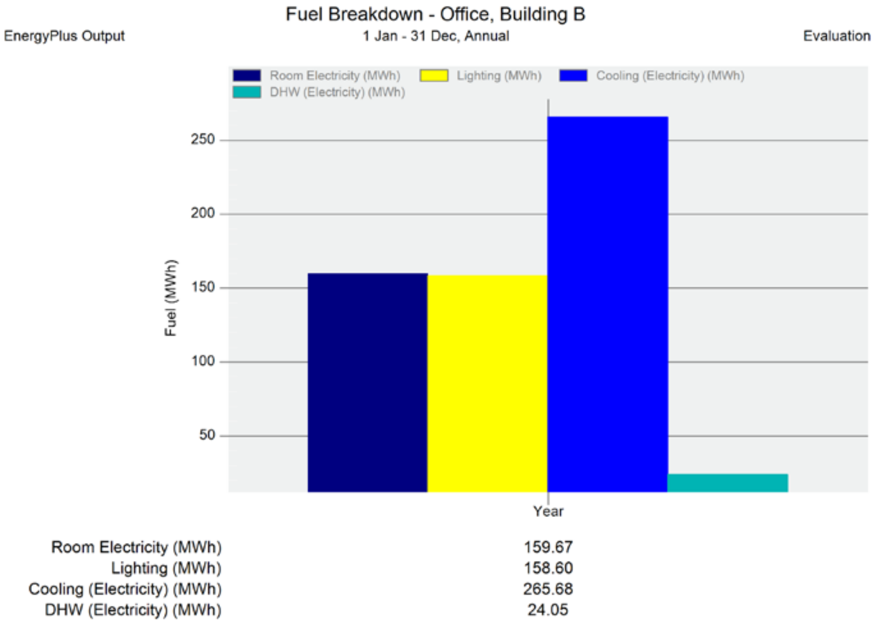


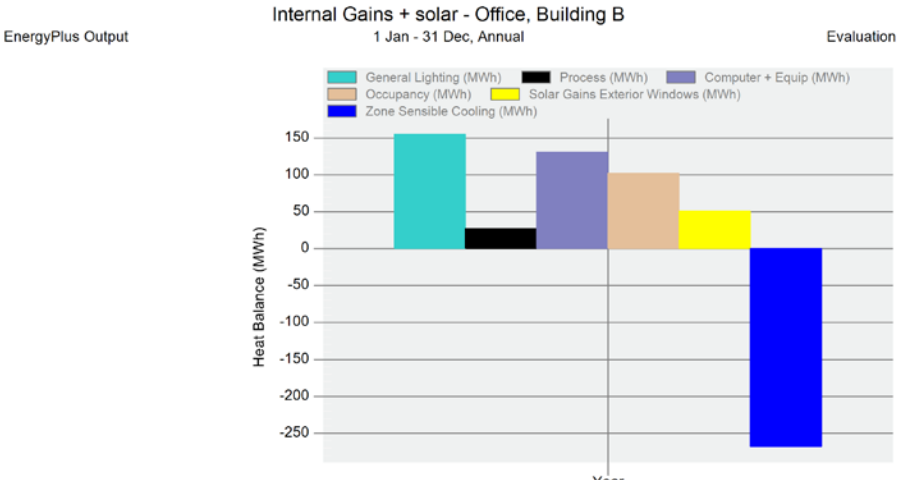
Figure 5.15: Simulated lighting consumption and cooling load after retrofitting LED.

Based on a budgetary order of magnitude estimate of R200 per m² with 10% added for fees and installation as well as a 5% discount rate, the payback period for LED retrofitting was estimated to a cost of R 1.28 million, with a 7 year payback period. (See Table 5.8)

	Saving per yr (kWh)	tariff +8%pa		NPV (5%)
year 1	123 420	1.5728	194 115	194 115
year2	123 420	1.6986	209 641	190 151
year3	123 420	1.8345	226 414	195 585
year 4	123 420	1.9812	244 520	201 167
year 5	123 420	2.1397	264 082	206 915
year 6	123 420	2.3109	285 211	212 829
year 7	123 420	2.4958	308 032	218 913
			1 732 015	1 419 675

Table 5.8: Derivation of payback period for LED.

Internal heat gains were also decreased by retrofitting with energy efficient LED. Normalised power density thus decreases from 4.4 W/m² to 2.5W/m² which led to internal heat gains due to lighting to decrease from 272 534 kWh to 149 130 kWh per year. This led to a reduction in zone sensible cooling load, which was reduced by 94 561 kWh to a figure of 295 786 kWh. The lighting retrofit reduced annual electricity consumption from 839 797 kWh to 629 845 kWh, which is a reduction of 209 952 kWh or 25%.



General Lighting (MWh)	154.86
Process (MWh)	26.92
Computer + Equip (MWh)	130.63
Occupancy (MWh)	101.90
Solar Gains Exterior Windows (MWh)	50.98
Zone Sensible Cooling (MWh)	-268.39

Figure 5.16: Simulated internal gains after LED retrofit.

HVAC

The modification to HVAC was purposely made after the lighting intervention such that reductions in internal heat gains as a result of retrofitting a LED lighting system could be incorporated into HVAC savings. Case study building B uses a centralised CAV HVAC system with water cooling, which employs a simple on-off switch, thus negating the possibility of controlling for different zone requirements. The system runs on a daily schedule from 7am- 6pm continuously at a set temperature of 24 degrees C. Offices adjacent to windows are fitted with split unit systems and are not cooled by the centralised system. The centralised system was modified and replaced by a VAV closed loop system which incorporates a small building management system, thus allowing for autonomous control of each compressor station (on each floor) in order to provide for more control for the various user needs. The simulation of the upgraded HVAC system reflect a reduction in total annual electricity consumption from 629 845 kWh/yr to 551 250 kWh/yr which is a reduction of 78 595 kWh/yr (9%) of the total annual baseline electricity consumption.

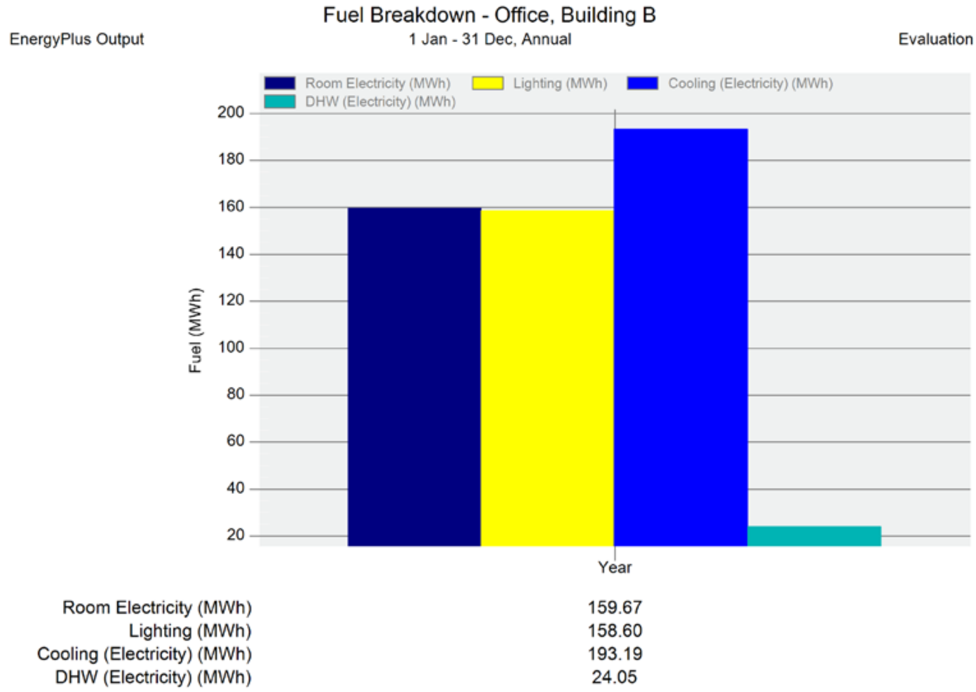


Figure 5.17: Simulated consumption after lighting and HVAC upgrades.

The capital cost based on a rough order of budgetary magnitude of R300/m² with 10% installation and professional fees is roughly R1.9 million. A simple return on investment calculation based on an 8% tariff increase using 2017 tariffs of R1.5728/kWh as the starting year reveals that the system has an estimated 13.5 year payback period, when a 5% discount rate was applied to determine the NPV.

	Saving per yr (kWh)		tariff +8%pa			NPV (5%)	
year 1		78 595	1.5728		123 614	123 614	
year2		78 595	1.6986		133 501	121 089	
year3		78 595	1.8345		144 183	124 551	
year 4		78 595	1.9812		155 712	128 105	
year 5		78 595	2.1397		168 170	131 766	
year 6		78 595	2.3109		181 625	135 531	
year 7		78 595	2.4951		196 102	139 366	
year 8		78 595	2.6947		211 790	143 348	
year 9		78 595	2.9103		228 735	147 445	
year 10		78 595	3.1431		247 032	151 651	
year 11		78 595	3.3945		266 791	155 987	
year12		78 595	3.666		288 129	160 441	
year13		78 595	3.9593		311 181	165 026	
					2 221 771	1 827 920	

Table 5.9: Derivation of payback period of HVAC intervention.

5.4 PV grid tie proposal

Annual baseline electricity consumption was reduced by 36 % from 839 797 kWh/yr to 536 000 kWh/yr through the retrofitting solar shielding, lighting and HVAC systems. In addition, PV installation on the available site area was simulated to test how close the building could get towards achieving net zero energy balance. This was done as follows:

Based on PV specification product data of a 250W mono-crystalline panel at 1.6 m² surface area, 6.4 m² would be required to generate 1 kWp. With the available area being the rooftop and the ground level car park, the building's total available space for PV is 950 m². However, when designing the system, the spacing required to ensure that panels do not shade one another makes it unviable to cover the full area.

Peak power:	108 kWp
Number of modules:	432 individual 250 W monocrystalline panels
Total area of array:	690 m²
Electricity generation potential:	142 080 kWh/yr
Angle of panel to the horizontal:	30º

Figure 5.18: Axonometric of PV array for Building B

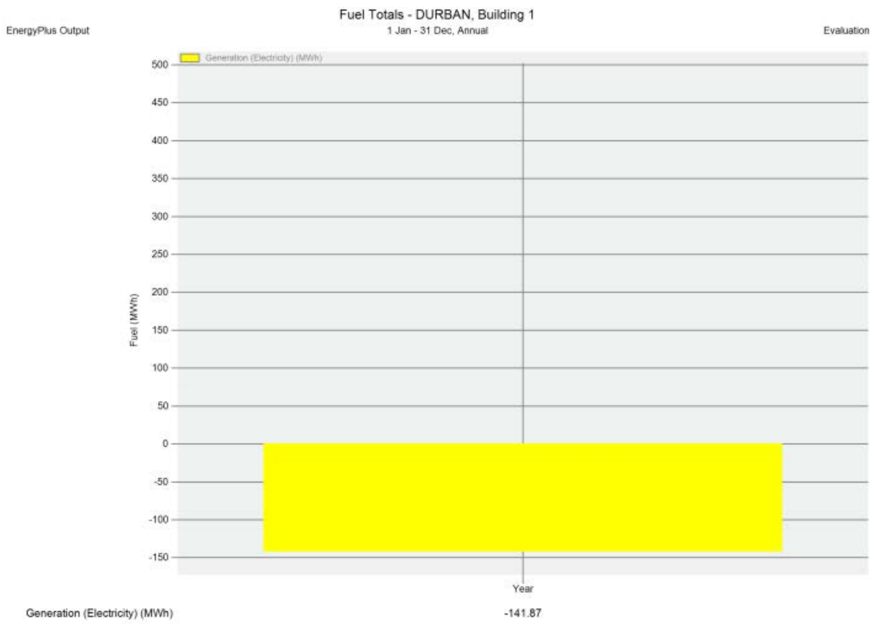


Figure 5.19: Annual electricity generation without shading.

The total electricity generated by the array, was simulated at 142 000 kWh/yr. This is however without any form of shading from surrounding buildings. From a solar shadow study carried out on the specific site it was found that building B experiences approximately 27% annual shading on surfaces that are suitable for PV installation which is accounted for as a loss in annual generation capacity, thus bringing annual generation to approximately 102 755 kWh/yr.

Consumption-export balance.

During a regular weekday when the building is operating, its peak loads occur in the late afternoon as the building heats up and more cooling is required. The simulations indicate that during a regular working day, peak PV generation, represented by the green bars in Figure 5.22 below, occur slightly earlier than do peak loads, but remain below consumption levels. This indicates that all generated electricity is accounted for by the building's self-consumption. This pattern was congruent with warmer and cooler months. On a weekend day PV generation exceeds the baseload consumption as its electricity consumption is much lower over these periods, whilst PV generation remains unchanged. This leads to the building having excess generation which either needs to be fed back into the grid or stored in batteries. Assuming an ideal scenario where net metering is available, energy balance for building B would see it consuming roughly 70% of its own electricity generated on-site, whilst exporting the remaining 30% to the grid. Based on this split, the value of electricity consumed by the building itself was derived from the shading modified generation potential value. Building B consumes approximately 71 930 kWh of the electricity it generates and this value was used to calculate the payback period.

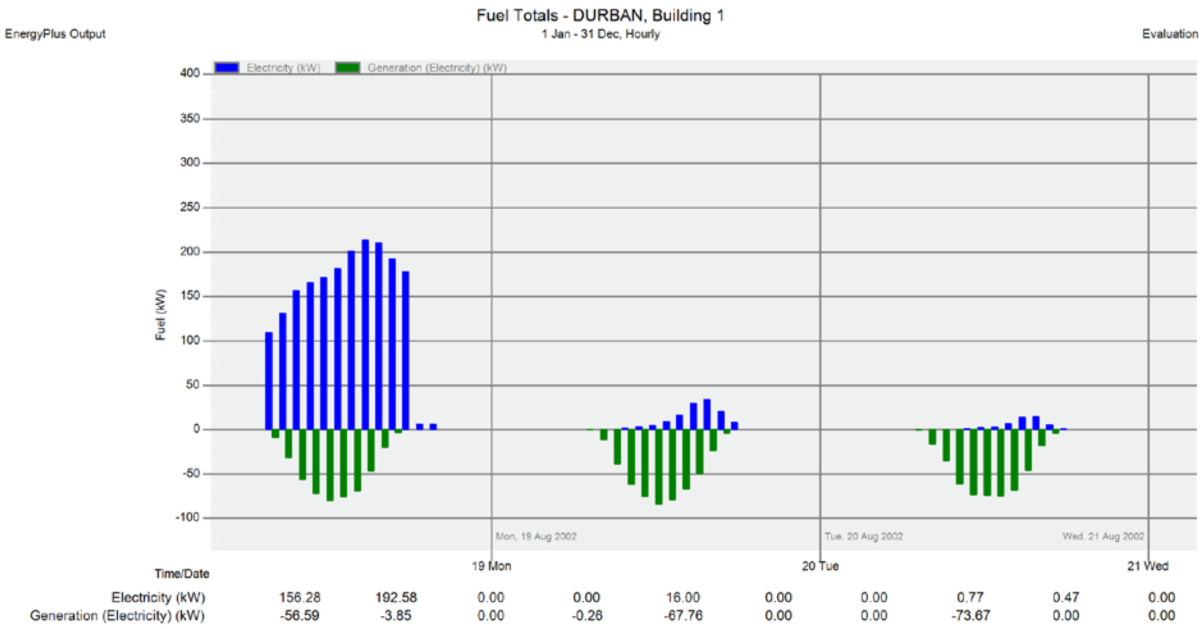


Figure 5.20: Daily consumption vs generation over a working day and the weekend.

Payback period

The reduced annual consumption of 536 000 kWh/yr was achieved through solar shielding, as well as optimising the HVAC and lighting systems. This was reduced further to 520 910 kWh/yr due to the shading of the roof-slab thermal mass by the PV array, thus bringing the total reduction in yearly consumption (excluding PV generation) to 318 887 kWh, which translates to a 38 % overall reduction. The savings of 14 590 kWh/yr from rooftop shading provided by the PV array have been included in the payback period calculations of the installation.

According to the eThekwini Municipality's Solar Map website for Durban (n.d.) the total system cost of a 108 kWp PV array is in the region of R2.15 million when applying a budgetary rough order of magnitude formula of R20 000 / kWp. Installation cost is estimated to be in the region of 10% of the system cost (Maehlum 2014) which brings the total capital cost of the PV system to R2.3million. To calculate the payback period, an electricity tariff inflation level of 8% per annum was used and the net present value (NPV) was calculated using a conservative 5% discount rate. Further to this, maintenance costs were factored at 2% of the price of the installation with a 5% inflation increase per annum. The payback period was estimated at 14 years (See Table 5.10)

Yr of op	pv gen - shading kWh/yr	Self-Consmp.	Shading Savings kWh/yr	Total Savings kWh/yr	Inflation adjusted tariff (8%)	Savings ZAR	Discount Rate 5% (NPV)	Maintain-ence cost - inflation	Savings total(ZAR)
Yr1	102 755	72 000	14 590	86 590	1.5728	136 189	136 189	R 2 300	133 889
Yr2	102 755	72 000	14 590	86 590	1.6986	147 082	133 408	R 2 415	130 993
Yr3	102 755	72 000	14 590	86 590	1.8345	158 849	137 220	R 2 535	134 685
Yr4	102 755	72 000	14 590	86 590	1.9812	171 552	141 136	R 2 660	138 476
Yr5	102 755	72 000	14 590	86 590	2.1397	185 277	145 170	R 2 800	142 370
Yr6	102 755	72 000	14 590	86 590	2.3109	200 101	149 318	R 2 940	146 378
Yr7	102 755	72 000	14 590	86 590	2.4951	216 051	153 543	R 3 090	150 453
Yr8	102 755	72 000	14 590	86 590	2.6955	233 403	157 976	R 3 240	154 736
Yr9	102 755	72 000	14 590	86 590	2.9942	259 268	167 126	R 3 400	163 726
Yr10	102 755	72 000	14 590	86 590	3.2337	280 006	171 900	R 3 570	168 330
Yr11	102 755	72000	14590	86 590	3.4924	302 407	176 811	3 750	173 061
Yr12	102 755	72 000	14 590	86 590	3.7718	326 600	181 863	R 3 940	177 923
yr13	102 755	72 000	14 590	86 590	4.0735	352 724	187 057	R 4 140	182 917
yr14	102 755	72 000	14 590	86 590	4.3994	380 944	197 453	R 4 350	193 103
									2 191 040

Table 5.10: Derivation of payback for PV system without ‘12B’ tax allowance.

Summary – Case study 2 – Building B (Office)	
Baseline conditions	
Date of construction	1978
Max bulk zoning regulations (FAR)	general business – FAR 8
Site area	1232 m^2
Coverage/net floor area	5760 m^2
FAR	4.7
Occupancy classification	Office
Design population	1 person/15m^2
Operation schedule	7am-6pm/5days/278 days
SANS max energy consmp. (Office)	190 kWh/m^2
Annual electricity consmp. (actual)	839 797 kWh/yr or 144 kWh/m2/yr
Simulated results of NZEB interventions.	
% site shading	27%
% reduction in overall consmp. From baseline (passive)	4%
% reduction in overall consmp. From baseline (active)	32%
Overall reduction through passive and active optimisation	303 800 kWh/yr- 36%
Reduction through roof slab shading by array	14 500 kWh/yr
PV generation (optimised) without shading effect	142 000 kWh – 26%
PV generation (optimised) with shading	102 755 kWh - 19%
RE consumed on-site	71 930 kWh/yr - 70%
RE available for export	30 825 kWh/yr – 30%
% Overall electricity consumption reduction	390 812 kWh/yr = 47%
Annual electricity consmp. After NZEB retrofit	448 985 kWh/yr or 77 kWh/m^2/yr
Overall cost	6 032 500
Estimated total payback period	8 years
Overall CO_2 reduction	272 200 kg $x(10)^3$

5.5 Summary of findings

Electricity consumption figures for office building's A and B revealed that the office with a significantly lower FAR has a higher energy use per unit area (m^2) and a higher annual consumption. This is in-line with literature reviewed, indicating that FAR is a poor indicator for EUI and thus contrary to theories that building size is the single biggest indicator of EUI. A high EUI for Building A, can be attributed to a combination of factors including a high density of office equipment, inefficient lighting controlled through block switches, inefficient HVAC as well as enjoying limited shading from the surrounding urban fabric. The lighting system was found to be responsible for a large percentage of overall electricity consumption as well as being the highest contributor to internal heat gains. Higher heat gains have the effect of increasing the operative temperature of the offices, which in turn increases the electrical load of the HVAC system which is thus forced to consume more energy towards the cooling of internal spaces. Solar gains through exterior windows are marginal, thus indicating that the heat gains are being exacerbated by the high thermal mass of the building's heavy masonry construction. In contrast, Building B experiences fairly substantive shading from surrounding urban fabric, which thus contributes to lower heat loads through the building fabric.

5.5.1 Reductions in annual electricity consumption through EE interventions

Buildings A and B were each capable of reducing baseline consumption by 2% and 4% respectively through retrofitting passive energy efficiency measures in the form of solar shielding. Building A achieved a further 33% reduction through the optimisation of lighting and HVAC, whilst Building B achieved a further 32% reduction through the optimisation of lighting and HVAC.

5.5.2 Reduction in annual energy consumption through on-site PV

Building A was able to generate approximately 200 000 kWh/yr from its on-site PV array after shading from surrounding buildings was taken into account. Of this total generation potential, 140 000 kWh would be for self-consumption while roughly 60 000 kWh could be available for export to the grid. Simulation of the PV system also revealed that it contributes significantly in lowering cooling loads caused by excessive heating of exposed roof slabs, through the effect of shading by the panels. These savings have been taken into account when calculating annual electricity consumption reduction from baseline. On-site PV was responsible for approximately 39% of the 456 561 kWh overall reduction in electricity consumption. Building B has a generation potential of approximately 142 000 kWh/yr which is reduced by approximately 27% due to the effect of shading from surrounding urban environment. 70% or 72 000 kWh/yr of the shading adjusted value of 103 000 kWh is consumed by the building on-site while roughly 31 000 kWh would be available for grid export. Cooling effect of 14 500 kWh/yr from roof-slab shading is included in the overall reduction in consumption due to on-site PV which accounted for 117 500 kWh/yr or 28% of the overall 418 500 kWh/yr consumption reduction.

5.5.3 Cost comparison

The larger floor area of Building B did have an impact on the size/quantity and thus cost of the retrofitted interventions. Although both buildings were able to reduce energy consumption by roughly 1/3 from baseline, the cost of retrofitting such measures was greater in the building with more floor area, based on the fact that there is more area to be conditioned by HVAC and more lights that were to be replaced. Building B also experienced a less than satisfactory payback period (14 years) for its PV installation. This was due to high levels of site shading (27%) which decreased on-site generation potential significantly. Was PV not incentivised by the '12B' tax allowance, overall payback periods would have been closer to 12 years rather than 7-8 years after deducting the tax allowance.

Conversely, Building A was more energy intensive, hence electricity savings were greater and the relative cost of retrofitting were lower, thus contributing to a shorter payback period. However, the implications of the '12B' RE tax allowance, as outlined in Chapter 3, would have significant implications in terms of pay back periods. The incentive allows the cost of the PV system to be deducted over a 3 year period, hence cost benefits from electricity generation from year 4 onwards, could be used to offset the cost of other EE interventions and shorten their payback periods. In the case of building A, payback periods were shortened from 6-7 years to 5 years.

5.5.4 CO_2 emissions reductions

Based on a conservative grid emission factor (0.7 $kgCO_2/kWh$) Building A, CO_2 emissions were reduced from 520(kg) x 10^3/yr to 182(kg) x 10^3/yr, by retrofitting NZEB interventions, which equates to a 338 (kg) x 10^3 (65 %) decrease. This is estimated as an equivalent of taking 66 cars off the road for a year. (yousustain.com) Emissions from Building B were reduced by 53% from 508(kg) x 10^3 to 238(kg) x 10^3 or 270(kg) x 10^3, which translates to the equivalent of taking 53 cars off the roads for a year. The levels of CO_2 emission reductions observed by retrofitting NZEB interventions in office buildings would ensure that the 38% cabinet-endorsed peak plateau-decline emissions path for 2050 would be met with regard to such buildings.

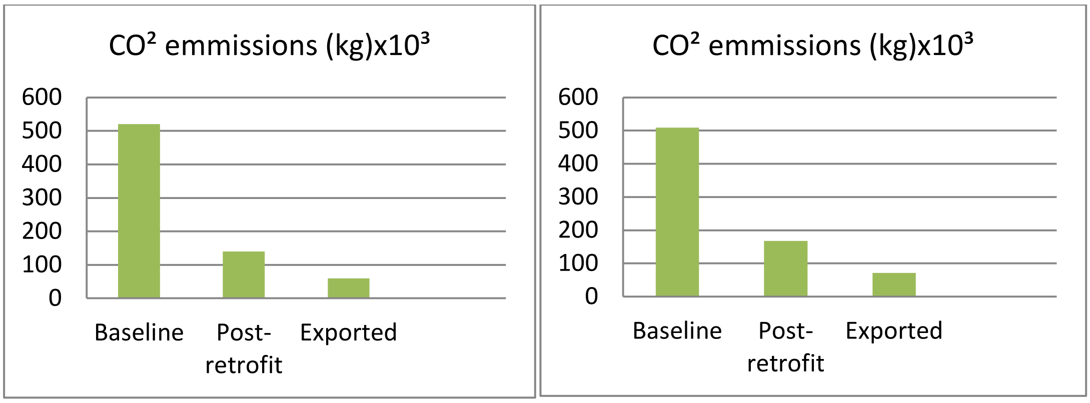
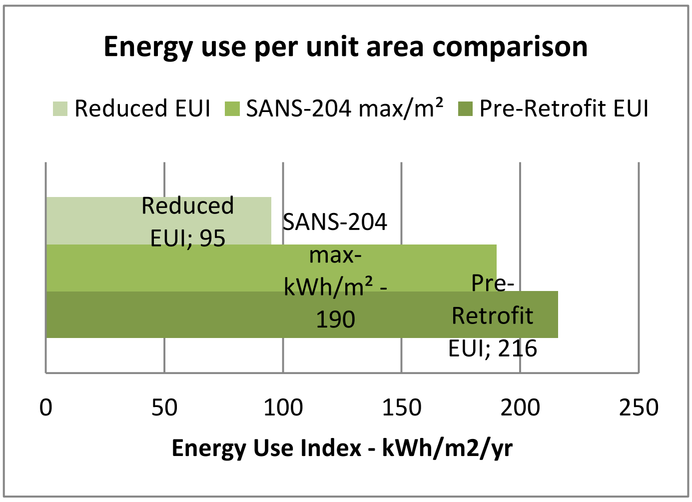
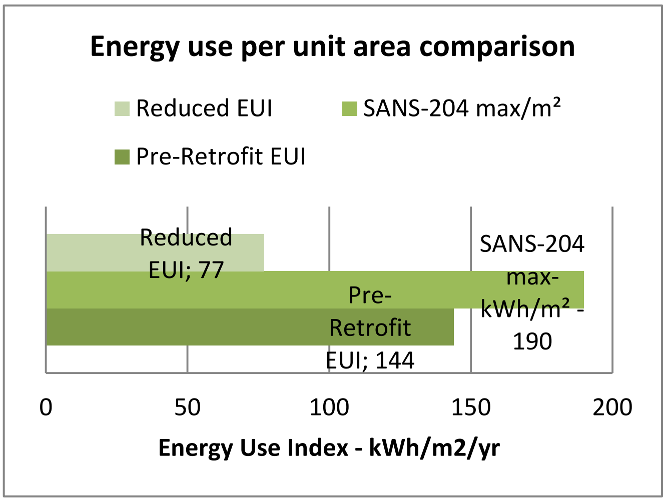


Figure 5.21 and 5.22: CO_2 emissions for Buildings A and B respectively, before and after NZEB interventions.

5.5.5 Annual electricity consumption benchmark values – SANS 204

Although Building A has a smaller FAR (1.5) than Building B (4.7) its annual electricity consumption per unit floor area is considerably more at 216kWh/m²/yr than the latter which is 146kWh/m²/yr. The maximum energy consumption per year for office buildings in climatic zone 5, as prescribed in SANS 10400XA, is specified as 190kWh/m²/yr, thus indicating that consumption for Building A is above the stipulated maximum with regards to new buildings. After simulating NZEB interventions, Building A's consumption was reduced to 101 kWh/m²/yr, whilst that of Building B was reduced to 77 kWh/m²/yr which equates to reductions in overall electricity consumption of 56% and 47% respectively.





Figures: 5.23 and 5.24: Energy use per m² before and after NZEB retrofit.(Building A and B respectively)

5.5.6 Conclusion

In terms of the effect of FAR on EUI it is clear that it is a poor indicator of energy efficiency. Both buildings were able to reduce baseline electricity consumption significantly through passive and active optimisation, although payback periods are found to be longer in buildings with more floor area which is generally indicative of higher FARs. This does impact on the overall viability of a retrofit intervention as larger buildings appear to have to invest more in retrofit optimisation and equipment to achieve similar reductions in electricity consumption. Conversely, an office building with a larger floor area and grater FAR has more rental potential and hence greater opportunity to off-set retrofit costs. Building A's superior generating capacity using on-site PV, accounted for approximately 40% of overall reduction in grid-electricity consumption whilst Building B's generation potential accounted for 28% of the overall consumption reduction. This illustrates that FAR could be a more reliable indicator for NZEB when looking at it in terms of site space available for PV installation as well as the associated effects of shadowing that are influenced by FAR and urban density. This is explored further in Chapter 6.

Chapter 6: The effect of building use-type (user density and operating schedules) on NZEB potential

6.1 Introduction

To substantiate on the effect of operating times and user density on NZEB potential, a hotel and an educational institution were purposely selected on the basis of the large variation in operating schedules and prescribed user density. Despite variation in occupancy rates, hotels are open all year around, 24 hours a day, which inevitably leads to increased consumption. Conversely, tertiary education facilities do not stay open all year, and are closed to students for between 20-25% of the year for holidays. Due to the absence of actual occupancy data the sample buildings were simulated to SANS maximum user density for a place of instruction which is 1 person per 5m², whilst for hotels the value is 2 persons per bedroom or in the particular case study, 1 person per 20m². To account for the effect of variation in occupancy, the hotel was simulated at a lower density and higher density occupancy values. The working hypothesis is that longer periods of operation would increase electricity consumption and in a similar manner, higher user-density would translate to higher use intensity. But how significant would the impact of the two factors be on the NZEB potential?

6.2 Baseline conditions – Building C (place of instruction)

Building C is classified as 'place of instruction' and is a 10 storey educational institution in the Durban CBD, that is zoned for general business with a bulk zoning regulation of 8 FAR. The building was formerly an office that has been re-purposed as a place of instruction. With a site area of 1 290 m² and a net floor area of 5 500 m², the college has an actual FAR of 4.3.

Figure 6.1: Site boundary of Building C. (Source: Adapted from Google Maps)

Walls of the masonry structure are predominantly 220 mm clay brick and are simulated with a thermal resistance of (R-value of 0.5 Km²/W). Standard tinted glass and aluminium frames have been simulated with a total solar transmission co-efficient (SHGC) of 0.427 and U-value of 6.066 Km²/W. Slabs (including roof-slab) and columns are cast from reinforced concrete.

The occupancy density is simulated at 1 person per 5m² in areas designated for teaching, as per SANS 204. Being an educational institution, the annual operation schedule reflects the holiday/ breaks format of tertiary education institutions in SA, with a total of 87 days for holidays within a typical year. The building consumes 529 610 kWh/yr with HVAC consuming the largest portion of this, followed by lighting, plug and process loads respectively.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
43 359	48 670	46 805	45 755	41 470	38 440	32 320	39 950	46 970	46 060	48 780	51 031	529 610

Table 6.1: Monthly electricity consumption from bills over 12 months.

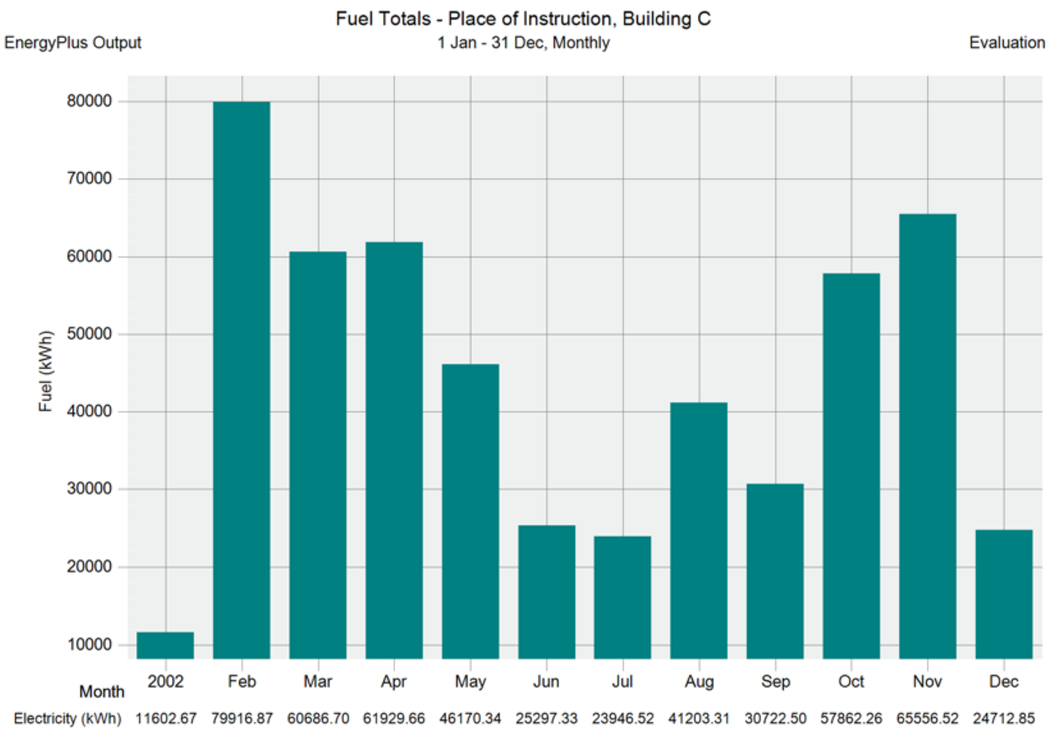


Figure 6.2: Simulated monthly electricity consumption over 12 months

Simulated annual peak demand, for the building occurs in February, and it is approximately 37% higher than metered data for the same period. The lowest simulated consumption occurs in July and is approximately 25% lower than metered data averages for the same period. Simulated results for December and January show a very weak correlation to billed consumption over the same months. The simulated values for these months are considerably lower, due to the building being closed for summer holiday.

In this instance the 'performance gap' between simulated and billed consumption values can be attributed to the simulation settings which 'shuts down' building systems completely on days that are identified as holidays. But based on utility estimates it can be deduced that during holiday periods, the building is still consuming fairly significant amount of electricity. This can be attributed to a number of possible reasons. This highlights a key limitation of the study, where without a meter profile recorder, that can measure daily peak demand as well as the baseload consumption, it is very difficult to estimate these values.

As discussed in the literature review, the majority of studies found weak links between occupancy and EUI with a popular explanation being that regular non EE building systems operate at close to full capacity despite there being 1 user or 5 users in the same space. In this instance, a building with more users can be said to be more efficient as it is using the same resources to cater to the needs of more users. Another explanation is that the baseload of the building, that is the minimum continuous consumption over un-occupied periods, has a greater impact on annual consumption than the simulation results would indicate. This can be attributed to the influence of resistive loads from the HWS as well as lighting systems which may remain running during holiday periods. Larger inductive loads from elevators are also suspected to contribute to baseload demand. Correcting the power factor by installing power factor correction equipment is recommended to ensure the current flowing in the system is not larger than it needs to be, but this is beyond the scope of this study.

Annual Simulated electricity breakdown by building system shows HVAC as the largest consumer at 45% followed by lighting and plug loads at 33% and 20% respectively. Despite the performance gap experienced in monthly data (which can be attributed to HVAC), on an annual basis, the higher summer consumption balances the lower winter consumption value.

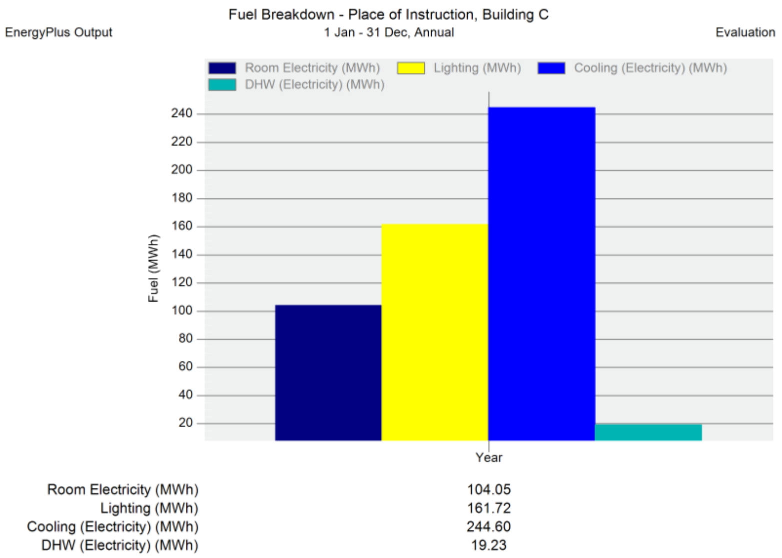
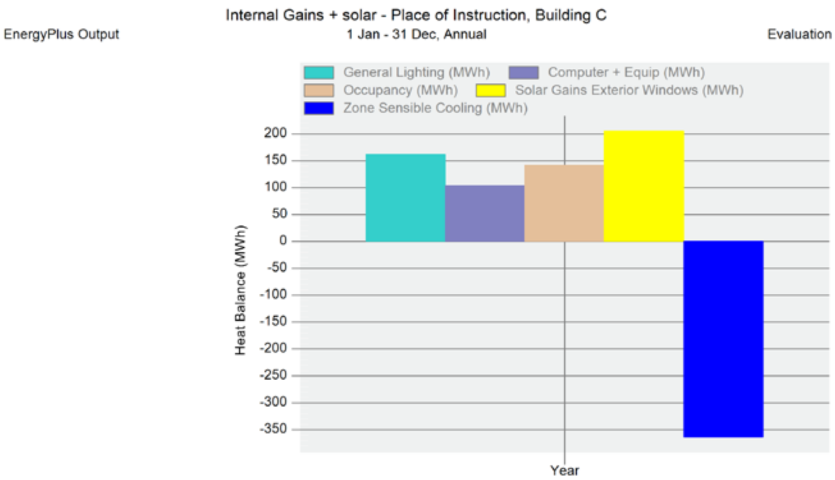


Figure 6.3: Baseline fuel breakdown – building C

6.3 NZEB interventions – Building C (place of instruction)

6.3.1 Passive interventions

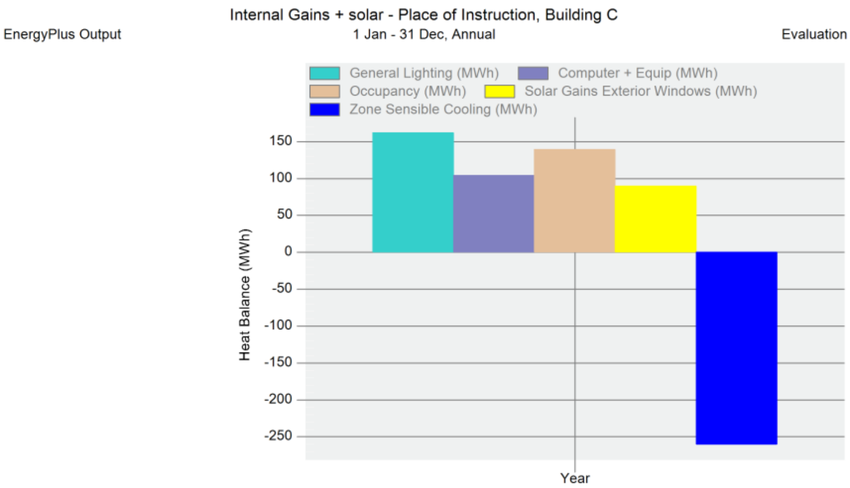
Due to the high levels of noise and air pollution within the CBD, the facilities management of the institution decided that natural cross ventilation interventions should not be retrofitted. Students found the noise levels from the city to be highly distracting and in most instances, windows are kept closed for these reasons. Windows had already been retrofitted with solar film in order to reduce thermal gains, and internal blinds had also been introduced as an additional intervention for reducing solar gains, both of which are reflected in the baseline analysis.



General Lighting (MWh)	161.72
Computer + Equip (MWh)	104.05
Occupancy (MWh)	141.66
Solar Gains Exterior Windows (MWh)	204.91
Zone Sensible Cooling (MWh)	-364.09

Figure 6.4: Baseline fuel breakdown and solar gains for Building C

Despite these measures, solar gains through exterior windows still contribute significantly to the overall internal heat gains, which led to solar shielding being retrofitted and tested as the first passive intervention.



General Lighting (MWh)	161.72
Computer + Equip (MWh)	104.05
Occupancy (MWh)	139.22
Solar Gains Exterior Windows (MWh)	89.70
Zone Sensible Cooling (MWh)	-260.22

Figure 6.5: Fuel breakdown and solar gains after solar shielding intervention – building C

The building was simulated with aluminium vertical finned external solar shielding on the east and west facades, which are the only facades that are exposed to direct solar radiation due to the north façade being butted up against neighbouring building. Solar gains through exterior windows were decreased from 204 910 kwh/yr to 89 700 kWh/yr. This led to a 12% overall reduction in total electricity consumption, from 529 610 kWh/yr to 466 620 kWh/yr. This can be attributed to a combination of effects, where lower solar gains through external windows contribute to lowering the overall cooling load from 364 090 kWh/yr to 260 220 kWh/yr.

The estimated cost of retrofitting the intervention is estimated at R900 per m² of fenestration with 10% for fees. With 630m² being shaded, the estimated capital cost aluminium solar shielding is R623 700. A discount rate of 5% was applied to calculate NPV. The payback period is 7 years as reflected in Table 6.2.

	Saving per yr (kWh)			tariff +8%pa			
year 1		62 990		1.5728	99 071	99071	
year2		62 990		1.6986	106 995	97048	
year3		62 990		1.8345	115 555	99821	
year 4		62 990		1.9812	124 796	102670	
year 5		62 990		2.1397	134 780	105604	
year 6		62 990		2.3109	145 564	108 622	
year 7		62 990		2.4958	157 210	111726	
					883 970	724 562	

Table 6.2: Derivation of payback period for aluminium solar louvres.

6.3.2 Active interventions

Lighting

Inspection of the building revealed a combination of T5 and T8 florescent lighting tubes, which when simulated, contribute 161 720 kWh of the building's baseline lighting consumption. By retrofitting these with less energy intensive LED fixtures, electricity consumption through lighting was reduced by 40% to 96 590 kWh/yr, which also significantly contributes to a reduction of the cooling load. With LED retrofits simulated, overall electricity consumption was reduced further from 466 620 kWh/yr to 373 390 kWh/yr – 17 % of overall consumption.

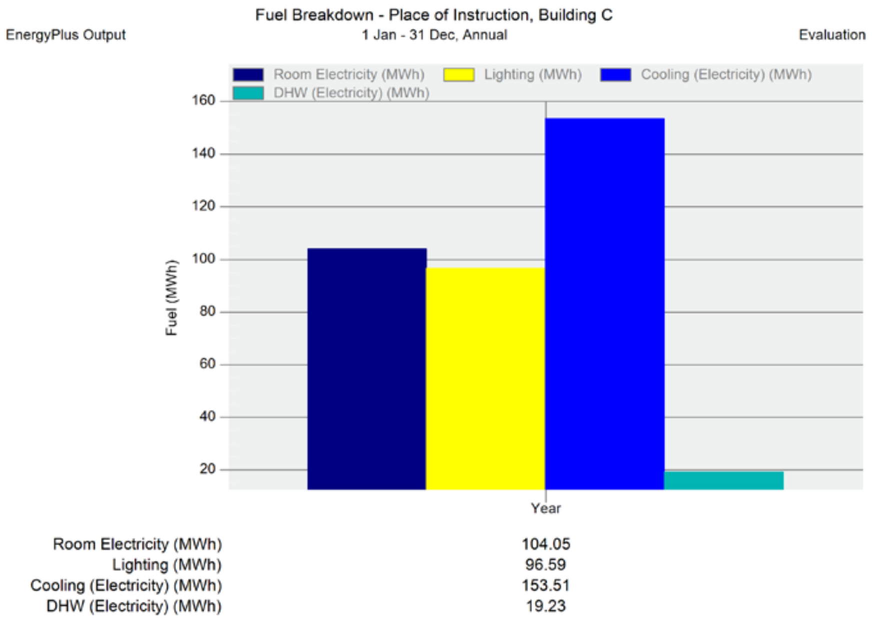


Figure 6.6: Simulated consumption with solar shielding and LED lighting retrofits.

A budgetary rough order magnitude estimation of R200/m² plus 10% installation costs was used to calculate the payback period of retrofitting LED lights. An 8% electricity tariff increase and a 5% discount rate were applied to the calculation. Capital costs are thus estimated to be R 1.2 million. The payback period for the LED retrofit is 8 years as shown in Table 6.3

	Saving per yr (kWh)			tariff +8%pa		NPV (5%)	
year1		93 230		1.5728	146 632	146632	
year2		93 230		1.6986	158 360	143637	
year3		93 230		1.8345	171 030	147742	
year4		93 230		1.9812	184 707	151959	
year5		93 230		2.1397	199 484	156301	
year6		93 230		2.3109	215 445	160768	
year7		93 230		2.4951	232 618	165317	
year8		93 230		2.6947	251 227	170040	
					1 075 660	1242396	

Table 6.3: Derivation of payback period for LED lighting retrofit.

HVAC

Various improvements had previously been made to the buildings central water cooled air-conditioning system. These included a shading of the rooftop chiller, as well as replacements of individual split units to more efficient and responsive units thus allowing for better individual zone temperature manipulations. Without retrofitting any HVAC components, reductions in the overall HVAC electricity consumption were significantly reduced by reducing solar gains through windows as well as internal heat gains through lighting. The knock on effect of retrofitting these measures translates to a reduction in the overall annual cooling load from 364 090 kWh/yr to 214 510 kWh/yr or 30%.

6.4 PV grid tied proposal

Baseline yearly electricity consumption was reduced by 33 % from 529 610 kWh/yr to 373 390 kWh/yr through the retrofitting of solar shielding louvres to the fenestration on the east and west facades, lighting and HVAC systems. A PV array on the available site area was simulated to test how close the building could get towards achieving net zero energy balance. This was pursued through the methodology outlined in Section 3.7.5 in Chapter 3.

Based on PV specification product data, a 250W mono-crystalline panel has a 1.6 m² surface area which indicates 6.4 m² is required to generate 1 kWp while the available site area for PV installation on Building C is 1 200 m² (site area minus south facing roofs). At this point the building energy model was used to simulate for following system:

Peak power:	99 kWp
Number of modules:	394 individual 250 W monocrystalline panels
Total area of array:	633 m²
Electricity generation potential:	104 980 kWh/yr
Angle of panel to the horizontal:	30º

Figure 6.7: Axonometric view of PV array building C

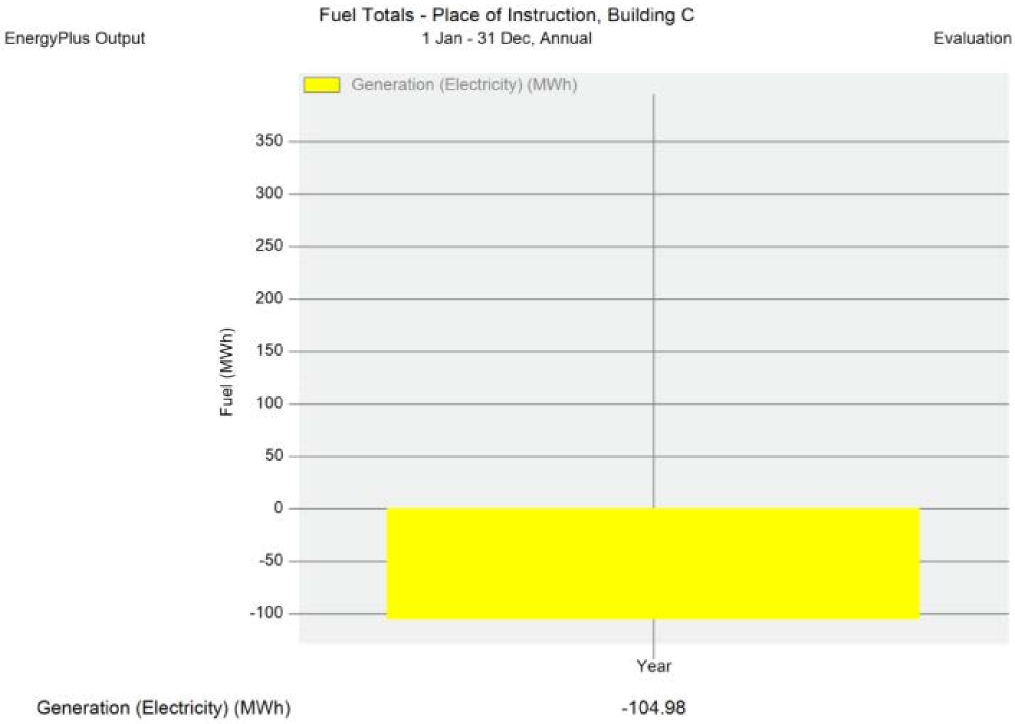


Figure 6.8: Simulated PV generation potential for Building C without shading.

The total electricity generated by the array (excluding areas experiencing shading from the surrounding urban fabric) is 104 980 kWh/yr. From the solar shadow study conducted on the specific site, Building C experiences approximately 37% annual shading of site area suitable for PV installation. This reduces the generation potential to 66 150 kWh/yr.

Consumption-export balance.

As an educational institution, Building C experiences long periods of low or no occupancy, over holidays. During a regular weekday when the college is open to students, its peak loads occur in the late afternoon as the building heats up and more cooling is required. The simulations indicate that during a regular working day, peak PV generation (represented by the green bars in Figure 6.9), occur slightly earlier than do peak loads, but remain below consumption levels. This indicates that all generated electricity is consumed by the building itself. This pattern was congruent with warmer and cooler months. On Sundays and holidays, (which account for 127 days annually), PV generation exceeds the baseload consumption as electricity consumption is much lower over these periods, whilst PV generation remains unchanged, leading thus to the building having excess capacity.

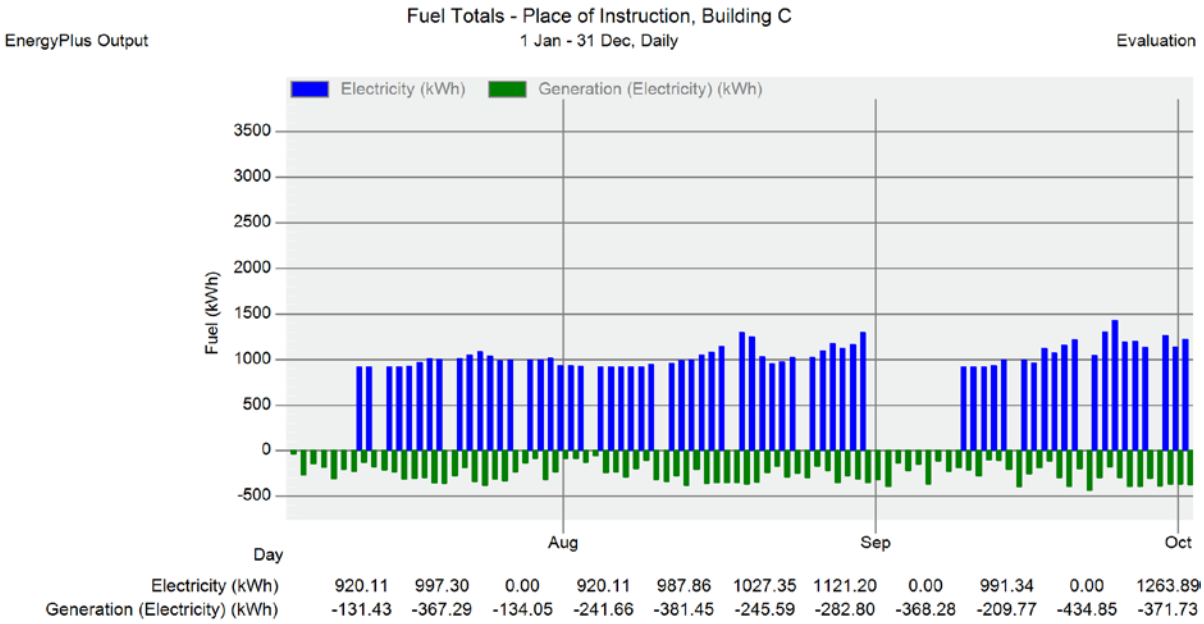


Figure 6.9: Daily generation versus consumption over a period of 3 months

Assuming an ideal scenario where net metering is available, Building C's energy balance would see it consuming roughly 65% of its own electricity generated on-site, whilst exporting the remaining 35%. Based on this split, the value of electricity consumed by the building itself was derived from the shading-modified generation potential value. Building C would therefore consume approximately 43 000 kWh/yr of the overall electricity it generates (66 150 kWh/yr) and this value was used to calculate the payback period.

Payback Period

The simulated PV array also contributed to a 2 000 kWh/yr reduction in the overall consumption of 371 410 kwh/yr through the shading effect of the PV array on the exposed concrete roof slab. This was included as 'savings through shading' in the payback period calculation in the payback period as derived in Table 6.4. The total reduction in yearly consumption (excluding PV generation) is thus 158 200 kWh/yr which constitutes a 30% overall reduction from the baseline.

To calculate the potential return on investment for the PV array, a budgetary rough order of magnitude formula of R20 000 /kWp was used to calculate the estimated cost of 99 kWp array. With professional fees and installation estimated to be 10% of the capital cost, (Maehlum 2014), the overall cost of the PV system is estimated at R 2 .2 million. When calculating the payback period, an electricity tariff inflation level of 8% per annum was used and the net present value (NPV) was calculated using a conservative 5% discount rate. Further to this, maintenance costs were factored at 2% of the price of the installation with a 5% inflation increase per annum. The projected payback period is estimated as 25 years as shown in Table 6.4.

Yr of op	pv gen - shading kWh/yr	Self-Consmp.	Shading Savings kWh/yr	Total Savings kWh/yr	Inflation adjusted tariff (8%)	Savings ZAR	Discount Rate 5% (NPV)	Maintain-ence cost - inflation	Savings total(ZAR)
Yr1	66 150	43 000	2 000	45 000	1.5728	70 776	70 766	R 4 000	66 776
Yr2	66 150	43 000	2 000	45 000	1.6986	76 437	69 330	R 4 200	65 130
Yr3	66 150	43 000	2 000	45 000	1.8345	82 553	71 312	R 4 410	66 902
Yr4	66 150	43 000	2 000	45 000	1.9812	89 154	73 347	R 4 630	68 717
Yr5	66 150	43 000	2 000	45 000	2.1397	96 287	75 443	R 5 600	69 843
Yr6	66 150	43 000	2 000	45 000	2.3109	103 991	77 600	R 5 880	71 720
Yr7	66 150	43 000	2 000	45 000	2.4951	112 280	79 795	R 6 190	73 605
Yr8	66 150	43 000	2 000	45 000	2.6955	121 298	82 100	R 6 500	75 600
Yr9	66 150	43 000	2 000	45 000	2.9942	134 739	86 854	R 6 825	80 029
Yr10	66 150	43 000	2 000	45 000	3.2337	145 517	89 335	R 7 160	82 175
Yr11	66 150	43000	2000	45 000	3.4924	157 158	91 887	7 515	84 372
Yr12	66 150	43 000	2 000	45 000	3.7718	169 731	94 513	R 7 890	86 623
yr13	66 150	43 000	2 000	45 000	4.0735	183 308	97 212	R 8 285	88 927
yr14	66 150	43 000	2 000	45 000	4.3994	197 973	99 990	R 8 700	91 290
									1 071 709

Table 6.4: Derivation of payback period for the PV system applying '12B' tax allowance.

Summary - Case study 3 – Building C (Place of instruction)	
Baseline conditions	
Date of construction	1977
Max bulk zoning regulations (FAR)	general business – FAR 8
Site area	1300 m^2
net floor area	5500 m^2
Coverage	42%
FAR	4.3
Occupancy classification	place of instruction
Design population	1 person/5m^2
Operation schedule	7am-5pm/6days/278 days
SANS max energy consmp. (place of instruction)	400 kWh/m^2/yr
Annual electricity consmp. (actual)	529 610 kWh or 96 kWh/m^2/yr
Simulated results of NZEB interventions.	
% site shading	37%
% reduction in overall consmp. From baseline (passive)	12%
% reduction in overall consmp. From baseline (active)	17%
Overall reduction from active and passive optimisation	156 220 kWh/yr
Reduction through shading by PV array	2000 kWh/yr
PV generation without shading	105 000 kWh/yr 20%
%PV generation potential with shading	105 000 kWh/yr – 38 850 kwh/yr = 66150 kWh/yr
RE consumed on-site	43 000 kWh/yr 65%
RE available for export	23 150 kWh/yr 35%
% Overall electricity reduction	158 220 + 45 000 = 203 220 = 38%
Annual electricity consmp. After NZEB retrofit	326 440 kWh or 60 kWh/m^2
Overall cost	R4 280 000
Estimated total payback period	8 years
Overall CO_2 reduction	160 kg x $(10)^3$/yr

6.5 Baseline condition – Building D (Hotel)

Case study Building D is a ten storey self-catering hotel located on Durban's beachfront. The site has a maximum bulk zoning regulation of 5.3 FAR, with a net floor area of 8 100m² on a 2 039 m² site giving it an actual FAR of 3.9. Walls of the masonry structure are predominantly 220 mm clay brick and are simulated with a thermal resistance of (R-value) of 0.5 m²·K/W). Standard tinted glass and aluminium frames have been simulated with a total solar transmission co-efficient (SHGC) of 0.427 and U-value of 6.066 Km²/W. Slabs (including roof-slab) and columns are cast from reinforced concrete. The schedule of accommodation includes 123 self-catering rooms, two conference rooms, a ground floor café as well as administrative offices on the ground and first floors.

Figure 6.10: Site boundary of Building D (Source: Adapted from Google Maps)

Initially, occupancy density was simulated to SANS 204 standards of two people per room assuming full occupancy. It was re-simulated at 1 person per room to replicate a 50% occupancy rate. The hotel has a café on the ground floor which is open from 7am to 5 pm daily as well as a dedicated conference facilities. Rolling blackouts in 2008 led the owners to retrofit improvements to the HVAC and lighting systems, which included a heat recovery system, additional ice-cooled chillers and the replacement of incandescent and fluorescent lighting with LED among other energy saving systems. A smart card system installed in each room requires guests to insert their key-cards into a switch which activates room electricity during occupancy period. This also ensures that no electrical appliances or systems can be left on when guests are not in the room. These energy efficient retrofits have been included in the baseline model simulation, where the hotel's annual electricity consumption is just over 1MWh.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
100 450	100 430	88 360	100 200	90 790	78 480	82 160	83 240	81 780	80 140	86 750	88 780	1 061 560

Table: 6.5: Monthly energy consumption for Building D.

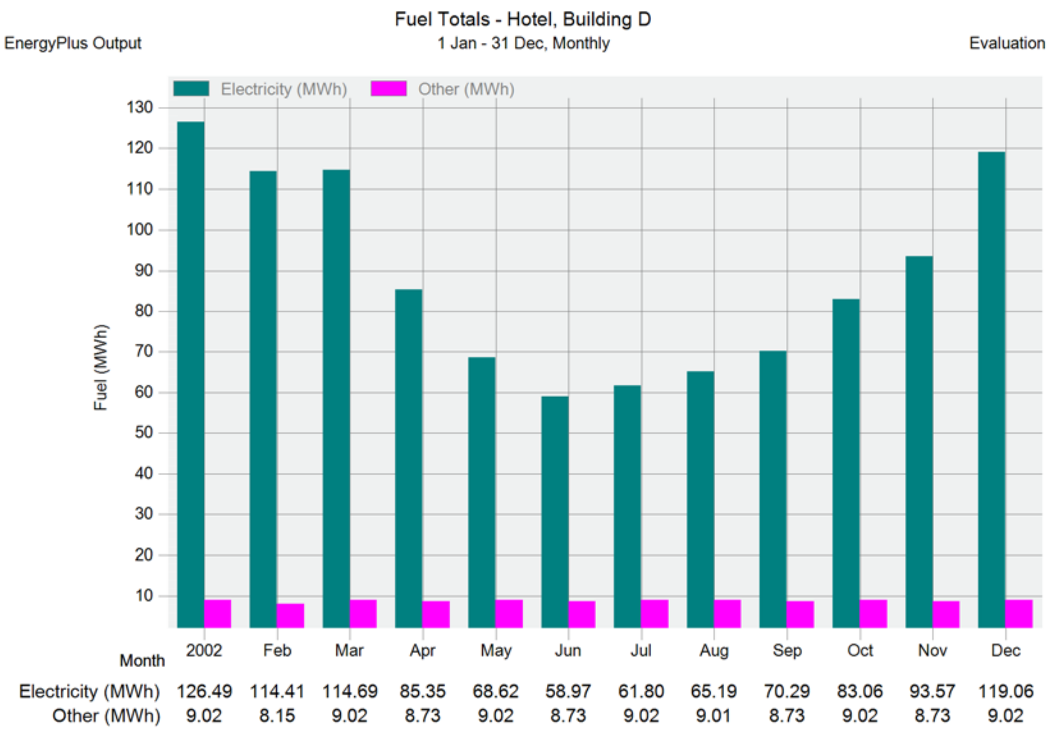
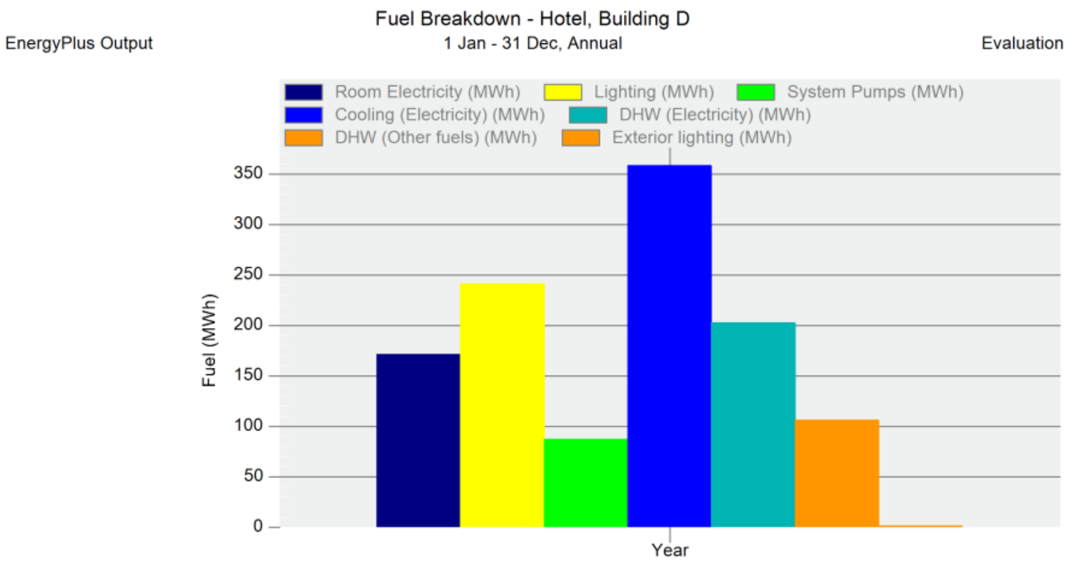


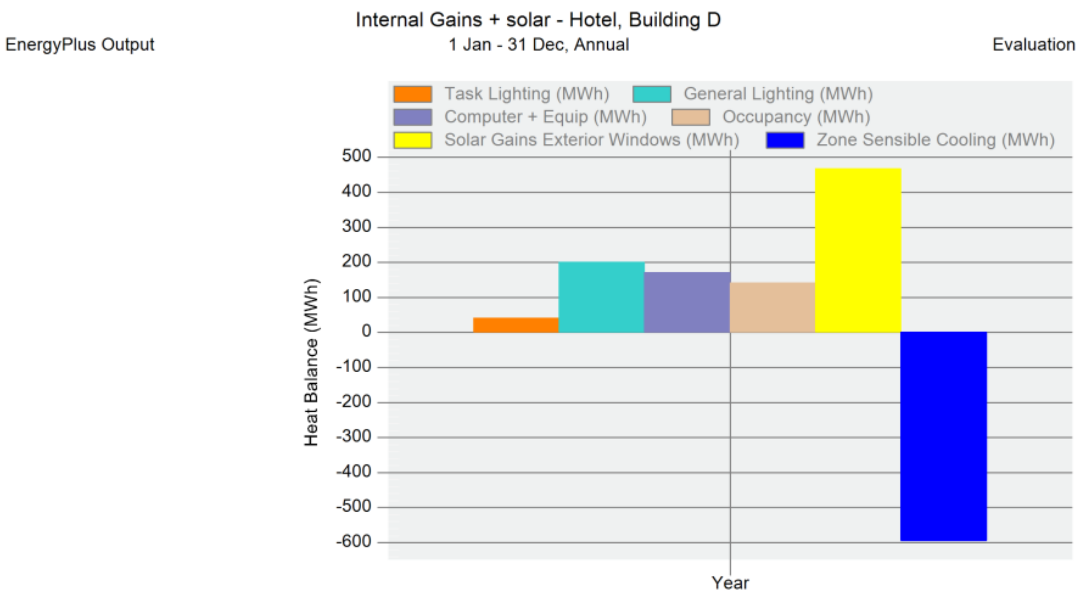
Figure 6.11: Baseline fuel totals for hotel Building D. ('other' fuel totals, represents recovered waste heat from the HVAC system which is utilised in the HWS system)

When comparing monthly data between simulated and metered consumption, the simulated results display a greater variation between the highest and lowest monthly consumption values. In Building D, simulated annual peak demand (which occurs in January) is approximately 20% higher than billed data for the same period. The lowest consumption simulated occurs in June and is approximately 25% lower than billed data averages for the same period. As with office Buildings A and B it is possible that the core of the 'performance gap' can be attributed to the cooling and ventilation. This can be attributed to the influence of weather variations on the HVAC system, as occupancy density, operating times and lighting can be expected to remain constant.



Room Electricity (MWh)	171.13
Lighting (MWh)	241.07
System Pumps (MWh)	87.02
Cooling (Electricity) (MWh)	358.49
DHW (Electricity) (MWh)	202.47
DHW (Other fuels) (MWh)	106.20
Exterior lighting (MWh)	1.32

Figure 6.12: Baseline fuel breakdown by building system.



Task Lighting (MWh)	40.42
General Lighting (MWh)	200.64
Computer + Equip (MWh)	171.13
Occupancy (MWh)	140.69
Solar Gains Exterior Windows (MWh)	467.20
Zone Sensible Cooling (MWh)	-595.13

Figure 6.13: Baseline condition of internal gains and solar gains through fenestration.

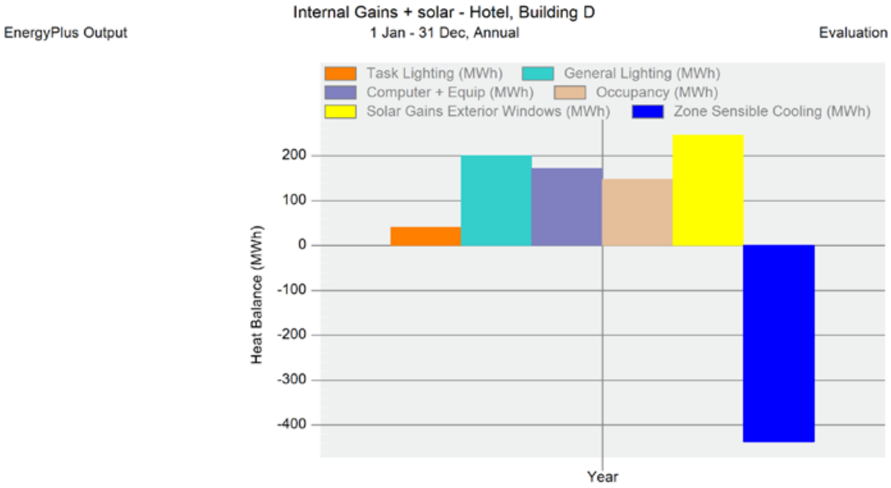
6.6 NZEB interventions – Building D (hotel)

6.6.1 Passive interventions

Vertical solar shield louvres were simulated on the east and west facades with horizontal shading on the north fenestration in order to reduce solar gains, which were thus lowered from 467 200 kWh/yr to 246 290 kWh/yr (a reduction of 220 910 kWh/yr, equivalent to 47% of overall solar gains. The cooling load was lowered from 595 130 kWh/yr to 438 490 kWh/yr, a reduction of 156 640 kWh/yr). Overall electricity consumption was therefore lowered from 1 061498 kWh/yr to 926 330 kWh/yr (a reduction of 135 168 kWh/yr). This was used to calculate the payback period for the solar louvre intervention using a rough budgetary order of magnitude of R900 per m² of glazed area. The shielding was applied to a total of 1 110m² of fenestration at an estimated cost of R1 million, which is then increased to R1.1 through the inclusion of 10% installation and professional fees.

	Saving per yr (kWh)			tariff +8%pa		NPV(5%)	
year 1		135 168		1.5728	212 592	212592	
year2		135 168		1.6986	229 596	192 827	
year3		135 168		1.8345	247 966	214 202	
year 4		135 168		1.9812	267 795	220 316	
year 5		135 168		2.1397	289 219	226 611	
year 6		135 168		2.3109	312 360	233 088	
						1 299 636	

Table 6.6: Derivation of payback period of solar shielding louvres.



	Year
Task Lighting (MWh)	40.42
General Lighting (MWh)	200.64
Computer + Equip (MWh)	171.13
Occupancy (MWh)	147.65
Solar Gains Exterior Windows (MWh)	246.29
Zone Sensible Cooling (MWh)	-438.49

Figure 6.14: Reductions in solar gain and cooling loads after simulating solar shielding louvres.

6.6.2 Active interventions

Unlike the previous case studies, the hotel has already been retrofitted with LED lighting and improvements to the HVAC system. The chiller system has a constant flow primary loop with 3 ice storage banks which initially provided thermal storage during night time from 23h00 to 06h00. The chiller is therefore sized to allow the system to provide the peak cooling capacity with assistance from the ice melt. However, complaints were experienced during the commissioning period while the ice tanks were being charged, and therefore the ice storage system was disabled (thus not reflected in the baseline consumption). The aim of the initial retrofit was to use off-peak power to generate ice, which would then be used instead of electricity for the peak cooling period.

The secondary loop of the system has variable flow as the chilled water circulation pump has its flow delivery controlled with variable speed drive in order to match the water flow required by the space air-conditioning units which have flow control valves which in turn open when the unit temperature controls switch to cooling.

The chiller has a supplementary heat exchanger which is a heat recovery system which produces hot water from heat recovered from the refrigerant. The hot water is circulated through the heat exchanger by a small circulation pump and delivered it to the hot water storage tanks when suitably heated to the set temperature for storage. The heat exchange system saves roughly one-third of the overall HWS consumption which accounts for 106 200 kWh/yr of the 308 670 kWh/yr. The remaining 202 470 kWh/yr required to meet the hot water needs, is met through grid electricity. With overall electricity consumption now reduced by 13% (to 926 330 kWh/yr) through retrofitting solar shielding louvres, the hotel was then modelled with solar PV installation on its available site area.

6.7 PV grid tied proposal

A PV array on available site area was simulated on the available site area in order to test how close the building could get towards achieving net zero energy balance. Based on PV specification product data, a 250W mono-crystalline panel has a 1.6 m² surface area which indicates 6.4 m² is required to generate 1kWp. The available site area for PV installation on Building D is 2 039 m². The building energy model was used to simulate following system:

Peak power:	123kWp
Number of modules:	492 individual 250 W monocrystalline panels
Total area of array:	787 m²
Electricity generation potential:	144 990 kWh/yr
Angle of panel to the horizontal:	30°

Figure 6.15: Axonometric view of Building D with solar PV array.

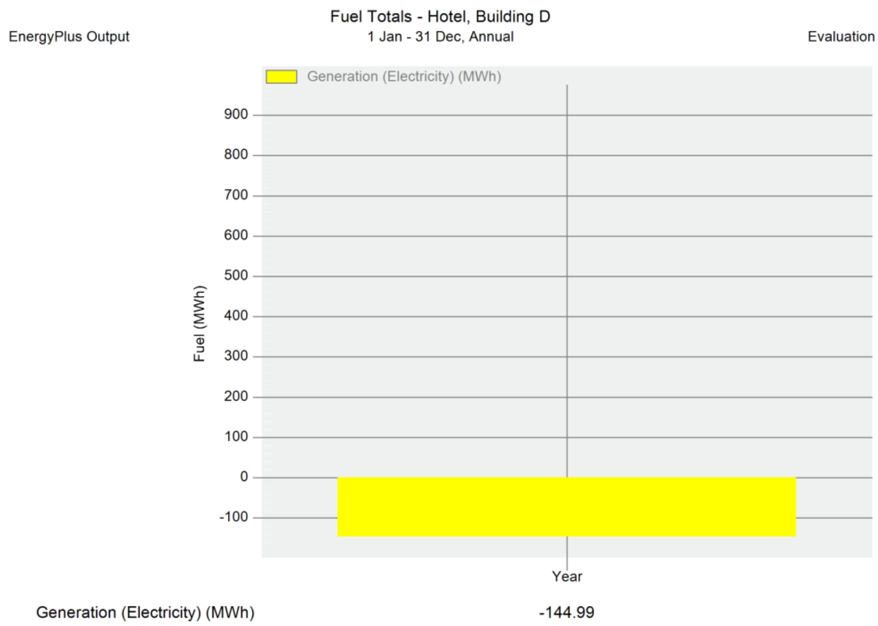


Figure 6.16: PV generation for 1 year without the effects of shading.

The total electricity generated by the array, excluding any form of shading from the surrounding urban fabric is 145 000 kWh/yr. With Building D experiencing approximately 6% annual site shading, this value is reduced to 136 300 kWh/yr.

Consumption-export balance.

The hotel building operates all year around, but unlike the other buildings assessed earlier, it has a different peak consumption demand profile, which, according to simulation results, reflect higher loads in the mornings and evenings, which is more akin to the profile of the residential sector. The simulations indicate that despite monthly consumption values being significantly higher than generation potential, on certain days during certain periods of the year, hourly peak PV generation, represented by the green bars in Figure 6.18 below, is higher than consumption values for that hour. This occurs in most instances between 12-1pm, where generation exceeds consumption by up to 40 kwh for that hour. Over the period of one year it is estimated that approximately 2 % of total generation potential or 2 200 kWh of RE will require to be exported to the grid. Based on this split, the value of electricity consumed by the building itself was derived from the value of shading-modified generation potential. Building D consumes approximately 133 575 kWh/yr or 98% of the electricity it generates on-site and this value was used to calculate the payback period which was estimated as 12 years (see Table 6.7)

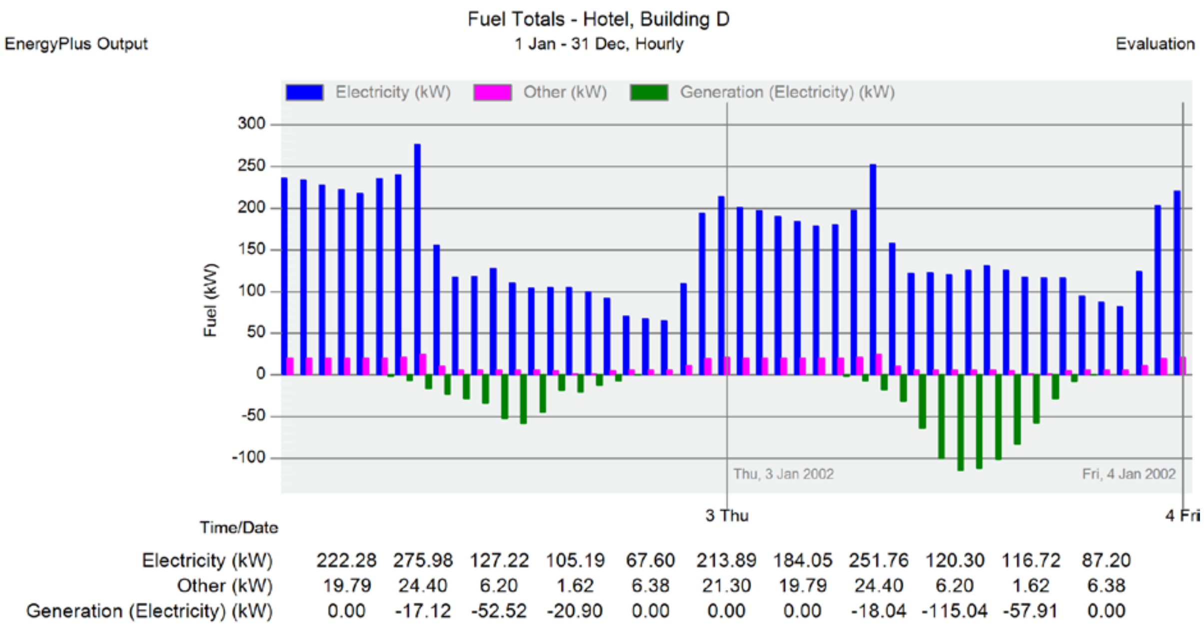


Figure 6.17: Typical hourly consumption and generation over a 48 hour period

Payback period

Overall reduction in electricity consumption from the baseline condition of 1 061 498 kWh/yr to 926 330 kWh/yr was achieved by simulating solar shielding louvres to the fenestrated areas of the east and wet facades. This was decreased by a further 3 650 kWh/yr to 922 680 kwh/yr through the shading effect of the PV array on the exposed concrete roof slab. (This was included as ‘savings through shading’ in the payback period calculation in the payback period table that follows). The total reduction in yearly consumption (excluding PV generation) is thus 138 820 kWh/yr, a 13% overall reduction from the baseline.

To calculate the potential return on investment for the PV array, a budgetary rough order of magnitude formula of R20 000 /kWp was used to calculate the estimated cost of 123 kWp array. With professional fees and installation estimated to be 10% of the capital cost, the overall cost of the PV system is estimated at R 2 .7 million. In order to calculate the payback period, an electricity tariff-inflation level of 8% per annum was used and the net present value (NPV) was calculated using a conservative 5% discount rate. Maintenance costs were factored at 2% of the price of the installation with a 5% inflation increase per annum. The derived payback period is estimated as 12 years as shown in Table 6.7.

Yr of op	pv gen - shading kWh/yr	Self-Consmp.	Shading Savings kWh/yr	Total Savings kWh/yr	Inflation adjusted tariff (8%)	Savings ZAR	Discount Rate 5% (NPV)	Maintain-ence cost - inflation	Savings total(ZAR)
Yr1	136 300	133 575	3 650	137 225	1.5728	215 827	215 827	R 5 400	210 427
Yr2	136 300	133 575	3 650	137 225	1.6986	233 090	227 405	R 5 670	221 735
Yr3	136 300	133 575	3 650	137 225	1.8345	251 739	217 462	R 5 950	211 512
Yr4	136 300	133 575	3 650	137 225	1.9812	271 870	223 668	R 6 250	217 418
Yr5	136 300	133 575	3 650	137 225	2.1397	293 620	230 059	R 6 560	223 499
Yr6	136 300	133 575	3 650	137 225	2.3109	317 113	236 635	R 6 890	229 745
Yr7	136 300	133 575	3 650	137 225	2.4951	342 390	243 330	R 7 235	236 095
Yr8	136 300	133 575	3 650	137 225	2.6955	369 890	250 356	R 7 595	242 761
Yr9	136 300	133 575	3 650	137 225	2.9942	410 879	264 856	R 7 970	256 886
Yr10	136 300	133 575	3 650	137 225	3.2337	443 744	272 420	R 8 370	264 050
Yr11	136 300	133575	3650	137 225	3.4924	479 245	280 205	8 790	271 415
Yr12	136 300	133 575	3 650	137 225	3.7718	517 585	288 210	R 9 230	278 980
									2 864 523

Table 6.7: Derivation of payback period without ‘12B’ tax allowance applied.

Summary – Case study 4 – Building D (Hotel)	
Baseline conditions	
Date of construction	1979
Max bulk zoning regulations (FAR)	general residential 5 – FAR 5.3
Site area	2039 m²
Coverage/net floor area	8100 m²
FAR	3.9
Occupancy classification	hotel
Design population	2 person per rm/+- 1 person per 20m²
Operation schedule	24/7 - 365 days
SANS max energy consmp. (place of instruction)	6 20 kWh/m²/yr
Annual electricity consmp. (actual)	1 061 500 kWh or 131 kWh/m²/yr
Simulated results of NZEB interventions.	
% site shading	6%
% reduction in overall consmp. From baseline (passive)	13%
% reduction in overall consmp. From baseline (active)	na
Overall reduction from passive and active optimisation	135 170 kWh/yr
Reduction through shading by PV array	3 650 kWh/yr
PV generation optimised)without shading	145 000kWh-16%
PV generation (optimised)after shading	145 000kWh- 8 700 kWh =136 300 kWh=13%
RE consumed on-site	133 575 kWh/yr 98%
Re for export	2 725 kWh/yr
Overall electricity reduction	272 400 kWh/yr 26%
Annual electricity consmp. After NZEB retrofit	789 100 kWh or 97 kWh/m²/yr
Overall cost	R3 930 000
Estimated total payback period	4 years
Overall CO_2 reduction	172 x (10) kg³/yr

6.8 Summary of findings

Buildings C and D are both 10 storey buildings with moderate to high FAR. Both buildings have recently undergone forms of renovation with Building C having replaced inefficient HVAC components whilst Building D had undergone lighting retrofits, was fitted with efficient HVAC and a heat recovery system. Despite having the same number of floors and similar FAR, the hotel Building (D) has an annual consumption of roughly double the college (C). This is attributed to its considerably higher floor area and a 24 hr/365 day operation schedule while the college is closed for approximately 3 months annually. Both buildings display relatively low EUI's when compared to nationally stipulated benchmark levels.

6.8.1 Reductions in annual electricity consumption through EE interventions

Buildings C and D were each capable of reducing baseline consumption by 12% and 13% respectively through retrofitting passive energy efficiency measures in the form of solar shielding. Building C achieved a further 17% reduction through the optimisation of lighting, whilst Building D is estimated to already have achieved an 18-20% reduction through the optimisation of lighting (this estimate was obtained by reverse simulating the hotel with less efficient fluorescent lighting which enabled this potential saving to be estimated)

6.8.2 Reduction in annual energy consumption through on-site PV

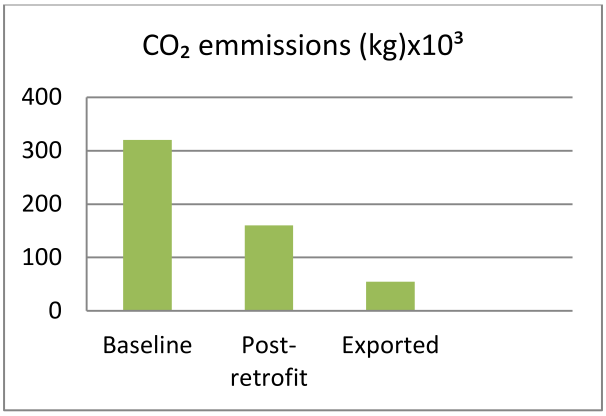
When PV was simulated on available site area, Building C and D were able to reduce annual energy consumption from the grid by a further 12% and 16% respectively. However, the hotel consumed approximately 98% of the electricity it generated on-site, whilst building C was able to consume 65% of its own electricity generated on-site.

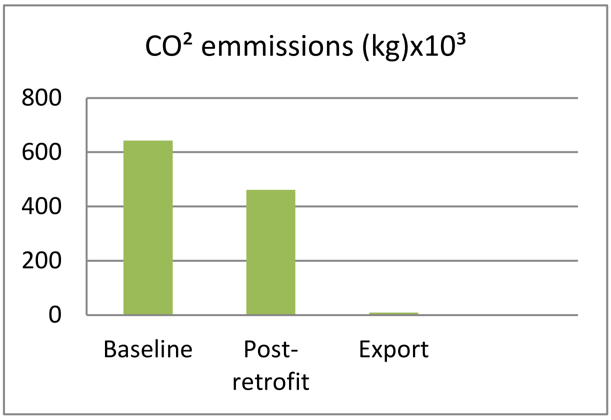
6.8.3 Cost comparison

Unlike the previous comparison of two offices, Building C and D were not retrofitted with identical EE interventions. Although both buildings were retrofitted with solar shielding louvers, the hotel had already been retrofitted with LED and HVAC upgrades. Building C had previously upgraded its HVAC system but was simulated for LED-retrofit. Building C was also found to have an excessively long payback period for its PV system (25 years) that would be unviable without the '12B' RE tax allowance, which is outlined in Chapter 3. The reason for high payback period is due to the high levels of shading (37%) that Building C experiences (which mitigates its generation potential by more than one-third) as well as its relatively low levels of self-consumption (only RE self-consumed by the building has been used to calculate the payback period). Both of these factors contributed significantly to Building C's long payback periods. With the tax allowance applied, the payback period for all interventions was reduced from 12 years to 8 years. Building D experienced very little site shading (6%) and consumed the majority of its self-generated RE, which contributed to a more favourable payback period for PV (12 years) was shortened from 9 years to 4 years.

6.8.4 CO_2 emissions reductions

In Building C, CO_2 emission reductions through retrofitting solar shielding and lighting interventions is estimated to be 160(kg) x 10^3 which is 50% from baseline (the equivalent of taking 31 cars off the road for a year). In Building D, CO_2 emission reductions after implementing solar shielding were reduced by 172(kg) x 10^3 (27%). This was based on a conservative grid emission factor (0.7 $kgCO_2/kWh$)



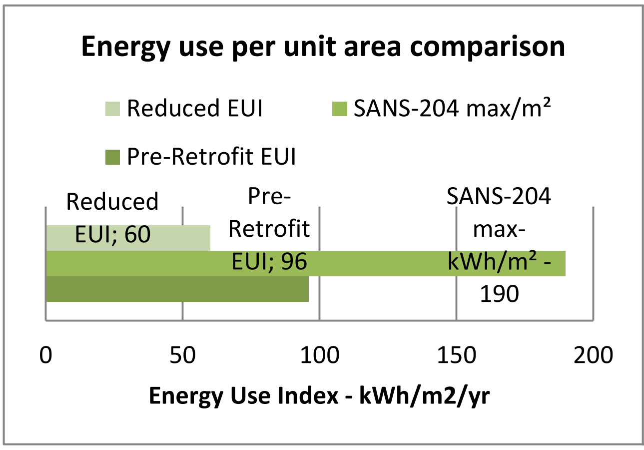


Figures 6.18 and 6.19: CO_2 emissions before and after NZEB interventions. (Building C and D respectively)

6.8.5 Maximum consumption values – SANS 204

Building C (place of instruction) has a FAR of 4.3 with an annual electricity consumption of 144 kWh/m²/yr, thus falling well within the maximum energy consumption levels for places of instruction within climatic zone 5 (as prescribed in SANS 10400-XA), which is 400 kWh/m²/yr. After simulating NZEB interventions, consumption was reduced to 60 kWh/m²/yr – an overall reduction in electricity consumption of 38%. Building D (hotel) has a FAR of 5.3 and an annual baseline electricity consumption of 131 kWh/m²/yr, whereas the

SANS maximum energy consumption levels for hotels in climatic zone 5 is 620 kWh/m²/yr. After NZEB intervention electricity consumption was reduced to 97 kWh/m²/yr.



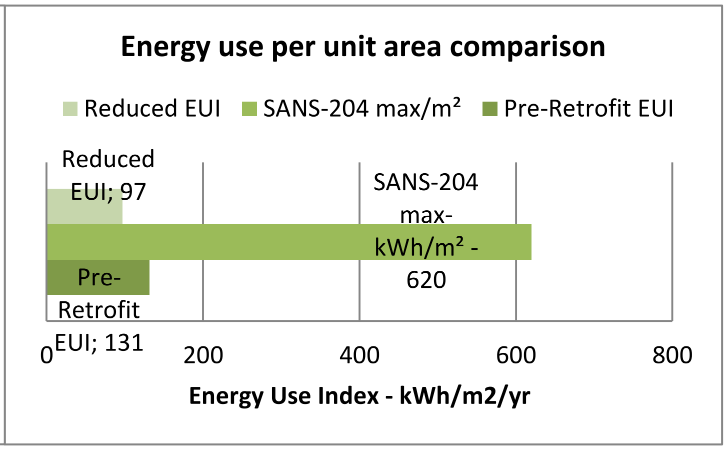


Figure 6.20 and 6.21: Energy consumption per m² before and after NZEB retrofit. (Building C and D respectively)

6.8.6 Conclusion

In the simulated case studies, occupant density and occupancy rates had very little impact on overall EUI. This is partly because, the major consumers amongst building systems (HVAC and lighting and plug loads) do not variably respond to changes in user density. This is true in many commercial buildings, where HVAC and lighting will operate at a constant level, regardless of changes in the number of people in the building. There are also limitations to the simulation methods, which do not effectively capture plug loads in relation to user density, but by area. The study recommends that future research using accurate user density data and user responsive building systems in order to reveal more about the possible correlations.

The operating schedules were found to have a far more significant effect on both EUI and on-site PV potential. Building C, with far fewer operating days in the year, had a far lower EUI which should be beneficial for NZEB optimisation. However, aside from experiencing high shading, Building C required to export in excess of 35% of the already limited generation capacity.

Chapter 7: Consolidation of findings and conclusions

7.1 Introduction

The overall objective of the study was to identify contextual and technical parameters that might influence NZEB retrofit potential in existing commercial buildings which are currently unregulated in terms of energy efficiency, even though they are contributing an estimated 60% of a typical municipality's GHG emissions. It is thus imperative that existing building stock is addressed to ensure that South Africa meets its climate change targets, and as discussed in Chapter 1, this will require "aggressive energy efficiency measures across all sectors," (SEA: 36) as well as the roll out of SSEG's and other renewable energy resources. NZEB has been identified as one such strategy towards ensuring that these targets are met, as it combines EE with RE generation. The challenge for this energy transitions pathway is to provide not only low-carbon electricity generation but also a supply that is affordable and secure. (Hammond 2013) Using energy modelling software as the primary research tool, four buildings were purposely selected, modelled and simulated to reflect their baseline conditions, from which NZEB interventions were simulated to assess:

- The portion of overall building EUI which can be achieved through implementing energy efficiency interventions in the form of passive design and building operation system optimisation. This would translate into energy reduction through energy efficiency interventions
- The extent to which rooftop PV generation can meet the optimised energy requirements. This would translate into energy reduction through renewable energy interventions
- The extent to which differing urban densities effect site shading
- The overall viability of NZEB interventions in the form of simple payback period calculations
- The extent to which carbon emissions can be reduced through the combined interventions

The results from the simulations has been summarised and tabulated below (see Table 7.1), for the purpose of a comparative analysis which has subsequently allowed for the substantiation on sub-questions 1-3, and thus allowing for the overall research question to be resolved.

Table 7.1 Summary of technical simulation sub-findings

Case-Study Building	Date of Const-ruction	Site area (m²)	Floor area (m²)	FAR	Use-density	Operation Schedule	Consumption (EUI) Before/after	% Shading	% Reduction Passive/ Active	PV with Shade Mod.	Overall reduction	Overall cost (ZAR)	Payback	CO2 Reduction
A	1992	2 656	3 980	1.5	1p/15m²	7am-6pm/5dy	216kWh/m²/yr 101kWh/m²/yr	6%	1.3%/33% =34%	38%	65%	6.3 million	5 yr	56%
B	1978	1 232	5 760	4.7	1p/15m²	7am-6pm/5dy	144kWh/m²/yr 77kWh/m²/yr	27%	4%/33% =37%	13%	47%	6.1 million	8 yr	47%
C	1977	1 290	5 500	4.3	1p/5m²	7am-5pm/6dy	96kWh/m²/yr 60kWh/m²/yr	37%	12%/17%=29%	12%	38%	4 million	8 yr	38%
D	1979	2 039	8 100	3.9	1p/20m²	24 hrs/d	131kWh/m²/yr 97kWh/m²/yr	6%	4%/13% =17%	13%	26%	3.8 million	4 yr	26%

7.2 Consolidation of sub-findings based on research sub-questions

7.2.1 Sub-question 1

What is the effect of urban density and zoning regulations on solar resource on specific sites and stands and how can insights gained guide subsequent densification regulations and development rights?

In Chapter 6, the study analysed the effect of shading on each of the case study buildings/sites with the aim of assessing its effect on their overall NZEB potential. The effect of zoning regulations and urban density on solar availability for the case study buildings revealed that the shading factor for the low density context of Building A was approximately 6% over the simulated period from 22 June to 21 December. The shading factor for the high urban density context of Building B through the same period was 27%, while High urban density Building C, experiences 37% shading of the available site area for PV. Medium density zoned Building D experienced site shading of 6%.

As was hypothesised, the study finds that there is clearly a greater incidence of site shading in high density urban zones of the CBD when compared to medium and low density zones in areas surrounding the CBD. Its effect on NZEB potential is most significant in relation to PV generation potential, which was reduced by between a quarter and a third due to the effect of shading in high density urban zones. However, the balance between urban density and solar availability should also be looked at in terms of daylighting potential, where if buildings are designed effectively and fitted with smart sensors, natural lighting can reduce lighting loads which has a knock on effect on cooling loads which compound to lower EUI significantly.

7.2.2 Implications of shading on generation capacity

Without taking into account the effect of site shading, Building A in a low density zone, has a generation potential of 37% of its optimised 580 000 kWh/yr grid-electricity consumption using on-site PV whilst Building B in the high density zone had a generation potential of 26% of its optimised 536 000 kWh/yr consumption. These percentages were modified to 34% and 20% respectively due to obstructions in the form of tall surrounding buildings. Building C was able to generate 28% of its 373 390 kWh/yr optimised consumption whilst generation potential for the hotel (Building D) was 16% of its optimised 926 330 kWh/yr consumption.

These percentages are modified to 21% and 13% respectively when the effect of respective site shading is taken into account.

7.2.3 Overall effect of site shading on NZEB potential

In a low density urban environment, shading of available site area for PV moderated generation potential by an insignificant level of 6%, which reduces overall NZEB potential by 2% in relation to optimised annual consumption. In high density urban zones, shading accounted for a 27% to 37% decrease in PV generation capacity in buildings B and C respectively. When calculated as a percentage of the optimised annual electricity consumption, overall NZEB potential was reduced by 3% and 10% respectively. Shading of the hotel (Building D) in a medium density urban zone was responsible for a 6% moderation in annual site PV generation potential, or a 1% reduction overall NZEB potential. The key sub-finding of the analysis is that increased urban density can reduce PV generation significantly, which can in turn compromise the payback period and hence the levelised cost of electricity to a point where it may not be economically viable.

7.2.4 Densification regulations and development rights with regard to solar access for on-site PV

Section 2.4 (see Chapter 2, page 17) highlights the importance of pursuing a balance between achieving high density development whilst maintaining solar access for on-site PV generation. This reflects the complex interactions between fixed site areas, maximum density targets, coverage and FAR restrictions versus optimal FAR for rental revenue purposes. Previous studies by Sarralde (2016) and Amado et al (2016) suggest that at high densities, random variation in building height as well as random variation in horizontal space between buildings is beneficial for maintaining solar access to ground and lower floor facades. Cheng et al (2006) assert that "High site coverage is in general not preferable as it undermines daylight and solar potential on ground and building façade, however, the extensive roof surface provided by high site coverage development is a major source for high level solar radiation which makes it advantageous for PV application." (ibid 5) There is thus a need to ensure a reasonable balance between optimising urban density for solar access (and its positive effect on natural lighting) and optimising urban density for PV generation potential.

7.2.5 Conclusion and discussion

As the uptake of passive design techniques and PV continues to increase, determining the correct form, height and layout of buildings so that they do not adversely affect surrounding buildings in terms of blocking solar resource will become a critical challenge for planners. This notion has inherent conflicts with contemporary sustainable urban planning strategies, where high density development is favoured for its compaction of urban form, and the associated socio-economic and environmental benefits relating to reduced reliance on the auto-mobile through situating a significant proportion of city residents close to hubs of economic activity. On the one hand, existing buildings have a right to solar access for their operation. Blocking solar availability has the potential to affect operating costs and capital value of the affected building. On the other hand, new developments are required to achieve good density, and if the development of an adjoining site is affected by restrictions due to solar availability requirements, it too can experience a sudden drop in value hence setting up the inherent tension between urban density and solar availability. (Littlefair 1998)

This could be problematic in terms of buildings which are aiming to or are already achieving NZEB through on-site PV generation. At high densities the amount of solar radiation for both passive solar design and PV generation can greatly affect a building's overall operational performance in terms of energy use and production. In such instances, centralised PV generation, where large PV plants are located outside the city, could be an alternative for very dense urban environments, although the benefits of a network that is not subject to line losses, resilient to a single point of failure and do not take up large areas of wildlife habitat or agricultural land are forfeited.

Centralised PV generation off-site does not however address the issue of solar access for passive design opportunities such as natural lighting and ventilation, which can impact NZEB significantly and should play a significant role in formulating development rights. For this reason the study guides the findings and conclusion that solar access for PV should not be the primary moderating factor when formulating development rights and zoning regulations as well as because decentralised generation connected in a smart grid could also help to circumvent the issue of excessive shading, by connecting buildings with little shading and good space for PV to those that are being overshadowed with a low generation potential. Although various studies have shown that it is possible to achieve high density developments whilst mitigating a compromise of solar access, there is inevitably a trade-off between solar access and increased density, especially when the density is increased the number of floors.

7.3 Sub-Question 2

What is the significance of FAR on EUI and NZEB potential?

In Chapter 4, the study examined the relationship between FAR, EUI and NZEB potential and found that although office Building A has a smaller FAR (1.5) than office Building B (4.7), its EUI is considerably higher at 216 kWh/m²/yr than the latter which is 146 kWh/m²/yr. Despite a general trend, where smaller office buildings were found to have lower EUI, it is not uncommon for smaller buildings to have a high EUI. After simulating EE interventions, the study finds that the energy intensive Building A was able to achieve 33% reductions which are comparable to that of Building B's reductions of 32%.

Given the findings from this comparison, it can thus be argued that FAR is not necessarily a good guide-factor on EUI as the office with a significantly lower FAR has a higher energy use per unit area (m²). This is predominantly attributed to energy intensive building systems, and exacerbated by poor passive design. There is also very limited shading from surrounding buildings, which can be deemed to be an outcome of zoning regulations for the mixed use neighbourhood. Building A is thus exposed to solar radiation all day which is advantageous for on-site PV generation but increases solar gain through the building fabric. FAR can be used as an indicator ton the extent to which a building will experience high levels of solar radiation, particularly when analysed along with site coverage and orientation. But to what extent this affects cooling loads due to heat gain and overall EUI would require a more complex urban modelling strategy which is beyond the scope and simulation-capability of this study.

There are however some clues provided on the effect of solar radiation and shading on EUI. In the case of Building A, shading from the PV panels simulated on the flat concrete roof slab of the building, reduced the cooling load by a significant 36 800 kWh/yr. This indicates that in hot coastal climates such as Durban, shading of buildings from direct solar radiation can have a significant impact on reducing EUI by lowering cooling loads. The saving through shading the roof slab is nearly 20% of the total electricity generated by the array, indicating that in hot humid coastal climates, the effect of shading will generally lower cooling loads and thus overall EUI.

7.3.1 The effect of FAR on on-site PV generation potential

What makes office Building A able to achieve better results in terms of overall reductions in EUI compared to Building B? Both buildings were retrofitted with the same set of EE interventions and simulated with PV on their available site areas. This indicates the majority of Building A's reduction can be attributed to its solar PV generation potential, which was able to generate nearly 40% of its annual consumption needs when compared to Building B which had generation potential of just under 20%. Generation potential is directly affected by the amount of available site area for PV and the extent of shading of that area.

The higher ratio of reductions achieved in building A can be attributed to its doubling the site-space for installation of PV and hence generation capacity in relation to its optimised EUI which is normalised by floor area. This is enhanced by the fact that there is far less shading of the PV system in building A, which is directly related to a buildings location within the urban fabric, particularly in terms of the effect and prevalence of shading of available site area by adjacent buildings.

In Building A, the ratio of area available for PV installation to net floor area was calculated as 1: 2.2 which translates to more PV area to unit floor area. In the case of Building B, that ratio is 1: 6 which translated into less space available for PV per unit floor area. Despite having a smaller area for PV, building B's 100% site coverage seems to have a positive effect on its PV potential, due to the resultant 0% shading of available area by the building itself. In the case of Building A, the larger site area available for PV combined with the very low levels of shading from adjacent buildings, significantly enhanced the potential for on-site PV generation (at 50% site coverage, approximately half of the 6% site shading can be attributed to shading from the building itself.) It can conversely be argued that the baseline EUI of Building A is increased through increased solar exposure. The extent of such impacts fall beyond the scope of this study.

7.3.2 The effect of FAR on capital cost and payback periods and hence NZEB

The cost of implementing EE interventions in the higher FAR Building B was higher due to its larger net floor area. In addition, it had less available space for the installation of PV which therefore dictated a smaller array thereby lowering the overall cost of PV when compared to Building A, which was able to accommodate a much larger array. This balanced out the overall cost of the NZEB retrofits, which were similar at R6.1 and R6.3 million respectively. When the 3 year tax allowance was applied to the PV interventions of both buildings, the most significant difference was found to occur in the estimated payback periods. The low FAR Building A yields a payback period of 5-6 years whilst Building B has a payback period that is nearly double, at10 years. This is due to Building A having lower capital costs for EE interventions as well as high PV generation capacity, from which fiscal savings after year 3 were significant enough to pay off the EE interventions in 1-2 years. Having a much smaller generation potential, Building B's savings after 3 years contributed significantly less to mitigating the longer payback period.

7.3.4 Conclusion and discussion

Whereas FAR may not serve as a good indicator of building EUI based on the above findings, it influences PV generation potential as well as the payback period of the overall retrofit. This leads to the finding that lower FAR can generally be expected to be beneficial for on-site PV generation but its efficacy as an NZEB indicator can be enhanced by considering the site coverage and orientation, where higher coverage and higher FAR could positively affect PV space but increase shading of surrounding sites. On the other hand, low coverage high FAR developments can create significant shading of their own site area if not appropriately orientated.

7.4 Sub-question 3

What is the significance of building use-type (occupancy density and operating hours) on EUI and NZEB potential?

7.4.1 Occupant density

In Chapter 5, the study substantiated on the relationship between occupancy density and operating schedules on NZEB potential by analysing two buildings of different use-types and hence occupation density as per building regulations as well as variation in operating periods throughout the year. Results from Chapter 4 (on the two office buildings) have been incorporated with findings in Chapter 5 in order to substantiate on sub-question 3.

The office buildings analysed in Chapter 4 were simulated at a density of 1 person/15 m² and displayed very similar internal heat gains (due to occupancy) of 17 107 kWh/m²/yr and

17 541 kWh/m²/yr which was 13% and 17% of total internal heat gains respectively. Building C (place of instruction) was simulated with an occupancy density for teaching areas of 1 person/5m², which led to internal heat gains (from metabolic activity) of 28 553 kWh/m²/yr or 23% of the total for internal gains. For full occupancy, the hotel, was simulated at 2 persons per room or approximately 1 person/20 m² resulting in internal heat gains due to user activity of 18 520 kWh/m²/yr or 14% of total internal heat gains. In order to derive consumption levels at 50% guest occupancy, the hotel building was re-simulated after adjusting occupancy density input to 1 person/10 m² in order to explore the effect on heat gains, cooling loads and overall electricity consumption. Internal heat gains attributed to occupancy decreased from 140 690 kWh/m²/yr to 110 600 kWh/m²/yr, and thus reducing cooling loads by 32 570 kWh/yr. This led to an overall annual consumption reduction of approximately 1.5 % or 15 500 kWh/yr. Thus the effect of internal heat gains through user metabolic process can be considered to be negligible in its impact on overall EUI.

Heat gains from user metabolic activities contribute between 6% and 10% more in Building C, which has the highest population density, compared to the others. However, as heat gains through occupancy constitute the lowest portion of internal gains, their effect on building EUI is less significant compared to gains experienced from technical services such as lighting and HVAC or through site specific factors such as solar gains. On the other hand, the higher population density can increase the amount of equipment associated with user activities such as cooking, HWS and appliance plug loads. Thus it can be asserted that increased population density increases building EUI, but the extent of this increase is more likely to manifest through consumption by related equipment and operating schedules.

7.4.2 The effect of building operation schedules on EUI

More significant than occupancy density is the duration of time that a building operates. This is evident from simulations of Building C in Chapter 5 where despite the place of instruction having occupancy gains higher than the other buildings, it displayed the lowest annual consumption. This can be attributed to its operation schedule where it is closed for 87 days of the year for holidays, thus greatly reducing its annual consumption. Conversely, the hotel (Building D) which operates all-year round and thus displayed the highest consumption levels, also has the highest EUI after NZEB retrofits.

7.4.3 The effect of building use-type on grid tied PV potential.

As alluded to under the literature review, (see chapter 2, Section 2.4) export of surplus generated by PV systems to the municipal grid with net metering is yet to be implemented and regulated in SA. However the theoretical implications of SSEG's and smart grids have been explored in order to assess their efficacy. For office buildings in warm climates such as Durban that operate on a daily schedule and are closed by night, PV is particularly effective as peak PV generation and peak loads tend to overlap due to cooling loads peaking in the afternoon. In the specific case study office buildings assessed in Chapter 4, peak generation was never greater than peak consumption, thus the buildings consumed the electricity they generated instantaneously, thus negating the need to store or export surplus to the grid. However, as the buildings are closed on weekends, their baseload consumption over these periods is greatly reduced, while the PV continues to generate electricity. Unless this excess is stored or fed back to the grid, it would translate to a waste of emissions free energy.

Places of instruction (which include colleges, universities and schools) are in most instances closed for student holidays. This can have a significant impact on deciding on the viability of on-site PV. With an increase in days that the building is not fully operational, comes excess capacity for those days, meaning that the building would rely on the grid to export a significant amount of electricity. The feasibility of exporting to the grid is dependent on connection and feed in tariffs, and/or market opportunity to transact on carbon credits.

For the case study buildings the offices consumed roughly 70% of their own electricity over five days, with two days off (weekends). The college, which was simulated with a 6 day operating schedule and student holidays, consumed just less than 65% of electricity generated on-site while the hotel was able to consume approximately 98% of its site generated electricity.

Operating schedules are therefore an important factor on viability of on-site PV generation, where buildings that consume a higher portion of energy generated on-site over a year lessen their reliance on the grid and improve their NZEB potential. The overall viability and practicality of NZEBs is connected to SSEG's and micro-grids as discussed in the following section.

7.5 Centralised versus decentralised electricity generation

7.5.1 Source Energy and Site Energy

"Source energy traces the heat and electricity requirements of the building back to the raw fuel input, thereby accounting for any losses and enabling a full thermodynamic assessment (EPA 2018:1). On the other hand, site energy is "the amount of heat and electricity consumed by a building as reflected in utility bills" (ibid). Source energy is regarded as being the most equitable metric for assessing energy efficiency, as it accounts for all the energy that is required to convert, generate and transmit it to site. (ibid)

The ratio of energy that is required to convert, generate and transport 1 unit of electricity from a coal fired plant to site (including the losses incurred from these processes) is known as the source-site ratio and can vary between countries, generation methods, utility providers, quality of infrastructure, fuel type etc. According to the US EPA, the national source to site ratio for conventional fossil fuel based grid electricity delivered to site is approximately 3 for the USA and 2 for Canada.(ibid) Simply put, it would take 2-3 units of energy to deliver 1 usable unit to site. This is significant in terms of CO_2 emissions as higher source-to-site ratios lead to higher emission levels.

RE generated on-site is classified as having a site to source ratio of 1 as it has negligible conversion, distribution and transmission losses (ibid) This indicates that for every 1kwh of RE generated on-site and consumed by the building, it is able to offset its consumption of fossil fuel based energy and thus emissions by a conversion factor equivalent to that of the source-site ratio. By generating and consuming RE on-site, GHG emissions reductions (when accounting for net source energy) rise proportionally to the conversion factor, which for coal fired electricity generation is generally very high across nations. "Much of increased carbon impact from residential and commercial electricity use comes from power plants and the relatively inefficient 'full fuel cycle' of production and delivery of electricity to buildings" (Czachorski & Leslie 2009:1). Thus, generating RE on-site is advantageous to NZEB as it emphasises the need to optimise building EUI (as space for PV is limited) as well as mitigating losses through generation, conversion and transmission.

7.5.2 Smart-grids

Theoretically, the widespread implementation of EE optimisation and the installation of PV in existing commercial buildings can contribute substantially to electricity demands in pursuit of sustainable city energy balance when connected in a smart micro-grid network. (Amado et al 2016) In theory, buildings can be connected to a micro-grid in a series of cellular networks, while still remaining connected to the centralised distribution network, thus allowing buildings or neighbourhoods to trade low carbon electricity in micro pools. The emergence of the smart-grid concept sees “electricity tariffs varying according to the time of day and year, the value of electricity drawn from or exported to the grid will affect the building operator financially and can thus be used as a steering mechanism” (Voss et al. 2011: 47) This allows buildings with excess generation to export clean electricity to other buildings in the micro-grid that are experiencing high loads or generally have a higher EUI. Micro-grids essentially transform the building into its own localised electricity generator that raises “the reliability, resilience, security, efficiency and quality of the electrical services and supply.” (Massoud 2016: 49)

However, small scale distributed generation (SSDG) does however present challenges, as in South Africa, where technical, regulatory and administrative aspects of all power from the central utility to the end-user are structured to support a one way flow electrical grid (Sewchurran et. al 2016). SSDG requires a bi-directional flow of electricity within the grid system which can negatively impact the quality and supply of power flow (ibid). One such problem of using the grid as a battery is the export of electricity during the day when there is low demand for it. In South Africa currently municipalities do not offer grid-feed tariffs, although in certain instances they have allowed a fixed monthly grid connection fee with very low feed-in tariffs which serves as a disincentive. (ibid) Thus the feasibility of PV SSDG is largely dependent on higher levels of self- consumption by the building users.

7.5.3 Testing the smart grid concept.

Through analysis of the simulated case study buildings it is apparent that the viability of NZEB depends largely on the quality of a buildings connection to the grid. This leaves no choice but for NZEB optimised buildings generating PV on-site to rely on the grid for RE-backup in times of excess generation.

If the smart grid concept of sharing RE in a power pool was applied to the case study buildings, (the buildings being connected to one another through the municipal grid) a theoretical analysis of the viability of the smart grid could be possible. Office Building A generates a total of 200 000kWh/yr, of which it utilises approximately70% or 140 000 kWh/yr. This is due to the building being closed on weekends where consumption figures are much lower and PV generation is greater. Building A thus has approximately 60 000 kWh of emission free RE to supply to a micro-grid over the course of one year. However this is on Saturdays and Sundays mainly when generation peaks around midday and early afternoon. Building B uses the same percentage or roughly 40 000 kWh/yr of self-generated RE and also at identical times as Building A, thus they have a combined surplus of RE that would be exported to the grid on weekends. Building C has a larger percentage of exported energy due to student holidays. Despite Hotel building D being continually open, its EE optimisation means that its peak daily generation is also between 12 and 1 pm, when its peak consumption is at its lowest, thus it would not require the excess generation by the other buildings. Thus in the theoretical scenario whereby the four buildings could share RE, none of them would need it at the time it was being exported. This would render the smart-grid ineffective as the grid does not require RE generated at the times that it is being exported. This highlights the limitations of on-site generation in the absence of micro-grid battery storage system.

7.6 Consolidation of findings and main research question

Without well adapted regulatory codes for existing buildings in South Africa, the decision on the implementation of energy efficiency retrofits remains voluntary, with economic factors such as high capital costs, lack of financial tools, policy support and incentives having previously been commonly cited as barriers to implementation. (Wafula 2012),(Jagaran et al 2016), (Darko et al 2016). However, increasing professional team know-how, an increasing desire for ‘green’ corporate image, stakeholder awareness as well as improvements in financial tools are likely to play significant roles in the successful expediting the up-take of NZEB retrofits. (UNDP 2012)

South Africa’s recently introduced solar PV tax allowance is one such example of the drive to expedite the integration of RE in the commercial building sector. This comes at a time when there has been a simultaneously effort towards lowering existing building EUI, which has been driven to some extent, by market forces which include on the demand side, rapidly escalating conventional electricity tariffs, as well as on the supply side, by advances in building science performance simulation and the prevailing cost and efficiency regimes related to EE technologies. As discussed in Section 7.4, on-site RE generation also has the added benefit of reducing grid-consumption and GHG emissions, due to the mitigation of conversion and transmission losses. This is creating favourable conditions in the socio-technical landscape where the opportunity for introducing aggressive cost effective carbon reduction strategies at a building scale is gradually emerging.

Contextual parameters that affect performance optimisation outcomes for NZEB commercial retrofits include climatic conditions and the immediate urban surroundings. In terms of NZEB, climatic conditions are used to guide appropriate passive design responses with the aim of reducing EUI. Despite requiring different responses to passive design, the NZEB framework for implementing interventions follows the same hierarchical protocol which involves reducing EUI through passive design and active system optimisation before introducing RE generation. The GBCSA energy and water benchmark study, found insignificant variations in simulated EUI outcomes, when identical office buildings were simulated under greatly varying climatic conditions (Bannister et al 2012).

For a humid sub-tropical coastal climate such as Durban, cooling is required for commercial buildings, the majority of the year round. As well as being found to be consistently the largest consumer of electricity amongst building systems, air-conditioning systems are also the single largest consumer of electricity across all commercial building use-types. Natural cross ventilation, although one of the passive design response prescribed for such climates was found to be unsuitable both in terms of the requirement for cellular office layouts (which mitigates cross-ventilation) and in terms of noise and air contamination, which were also deemed undesirable for both offices and learning institutions in dense urban environment. For the hotel, the warm evenings Durban experiences resulted in the decommissioning of a newly installed air-conditioning ice chiller, due to its incompatibility with the charging cycle(which required a full 12 hours) and guest preferences for air-conditioning during both day and night.

Main Research Question

What are the contextual and technical parameters that would influence performance optimisation outcomes of NZEB retrofits for existing commercial buildings based on EE and on-site PV generation interventions?

In order to consolidate on the contextual and technical parameters that would positively influence NZEB performance optimisation, the key findings can be summarised as follows:

- Lower zoning densities translate to lower levels of site shading from the surrounding urban fabric. Conversely higher levels of direct solar radiation on building envelope will generally increase EUI
- Lower FAR indicate a larger availability of effective site area available for the installation of solar PV in relation to the building EUI.
- Higher site coverage is generally better for PV potential but negatively affects daylighting levels. Lower site coverage is more likely to contribute to more shading from the building itself
- Payback periods are dependent on the extent of reduction in consumption levels through cost-optimal passive design interventions and active system optimisation, whilst also being positively affected by lower FAR because of the ratio between net floor area and area available for PV generation
- Variations in occupancy densities do not produce significant variations in EUI but operation schedules do have a significant effect on viability of grid tied PV generation especially where feed-in-tariffs are not applicable.
- Building use-types that operate at 7 days a week will benefit from consuming a greater portion of self-generated RE, when using on-site solar PV. This improves the overall economic viability of the NZEB using on-site PV when compared to building use types that operate for fewer days, hence consuming less of their own generation.

7.7 Conclusion and discussion

Arising from the sub-findings the study concludes that the primary technical and contextual parameters that influence NZEB optimisation outcomes can be summarised as follows: Lighting and HVAC contribute significantly to building EUI and optimising these systems can reduce EUI significantly. On average, plug loads are the third highest contributor to EUI. Substantial shading experienced in high density urban environments (where between one quarter to one third of the installed PV generation potential was lost due to shading from surrounding buildings) indicates that on-site PV generation is a less effective RE generation solution in high density urban contexts. However, one of the key findings of the study is that shading of direct solar radiation due to PV-installation can reduce heat gains, cooling loads and thus the overall EUI as well.

FAR was found to be a poor indicator of building EUI, even though lower FAR generally indicated a higher ratio of available PV area relative to net floor area. Occupant-density was found to have negligible impact in overall electricity consumption for Durban's climatic zone.

The study however finds that longer operating periods would in most instances increase EUI while positively affecting the balance of on-site generated RE consumed by the building. This highlights perhaps one of the more important findings of the study, that different commercial building use-types are not equally suited to NZEB optimisation with on-site PV especially when viability is factored into the analysis. Commercial buildings in warm climates such as Durban that predominantly operate on a daily schedule will benefit from PV particularly as peak generation and peak demand tend to overlap due to cooling loads peaking in the afternoon. In contrast, hotels generally have higher EUI due to their 24/7 operation, and are therefore suited for on-site generation, as they have a high self-consumption rate despite the fact that their peak demand occurs outside of PV peak generation. Buildings that are closed for long periods such as schools and colleges are less well suited for on-site PV generation, as their export surplus is high, while no reasonable feed-in tariff exists. Under current technical and regulatory conditions, the key conclusion is that NZEB optimisation using on-site PV in the commercial sector is not a one-size-fits-all solution. Instead certain building use-types are better suited for this than others, especially with regard to on-site generation rather than EUI optimisation.

The study has revealed that significant benefits can be achieved by retrofitting existing commercial buildings towards achieving NZEB. Reductions in annual electricity consumption of between 26-56% were observed across the buildings studied despite annual baseline electricity values already being well below the recommended maximum energy consumption values stipulated in SANS 10 400-XA in three of the buildings, thus indicating that the benchmark figures are too lenient, particularly when compared to SA's carbon emission reduction targets. The study also finds that the 'accelerated capital tax allowance' in the recently amended 'Section 12B of the Income Tax Act No.58 of 1962', which allows RE equipment to be deducted on a 50/30/20 basis over the first 3 years after installation, could be beneficial for exploring various RE options as it also applies to wind, hydro and biomass. In the context of this study, the act reduced payback periods for PV, which where typically 9-12 years, to 3years. Electricity generated by PV after the 3 year-period was used to pay off EE interventions, bringing overall payback periods for NZEB retrofits down by 2-3 years. Payback periods of 4-5 years were achieved in two of the case studies, and 6 to 8 years in the other two. This highlights another significant finding, where high levels of site-shading can reduce generation potential significantly, thereby driving payback periods up. Payback periods under 5 years are considered to be acceptable under prevailing efficiency and cost levels of the assessed interventions, and future gains in both factors are likely to improve on the payback-period.

The study also illustrates that for the majority of commercial buildings, reaching a 'net zero' status using on-site PV is impossible at prevailing levels of technical efficiency, due to two reasons. Firstly, under current EE technologies and costs, EUI cannot be reduced significantly enough for the balance to be met by PV and secondly, the size of the batteries or the amount of excess capacity exported would simply be too large. However, this is not the goal of NZEB. Instead NZEB philosophy is a rational methodology for improving energy efficiency and reducing GHG emissions by balancing optimised energy consumption with RE generation. But what would be the effect of wide-scale implementation of NZEB retrofits in existing buildings? Should and how could we expedite the large scale implementation of NZEB PV in commercial buildings under prevailing economic and technical conditions? How can this be done while still ensuring value and increased competitive advantage for various stakeholders, including local municipalities, who risk a considerable loss of revenue from their sale of grid-electricity.

7.8 Recommendations and future research

The NZEB building optimisation protocol offers an effective methodology for achieving South Africa's Nationally Determined Contribution (NDC) targets of 38% (from BAU) by 2050 within the existing-building sub-sector. (SEA 2015) However, the study finds that its diffusion into the mainstream, EE building practices remains highly dependent on the evolution of SSEG's within the broader regulatory, economic, socio-technical and market contexts. Drivers of distributed on-site generation have been identified as "feed in tariffs, net metering, net billing, self- consumption and generation export tariffs" (Sewchurran et al 2016: 68).The study highlights the dilemma facing the integration of SSEG to the grids, on one the hand, while on the other RE generated on-site can greatly reduce demand and consumption of fossil fuel based electricity, but may also have the effect of disrupting the existing supply grid with a surplus of exported energy at off-peak demand periods. This also creates an inherent conflict of interest between South Africa's commitments to climate change targets versus municipalities who heavily rely on the revenue from the re-sale of Eskom generated electricity towards fulfilling their service delivery mandate (SEA 2015).

In the current climate, it is recommended that building use-types which can consume the majority of RE they generate on-site, and are hence not limited by prevailing constraints on feeding-to- grid, would benefit most significantly from pursuing NZEB optimisation with on-site PV generation. Although beyond the scope of the current study and a topic for future research, reducing baseload consumption by implementing smart power points could substantially reduce unwanted 'draw'. Future research is recommended for alternative RE technologies for urban environments, which would be essential in addressing the limitation of available site area for PV-generation as density increases. On-site consumption of biofuels and waste-to-energy systems that are capable of generating electricity at different times compared to PV combined with various load shifting techniques could provide more stability towards mainstreaming NZEB within existing buildings. Future studies are also recommended for a larger sample of different commercial and industrial buildings, operating schedules, urban density and FAR in relation to space available for PV are indicators that can be used to identify those building-types and locations that may benefit from pooling power, thus enabling owners and municipalities to implement less disruptive smart grid integration, thereby ensuring that the commercial building sector meets its GHG emission reduction targets.

References

Abdullah, A. 2016. Sustainable and energy efficient commercial retrofit. *Perkins and Wills Research Journal.* Vol 8.01: 48-65.

Aksamija, A. 2016. Regenerative design and adaptive reuse of existing commercial buildings for net zero energy use. *Sustainable Cities and Society*. 27: 185-195.

Albadi, M., El-Saadany, E. 2008. A summary of demand response in electricity markets. *Electric Power Systems Research*. 78: 1989-1996

Amado, M., Poggi, F. 2014. Solar energy integration in urban planning: GUUD model. *Energy Procedia*. 50: 277-284

Attia, S. 2016. Towards regenerative and positive impact architecture: A comparison of two net zero energy buildings. *Sustainable Cities and Society*. 26: 393-406

Bannister, P., Chen, H. 2012. GBCSA energy and water benchmark methodology final report. Exergy Australia.

Bellingham, C., Davies, G., Human, A. 2010. Energy efficiency guideline. *Greening Durban guidelines* (GDG) eThekwini Environmental Planning & Climate Protection Department.

Brander, M., Sood, A.,Wylie, C., Haughton, A., Lovel, J. 2011. Technical paper. Electricity-specific emission factors for grid electricity. Available at: https://ecometrica.com/assets/Electricity-specific-emission-factors-for-grid-electricity.pdf

Ceranic, B., Latham, D., Dean, A. 2015. Sustainable design and building information modelling: Case study of Energy Plus House, Hieron's Wood, Derbyshire, UK. *Energy Procedia* 434-443

Cheng, V., Steemers, K.,Montavon M.,Compagnon, R. 2006. Urban form, density and solar potential. PLEA, Geneva Switzerland.

Dekay, M. and Brown, G. 2014. Sun, wind & light. Architectural design strategies Third edition. Wiley

Griffith, B., Long, N., Torcellini, P., Judkoff, R., Crawley, D., Ryan, J. 2007 Assessment of the technical potential for achieving net zero-energy buildings in the commercial sector. *A technical report by National Renewable Energy Laboratory & U.S. Department of Energy*.

Griffith, B., Long, N., Torcellini, P., Judkoff, R., Crawley, D., Ryan, J. 2008. Methodology for modelling building energy performance across the commercial sector. *A technical report by National Renewable Energy Laboratory & U.S. Department of Energy.*

Hammond, G., Pearson, P. 2013. Challenges of the transition to a low carbon, more electric future: From here to 2050. *Energy Policy*, 52: 1-9

Hay, J. 2016. Solar electric investment anaysis. Institute of Agriculture and Natural resources, University of Nebraska.

Hermelink, A., Schmscar, S., Boermans, T., Pagliano,L., Zangheri,P., Armani,R., Voss,K., Musall, E. 2013. Towards nearly zero-energy buildings. Definitions of common priciples under EPBD. Final report – executive summary. © Ecofys. 18 March 2013.

Higgins C,. Whitmore, L., Lyles M., Cochrane, R., Rehely, M., Jennings, J., Wilcox, P. 2011. *A case for deep savings.* New Building Institute (NBI). Colorado.

Idahosa, L., Marwa, N., Akotey, J. 2017. Energy consumption in South African hotels: A panel data analysis. Economic Research Southern Africa, working paper 685

Jahed, M., Amra, R. 2016. Electricity generation technology choice: Costs and considerations. *Parliamentary Budget Office*. Republic of South Africa.

Keltsch, M., Lang, W., Auer, T. 2017. Nearly zero energy standard for non-residential buildings with high energy demands – an empirical case study using the state-related properties of Bavaria. *Buildings* 2017*,* 7, 25

Littlefair, P 1998. Renewable and sustainable energy reviews. Issue 2: 303-326

Littlefair, P 2001. Daylight, sunlight and solar gain in the urban environment. *Solar Energy* Vol. 70, 3: 177-185

Marszal, AJ., Bourrelle J., Musall, E., Heiselberg, P., Gutavsen, A., Voss, K. 2010. Net zero energy buildings- calculation methodologies versus national building codes. Dept. civil engineering, Aalborg University. Norwegian University of Science and Technology. Bergische University Wuppertal.

Martin, M. 2013. Generating low-cost national energy benchmarks: A case study in commercial buildings in Cape Town, South Africa. *Energy and Buildings*, 64: 26-31

Massoud, A. 2016. The power of microgrids. *Electricity today*, January – March 2016: 48-53

Pless, S., Torcellini, P. 2010. Net-zero energy buildings: A classification system based on renewable energy supply options. *A technical report by National Renewable Energy Laboratory.* Colorado.

Rahman, M., Rasul, M., Khan, M. 2008. Energy conservation measures in an institutional building by dynamic simulation using DesignBuilder. College of engineering and built environment, Central Queensland University, Australia.

Rotimi, A., Jahromi,A., Mylona, A., Godfrey, P., Cook, D. 2017. Estimation and validation of energy consumption in UK existing hotel building using dynamic simulation software. *Sustainability*, 9, 1391

Sarralde, J., Quinn, D., Wiesman, D., Steemers, K. 2014. Solar energy and urban morphology: Scenarios for increasing the renewable energy potential of neighbourhoods in London. *Renewable Energy* 73: 10-17

Sewchurran,S., Kalichuran, J., Maphumulo. 2016. Drivers and application of small scale DG on municipal distribution networks. 65th AMEU Convention, 2016.

Spalding-Fecher, R. 2011. What is the carbon emission factor for the South African electricity grid? *Journal of Energy in Southern Africa*. Vol 22: 4

Spiegelhalter, T. 2014. Towards zero net energy buildings – bridging the gap between parametric 3D/4D-bim design and the AIA 2030 challenge. Florida International University, College of Architecture.

Sustainable Energy Africa. 2015(a). State of energy in South African cities report. Cape Town.

Sustainable Energy Africa. 2015(b). City-wide mitigation potential for South Africa. Cape Town.

Swilling, M., Robinson, B., Marvin, S. and Hudson, M. 2013. City level decoupling: Urban resource flows and the governance of infrastructure transitions. *A Report of the Working Group on Cities of the International Resource Panel*.

UNDP. 2010. Promoting energy efficiency in buildings: lessons learned from international experience. Available at: http://www.undp.org/content/undp/en/home/librarypage/environment-energy/sustainable_energy/promoting_energyefficiencyinbuildings.htm

UNDP and IEA. 2013. Modernising building energy codes to secure our global energy Future. Available at: https://webstore.iea.org/policy-pathway-modernising-building-energy-codes-2013

Ürge-Vorsatz, D., N. Eyre, P. Graham, D. Harvey, E. Hertwich, Y. Jiang, C. Kornevall, M. Majumdar, J. E. McMahon, S. Mirasgedis, S. Murakami and A. Novikova, 2012. Chapter 10 - *Energy End-Use: Building. In global energy assessment – Towards asustainable future*, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 649-760.

Voss, K., Musall,E., Lichtmes, M. 2011. From low-energy to net zero energy buildings: Status and perspectives. *Journal of Green Building.* Vol 6 (1):46-56

Website/online sources.

CIDB, 2009. Greenhouse gas emission reduction: Potentials from buildings. Construction Industry Development Board (CIDB) discussion document. Available at www.cidb.org.za (accessed 21 March 2017)

Daly, H. 2008. A steady-state economy. Available at: http://www.theecologist.org/investigations/politics_and_economics/269776/a_steadystate_economy.html (accessed 27 March 2017)

Development Control Practice (DCP). 2016. Vertical sky component – an explanation. Available at: http://latest.dcp-online.co.uk/vertical-sky-component-an-explanation/ (Accessed on 17 October 2017)

Du Plessis, C. 2017. Shortest possible payback period vital for commercial solar. Available at: https://propertywheel.co.za/2017/10/shortest-possible-payback-period-vital-for-commercial-solar/ (accessed on 10 October 2017)

eThekwini Municipal Solar Map Viewer. http://gis.durban.gov.za/solarmapviewer/ (Accessed 19 November 2017)

Hayes, R. 2016. Coming soon: Energy performance certificates for buildings. Available at: http://earthworksmagazine.co.za/coming-soon-energy-performance-certificates-for-buildings/ (Accessed 5 September 2017)

Investopedia. 2018. Present value and discounting. Available at: https://www.investopedia.com/walkthrough/corporate-finance/3/time-value-money/present-value-discounting.aspx (Accessed 14 August 2017)

Khambule, H. 2016. Next steps: Domesticating the Paris Agreement. Available at: www.adaptionnetwork.org.za/2016/05/next-steps-domesticating-paris-agreement/ (accessed on 14 May 2017)

Maehlum, MA. 2014. Solar panels and installation time. Available at: http://energyinformative.org/solar-panels-installation-time (accessed on 18 Feb 2018)

Mazria, E. 2017. Starchitect Ed Mazira on the 2030 challenge and how designers can beat climate change. Interviewed by W. Peck. Living Architecture Monitor. Vol.19 (1) Available at livingarchitecturemonitor.com

Manfredonia, W., Majewski, J., Perryman, J., (2016) Cost estimating. National Institute of Building Sciences. https://www.wbdg.org/design-disciplines/cost-estimating (Accessed 07 August 2018)

Ngwenya, S. 2016. Implementing energy performance certificates in government buildings. http://www.urbanearth.co.za/articles/implementing-energy-performance-certificates-epcs-government-buildings (accessed 06/08/17)

Ryecroft, M. 2015. Zero net-energy buildings. Available at: http://www.ee.co.za/article/zero-net-energy-buildings.html (accessed 20 March 2017)

Steenkamp, L. 2016. Powering up: A look at Section 12B allowance for renewable energy machinery. http://www.thesait.org.za/news/269950/Powering-up-A-look-at-section-12B-allowance-for-renewable-energy-machinery.htm (accessed 22 March 2018)

Thapar, H. 2014. Performance driven design. Available at: http://www.envirolyser.com/2014/08/31/performance-driven-design/ (accessed 19 October 2017)

YouSustain. (n.d). Calculate and Track Your Footprint. CO^2 equivalence calculator. http://www.yousustain.com/footprint/howmuchco2 (accessed 13 March 2018)

Appendix 1

Case studies – precedent: Extracted from: A case for deep savings. NBI 2011

1525 Wilson Boulevard.

Overview

Building Size: 29 102m²

Floors: 12

Location: Rosslyn, VA

Construction type: Deep Retrofit

Year: 1987, 2010

Building type: Office

Overall building EUI was reduced by 34% from its baseline condition through a combination of technologies and retrofit strategies. An aging HVAC system was identified as the buildings major energy consumer, and was upgraded with a whole building VAV system, replacement of compressors and sensors and the installation of CO_2 monitors. The building envelope U-value was deemed to be sufficient and was not altered. Floor layouts were redesigned to ensure maximisation of natural daylighting and older fixtures were replaced with efficient ones which are controllable through occupancy sensors and time control. Window cleaning was re-organised to take place during the day to ensure that lights were not needed at night.

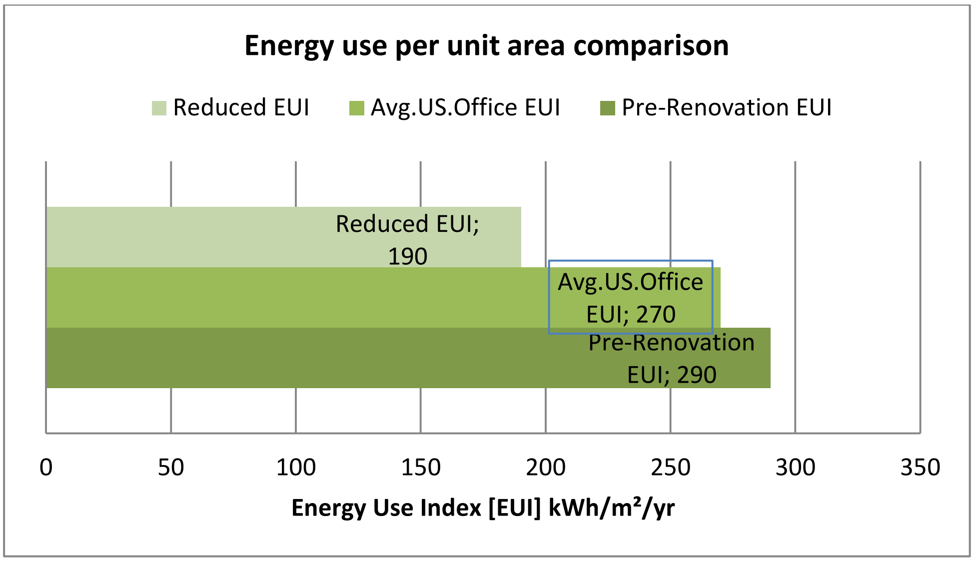


Figure 2.1: Reduced energy use intensity of 1525 Wilson Boulevard. (Author – Adapted from NBI 2011)

The building uses direct and digitally controlled (DDC) energy management. The intervention has seen financial savings of at least $280 000/yr which translated to a 2 year payback period for the retrofit costs versus a lifecycle of benefits over the remaining years of operation. The next phase of the upgrade process plans to replace the existing less efficient elevator equipment thereby lowering the EUI even further and enhancing the potential for achieving net zero through the introduction of on-site renewable energy technology.

Overview

Building Size: 23 500m²

Floors: 11

Location: Lajolla CA

Construction type: Renovation

Year: 1990, 2010

Building type: Medium_Office

The Aventine.

The prominent architect, Michael Graves' Aventine building uses a combination of passive design and active systems optimisation to reduce its baseline consumption from 290 kWh/m²/yr down to 190 kWh/m²/yr – a reduction of 63%. This was achieved largely through active system optimisation of HVAC, lighting and monitoring systems. The only passive intervention included was the introduction of a cool roof (changes the reflectivity and thermal properties of the roof by applying specialised paint). Chiller compressors and light fittings were replaced and automated. Digital-whole building monitoring systems allow for interactive control and monitoring of the building energy systems to ensure proper functioning.

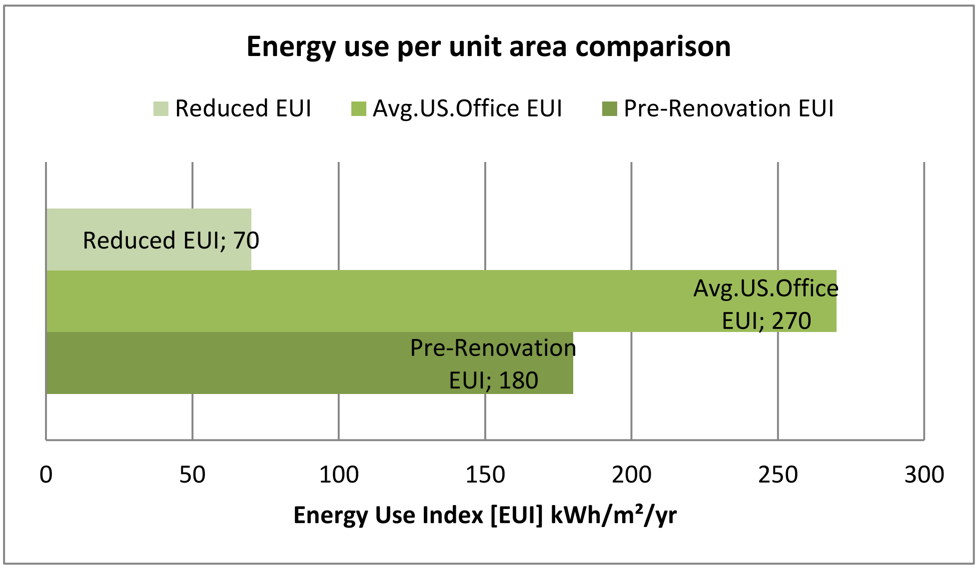


Figure2.2:Reduced energy use intensity of the Aventine. (Author – Adapted from NBI 2011)

The primary concern in the retrofit process was the disruption of occupancy/ use of existing tenants during the construction phase, which would inevitably affect the productivity and profit of both the building owner and lessee firm. In order to accomplish this, much of the work was carried out after hours. In its first year of operation post-renovation the building saved over 2 000 000 kWh of electricity, and cut operating expenses by $116 000 while thus decreasing CO_2 emission by 272 155 kg per year. Subsequently, the owner's conservative payback period of 2-3 years was extended to 4-5years for future renovations indicating an awareness of the longer term benefits of deep energy efficiency retrofits.

The Alliance Building.

Overview

Building Size: 3 530 m²

Floors: 6

Location: Denver Colorado

Construction type: Renovation

Year: 1908, 2006

Building type: Medium Office

The alliance retrofit reduced overall EUI by 22% through the use of a combination of passive design and active system optimisation. Improvements made to the building envelope include high efficiency glazing, solar shielding and added insulation. The active system optimisation interventions included a direct digital HVAC control system and replacement of underperforming components such as the introduction of occupancy sensors, photocells for daylight harvesting, replacement of lighting fixtures to more efficient ones and a host of sub-metering monitors. These monitors can be remotely viewed by the facilities managers who are located off-site, thus enabling them to recognise system faults and malfunctions. A 20 kWp rooftop PV array was included in the 22% reduction achieved by the ALLIANCE centre. The total project cost was $117 000. However, due to theowner being a non-profit multi-tenant scheme, it was able to benefit from multiple financial incentives for pursuing various low-carbon and sustainability incentives which included a $11 200 grant from a local ESCO for the PV array, a $25 000 grant from the Colorado Governor's Office, for user/visitor education and awareness surrounding sustainable building (which includes educational and informational signs within the building) and $15 000 grant for historical preservation and education. The intervention on the lighting system alone is responsible for a 40% reduction in annual energy costs and the expected payback period for the entire retrofit is 2.5 years.

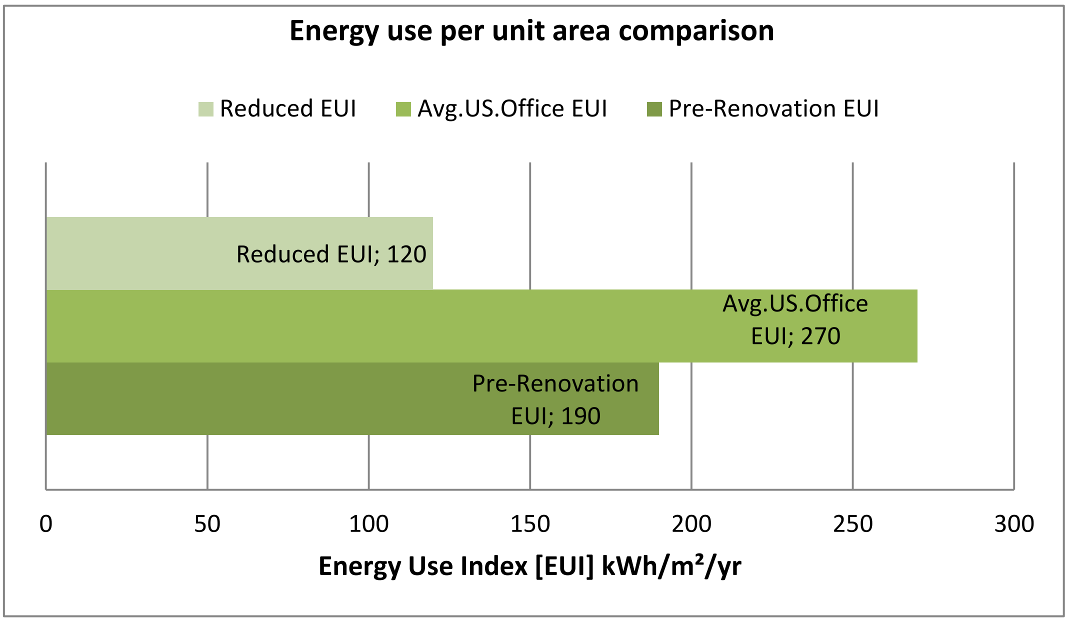


Figure 2.3: Reduced energy use intensity of the Alliance Building. (Author – Adapted from NBI 2011)**California Lottery Building.**

California Lottery's Santa Fe headquarters achieves net-zero through a combination of energy efficiency measures and a solar PV array. Lighting was improved through the introduction of prismatic sky-lights (which spreads natural light), solar tubes, relights and an upgraded motion-sensor integrated LED lighting system. The building envelope was already well insulated with U values twice those of the minimum code stipulation. This allowed for a down-sizing of the HVAC system to use a single variable air volume system with intelligent controls and thermal sensors.

Overview

Building Size: 1 193m²

Floors: 1/2

Location: Santé Fe Springs CA

Construction type: Retrofit

Year: 2015

Building type: Office

Climate zone: 09

Plug loads investigation revealed very interesting results where 36% of the load was being consumed after hours. By introducing smart plug stations with various turn-off options, it was estimated that as much as 65% of that unnecessary load could be reduced. This allowed a load reduction of over 100 kWh/m²/yr and nearly a $50 000 savings on the required PV system.

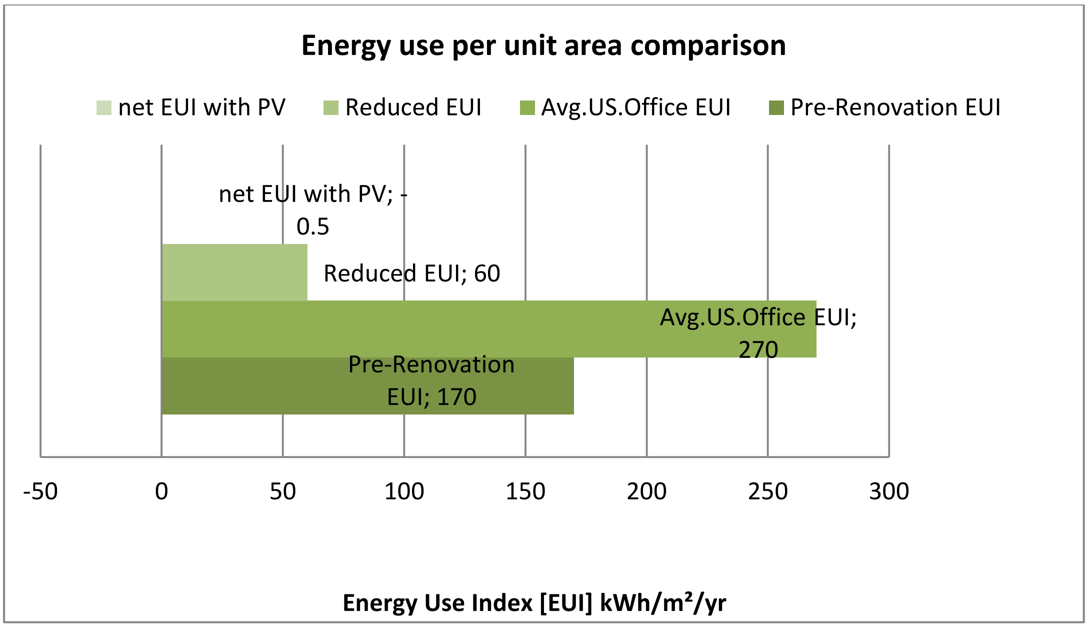


Figure 2.4: Reduced energy use intensity of the California Lottery Building. (Author – Adapted from NBI 2011)

The lighting, HVAC and plug load modification allowed for a 50% reduction in the overall size of the PV array. This was still fairly large as it needed to be capable of generating 84 000 kWh/yr with a thirty year simple payback period. The building produces slightly more energy than it consumes each year. However a 14 % increase in project costs was necessary in order to improve the building's performance from standard energy efficiency building code levels to that of net zero energy. The post-occupancy commissioning process involved education for staff on how to interact with smart digital dashboards and system monitors, encouraging energy saving and allowing flexibility through user controls. The measures introduced reduced site operating costs from $2,6 m² in the previous facility to $1,7 m² after the upgrade. This amounts to a savings of $10 000 per year (5%) total savings.

Overview

Building Size: 418m²

Location: San Diego, California

Construction type: Retrofit

Year: 1955, 2009

Building type: Small Office

Climate zone: CA 7

1955 Bacon Street.

1955 Bacon St. has improved daylighting through the use of sky-lights, combined with an advanced lighting and energy monitoring dashboard control system. Sky-lights double as exhaust apertures for cool breezes being drawn across the building's thermal mass. Renewable energy is generated by a 16 kWp photovoltaic roof array which gives the building a negative net EUI and a carbon emission reduction of 104%. The Bacon St retrofit demonstrates the relative ease with which a single storey office structure can achieve NZEB through addressing ventilation, lighting and thermal mass. Unfortunately data on overall project cost or payback period are not available from publicly available secondary sources.

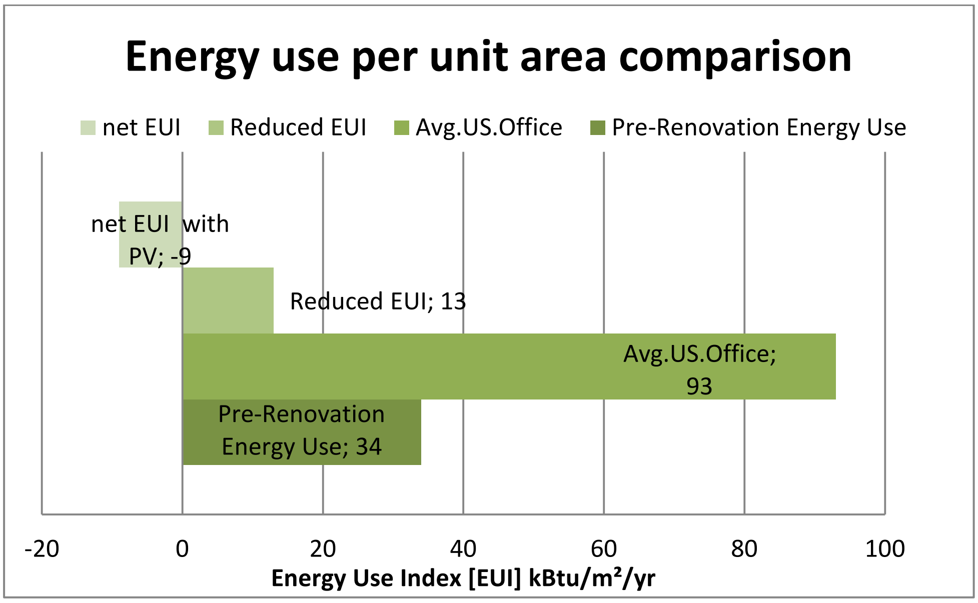


Figure: 2.5 Reduced energy use intensity of 1955 Bacon Street. (NBI 2015)

1315 Peachtree Street.

<u>Overview</u>

<u>Building Size</u>: 7 250m² (5100m² offices)

<u>Floors:</u> 6

<u>Location:</u> Atlanta, Florida

<u>Construction type:</u> Retrofit

<u>Year:</u> 1986/2010

<u>Building type:</u> Office

Climate zone: Hot Humid

Atlanta's 1315 Peachtree building is one of the highest green rated LEED performers as accredited by the American Green Building Council. The goal was to reduce CO_2 by at least 60% as per the AIA 2030 challenge. Through a combination of energy efficiency and system optimisation, its EUI has been reduced significantly (a reduction of up to 67% is estimated) from the average for commercial buildings.

The passive design strategy was based on a psychrometric chart analysis – of Florida's warm humid climate, which indicated the use of solar shading and cross ventilation as the primary strategies. The high humidity levels limits the viability of direct evaporative cooling, hence the need for a comprehensive HVAC system which can also serve the need for dehumidification.

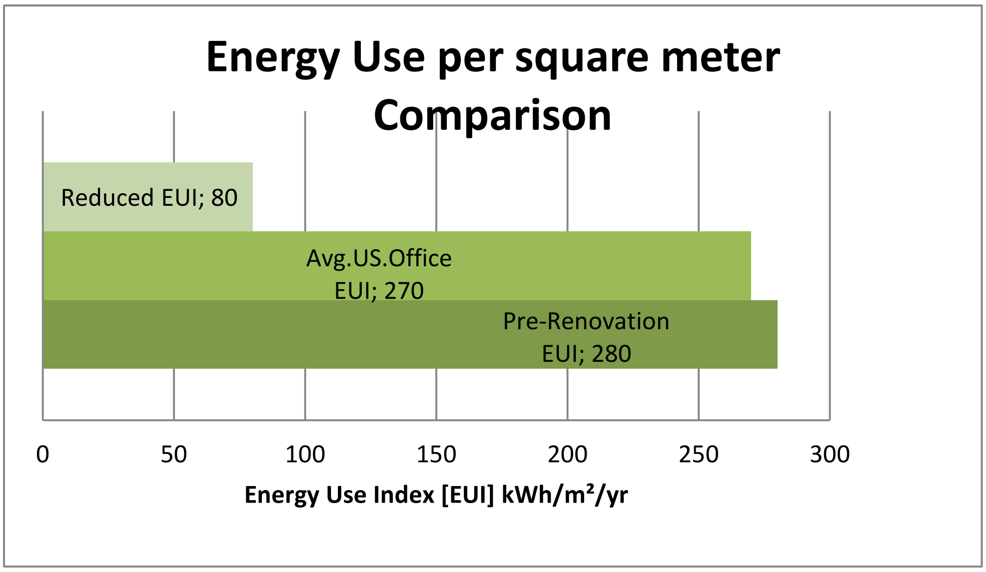


Figure 2.6: Reduced energy use intensity of 1315 Peachtree Street.

The HVAC system combines a high efficiency scroll chiller, gas powered twin Turbines, chilled beams, underfloor air distribution and an energy recovery wheel. The overall retrofit includes a 7 kWp rooftop PV array which generates roughly 10 000 kWh/yr which serves just over 10% of the buildings EUI . Plug loads were reduced and natural daylighting was addressed through the addition of high performance low e-glazing and automated solar shielding which allowed the lighting load to be greatly reduced without unwanted heat gains, and was further optimised by replacing fittings with T5 flourecent and LED as well as motion control and daylight sensors . However the case study report lacks adequate information regarding project cost and payback period. Prohibitive cost may have contributed to less than a quarter of the available roof space being used for pv thus skipping the potential to increase its PV array size to 40 000kWh/yr which would account for a further reduction of 30% of the building’s EUI.

Appendix 2 – Simulated shadow graphics

Building A

Figure 4.1: Aerial view of office building A. (Source: google Maps)

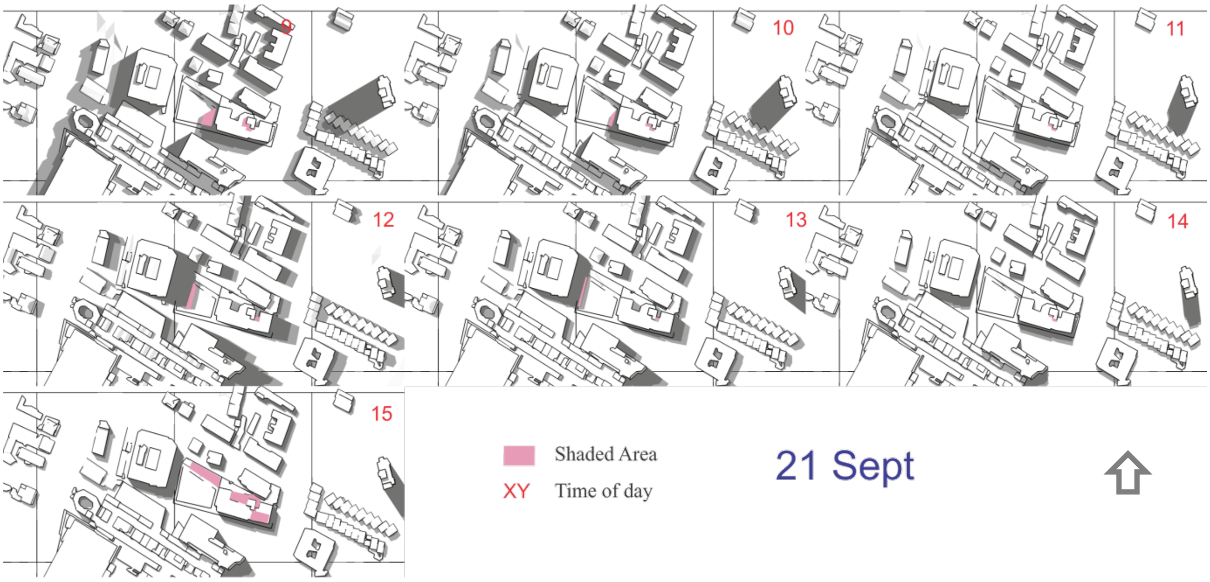


Figure 4.2: Building A – Low density solar analysis. Series of plans showing shadowing at hourly intervals for 21 Sept.

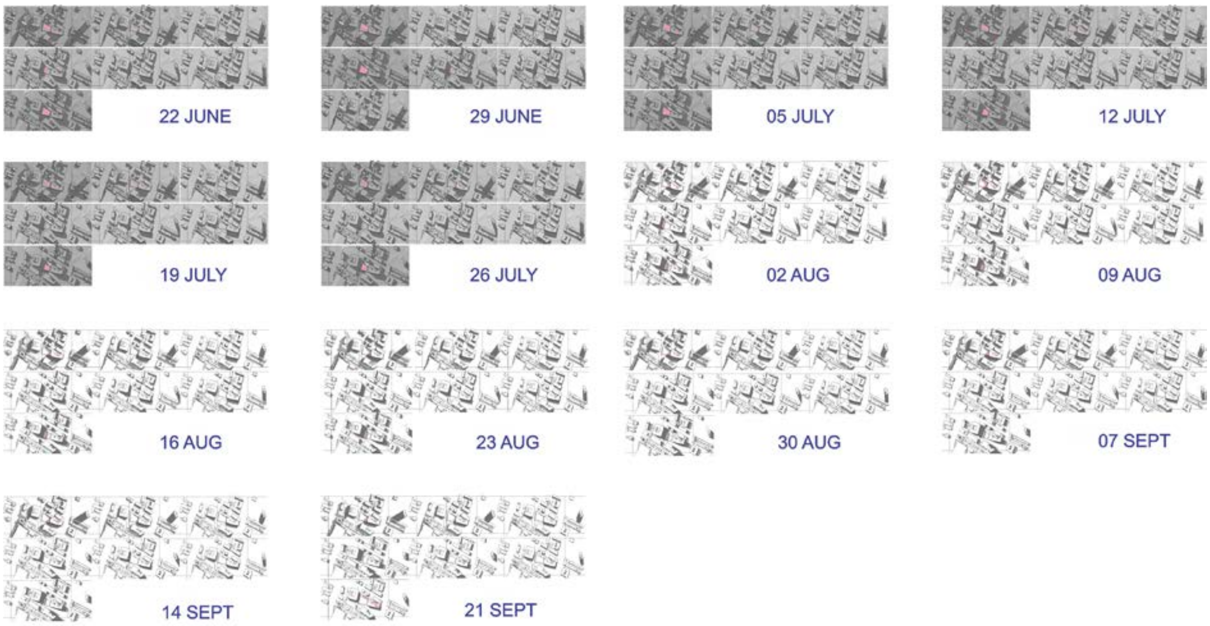


Figure 4.3: Series of daily shadow studies over 14 weeks starting on 22 June and ending on the spring equinox – Building A.

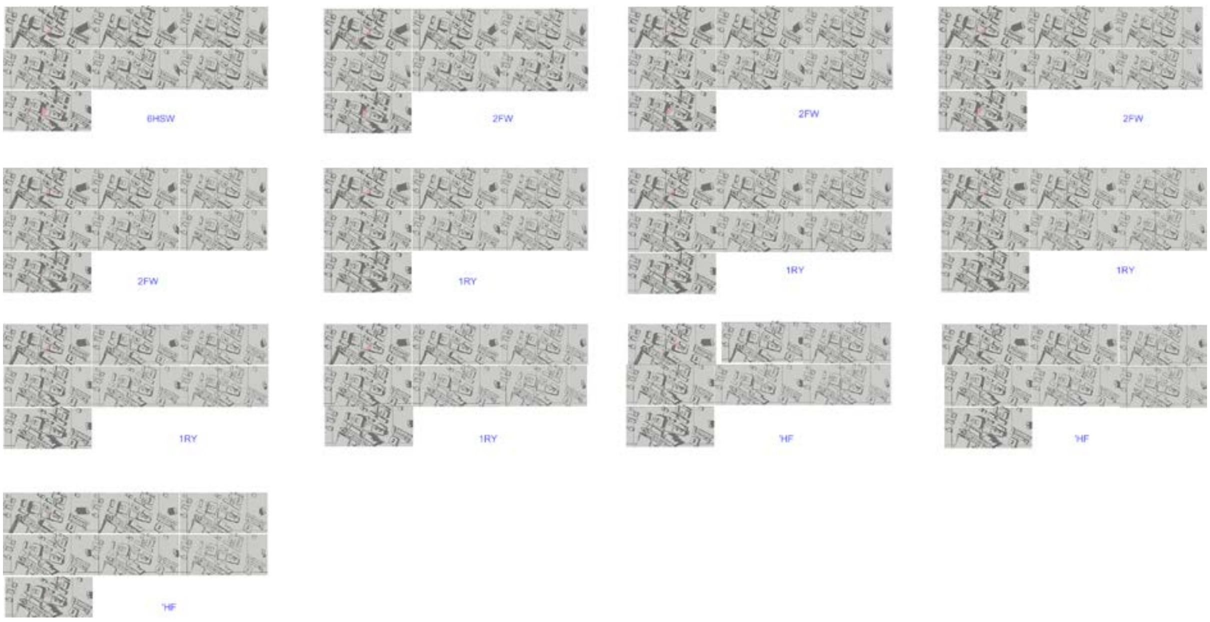


Figure 4.4: Series of daily shadow studies over 14 weeks from 28 September to 21 December

Building B

Figure 4.5: Aerial view of office building B. (Source: Google Maps)

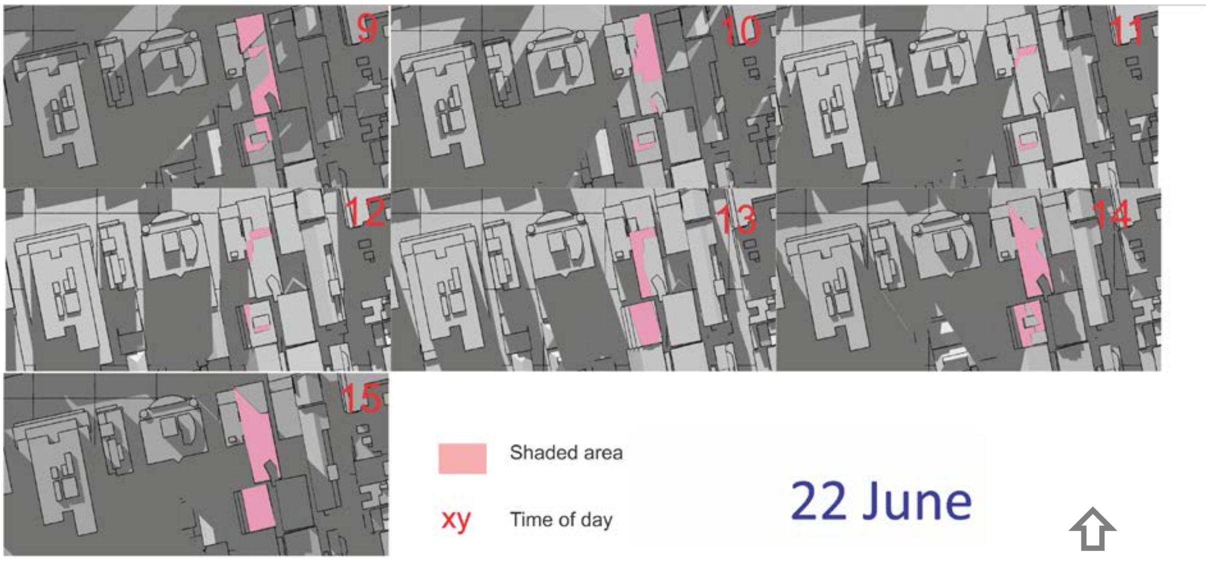


Figure 4.6: Building B – High density urban fabric. Detail of shadow study illustrating shadows (pink) from 9am – 3pm on 22 June.

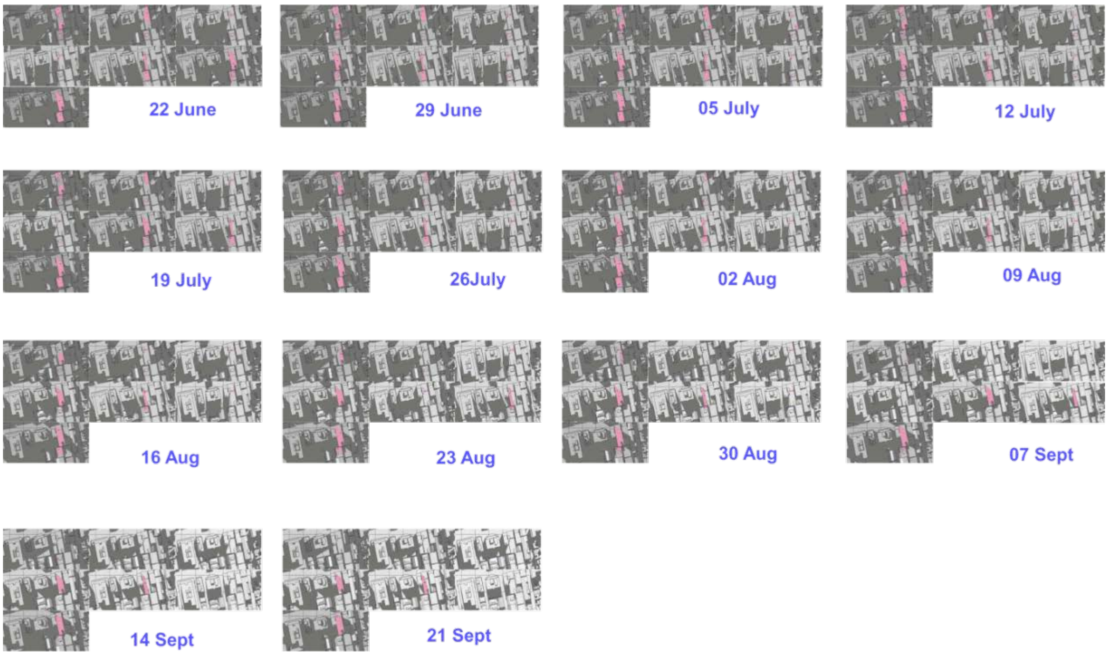


Figure 4.7: Building B. Overview of shadow study for 14 weeks from the winter solstice to the autumn equinox.

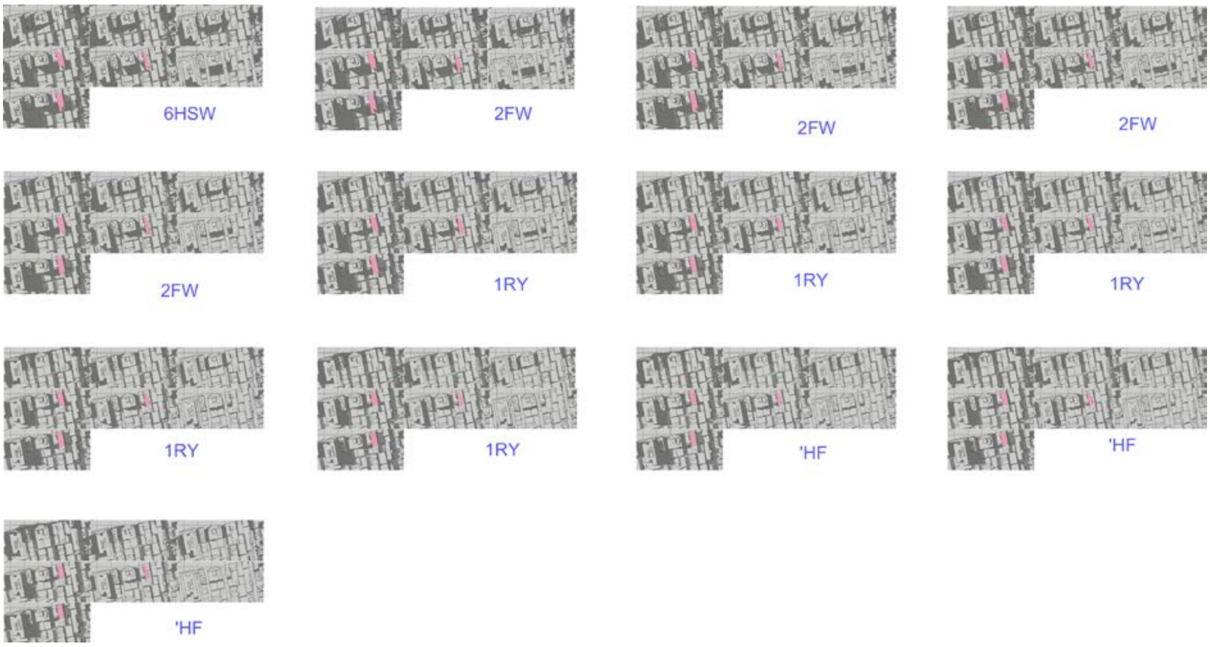


Figure 4.8: Building B. Overview of shadow study for 14 weeks from the 28 September to the 21 December.

Building C

Figure 4.9: Aerial perspective of place of instruction building C. (Source: Google Maps)

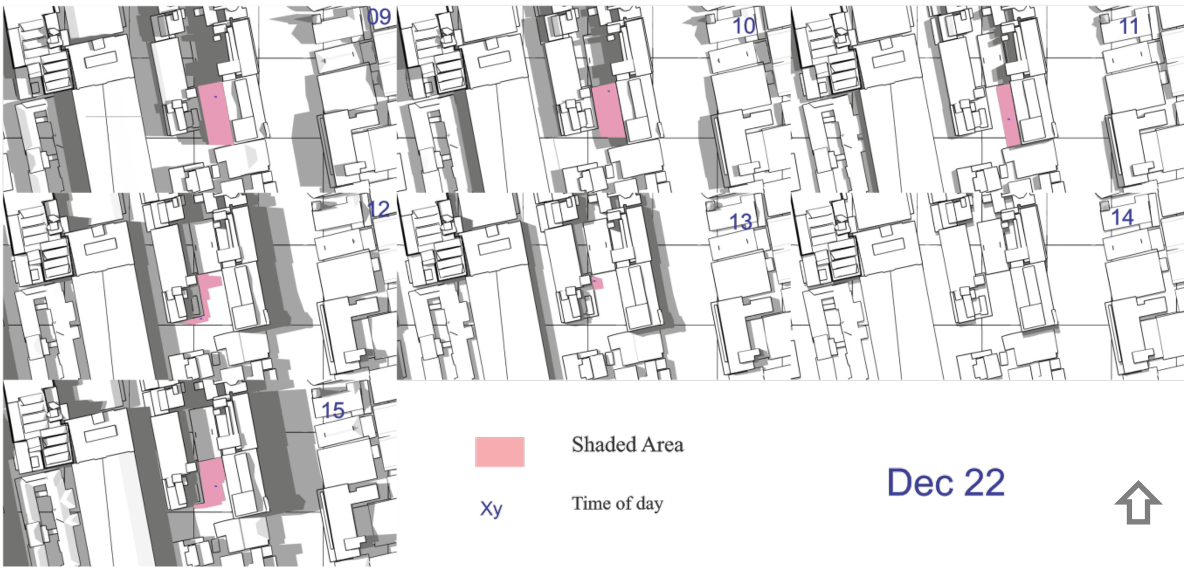


Figure 4.10: Building C –High density solar analysis. Series of plans showing shadowing at hourly intervals for 22 December.

Figure 4.11: Overview of shadow study for 14 weeks from the summer solstice to the autumn equinox. Building C

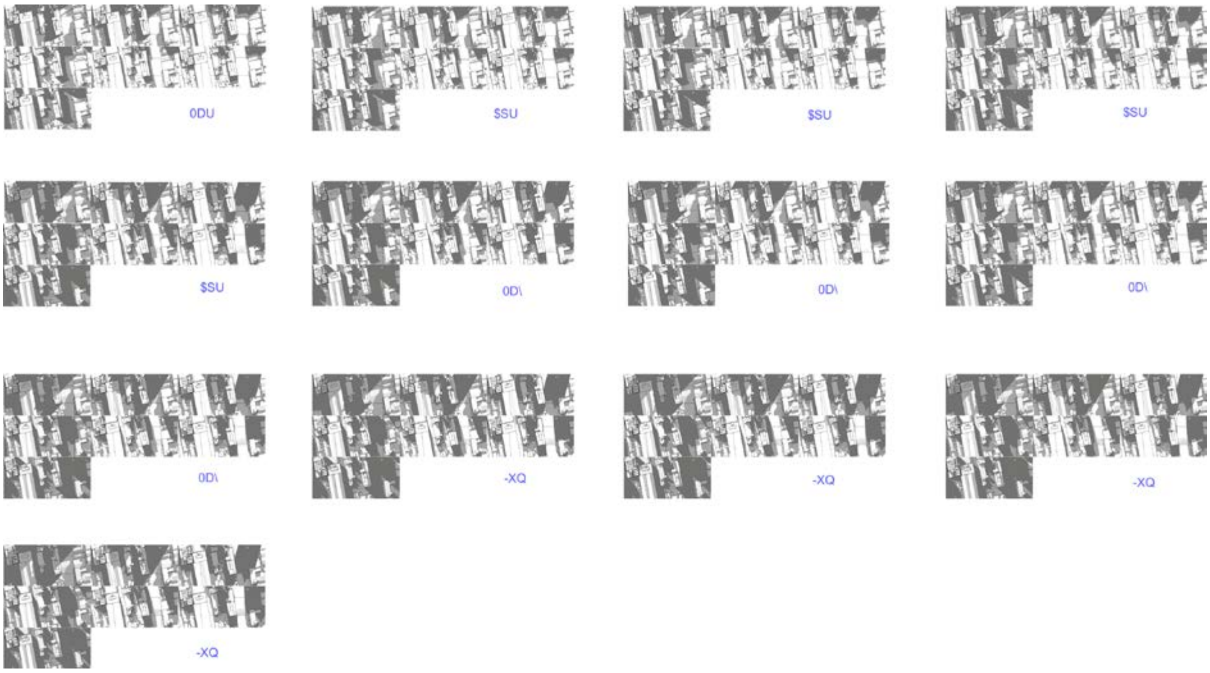


Figure 4.12: Overview of shadow study for 14 weeks from 30 March to the 22 June. Building C

Building D

Figure 4.13: Solar availability/ shadow analysis.

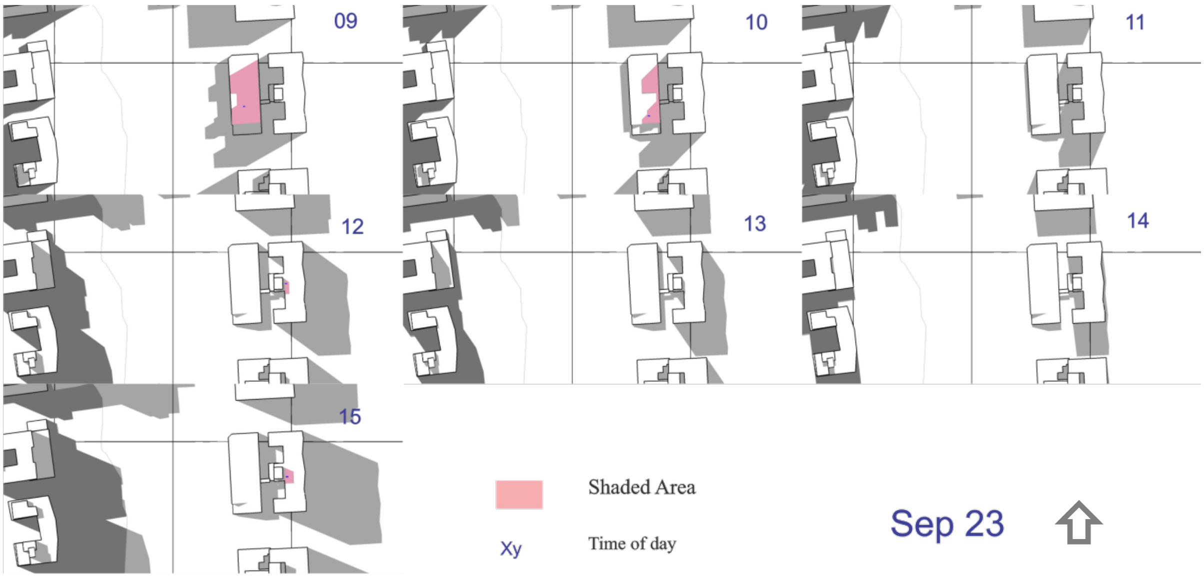


Figure 4.14: Building D – Medium density urban fabric. Detail of shadow study illustrating shadows (pink) from 9am – 3pm on 22 September.

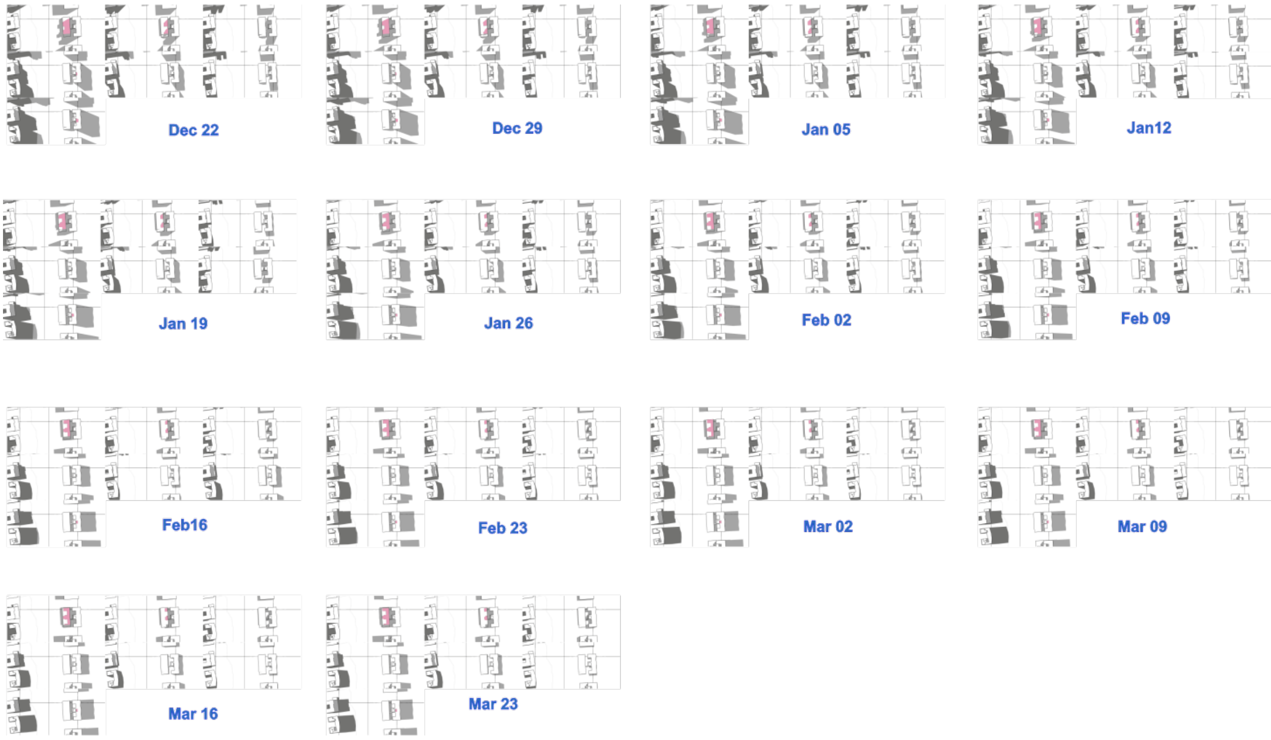


Figure 4.15: Overview of shadow study for 14 weeks from 22 December to 23 March - Building D

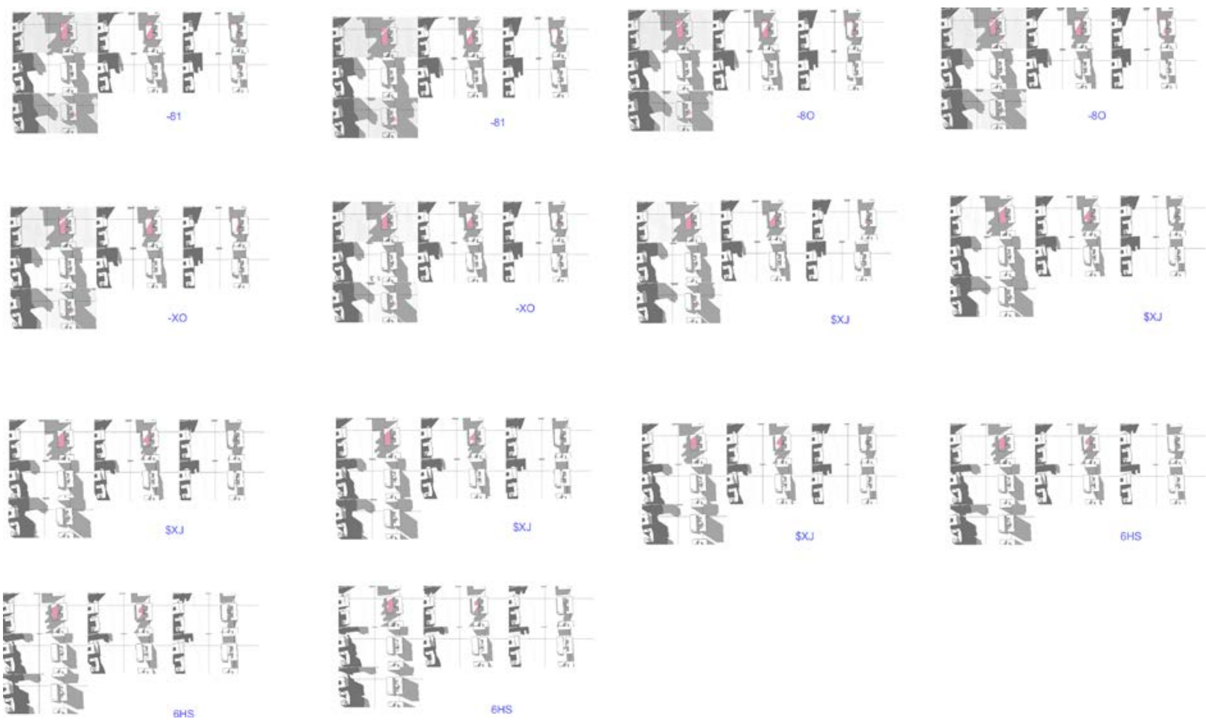


Figure 4.16: Overview of shadow study for 14 weeks from 30 March to 22 June - Building D

Appendix 3

SCHOOL OF ARCHITECTURE AND PLANNING
HUMAN RESERCH ETHICS COMMITTEE

CLEARANCE CERTIFICATE
PROTOCOL NUMBER: SOAP122/10/2017

PROJECT TITLE:	Assessing potential for net-zero energy building retrofits in commercial buildings using on-site photo voltaic (pv) generation -A case study of Durban-South Africa
INVESTIGATOR/S:	Gareth Davies (Student no#1558443)
SCHOOL:	Architecture and Planning
DEGREE PROGRAMME:	Master of Architecture -SEEC (MArch SEEC)
DATE CONSIDERED:	14 December 2017
EXPIRY DATE:	14 December 2018
DECISION OF THE COMMITTEE:	APPROVED

CHAIRPERSON ________________________
(Professor Daniel Irurah)

DATE: 14-12-2017

cc: Supervisor/s: Daniel Irurah

DECLARATION OF INVESTIGATORS

I/We fully understand the conditions under which I am/we are authorized to carry out the abovementioned research and I/we guarantee to endure compliance with these conditions. Should any departure to be contemplated from the research procedure as approved I/we undertake to resubmit the protocol to the Committee.

School of Architecture & Planning
University of the Witwatersrand
Private Bag 3 Wits 2050
Johannesburg South Africa
www.wits.ac.za

T + 27 11 717 7623
F + 27 11 717 7649