Modelling of Artificial Intelligence Based Demand Side Management Techniques for Mitigating Energy Poverty in Smart Grids

by

Chukwuka Gideon MONYEI

(217077516)

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As the candidate’s supervisor I have approved this thesis for submission.

Signed: .... Name: .... Date: ....

To the Almighty God, who in His infinite mercies has afforded me the luxury of life, health and unmerited opportunities.

To my dad and mum, who allowed me discover myself.

To HOPE...

ABSTRACT

This research work proposes an artificial intelligence (AI) based model for smart grid initiatives (for South Africa and by extension sub-Saharan Africa, (SSA)) and further incorporates energy justice principles.

Spanning the social, technical, economic, environmental, policy and overall impact of smart and *just* electricity grids, this research begins by investigating declining electricity consumption and demand side management (DSM) potential across South Africa. In addition, technical frameworks such as the combined energy management system (CEMS), co-ordinated centralized energy management system (ConCEMS) and biased load manager home energy management system (BLM-HEMS) are modelled. These systems provide for the integration of all aspects of the electricity grid and their optimization in achieving cost reduction for both the utility and consumers as well as improvement in the consumers quality of life (QoL) and reduction of emissions.

Policy and economy-wise, this research work further proposes and models an integrated electrification and expansion model (IEEM) for South Africa, and also addresses the issue of rural marginalization due to poor electricity access for off-grid communities. This is done by proposing a hybrid generation scheme (HGS) which is shown to satisfy sufficiently the requirements of the energy justice framework while significantly reducing the energy burden of households and reducing carbon emissions by over 70%.

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I do not take for granted this rare opportunity of successfully completing my doctoral research. In contributing my bit to scholarship, my research has basically seen me frolicking through fundamental and exciting research themes cutting across the sciences, engineering and the social sciences.

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PREFACE

The work described in this thesis was carried out in the School of Mathematics, Statistics, and Computer Science, University of KwaZulu-Natal from March 2017 to May 2018. This dissertation was completed under the supervision of Professor Serestina Viriri.

This study represents original work by the author and has not been submitted in any form for any degree or diploma to any other tertiary institution. Where use was made of the work of others it has been duly acknowledged in the text.

DECLARATION OF NON-PLAGIARISM

I, **Chukwuka Gideon MONYEI** declare that

1. The research reported in this thesis, except where otherwise indicated, is my original research.
2. This thesis has not been submitted for any degree or examination at any other university.
3. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.
4. This thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:
    (a) Their words have been re-written but the general information attributed to them has been referenced.
    (b) Where their exact words have been used, then their writing has been placed in italics and inside quotation marks, and referenced.
5. This thesis does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the thesis and in the References sections.

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DECLARATION OF PUBLICATIONS

Details of contribution to publications that form part of and/or include research presented in this thesis:

The following papers were used as chapters in this research:

1 C. G. Monyei, S. Viriri and K. Jenkins, "A just and sustainable smart grid approach for mitigating energy poverty and reducing climate change in South Africa".

2 C. G. Monyei and A O. Adewumi, "Demand Side Management potentials for mitigating energy poverty in South Africa", *Energy Policy*, Volume 111, Supplement C, 2017, Pages 298-311. ISSN 0301-4215, *https://doi.org/10.1016/j.enpol.2017.09.039*. (ISI)

3 C. G. Monyei and A O. Adewumi, "Integration of demand side and supply side energy management resources for optimal scheduling of demand response loads - South Africa in focus", *Electric Power Systems Research*, Volume 158, 2018, Pages 92-104. ISSN 0378-7796, *https://doi.org/10.1016/j.epsr.2017.12.033*. (ISI)

4 C. G. Monyei, S. Viriri, A. O. Adewumi, I. E. Davidson and D. Akinyele, "A smart grid framework for optimally integrating supply-side, demand-side and transmission line management systems", *Energies*, Volume 11(5), 2018, Pages 1-27. ISSN 1996-1073, *https://doi.org/10.3390/en11051038*. (ISI)

5 C. G. Monyei, A. O. Adewumi, D. Akinyele, O. M. Babatunde, M. O. Obolo and J. C. Onunwor, "A Biased Load Manager Home Energy Management System for Low-cost Res-

idential Building Low-income Occupants", *Energy*, Volume 150, 2018, Pages 822-838. ISSN 0360-5442, *https://doi.org/10.1016/j.energy.2018.03.016*. (ISI)

6 C. G. Monyei, K. Jenkins, S. Viriri and A. O. Adewumi, "Policy discussion for sustainable integrated electricity expansion in South Africa", (2018), *Energy Policy*, Volume 120, 2018, Pages 132-143. ISSN 0301-4215, *https://doi.org/10.1016/j.enpol.2018.05.021*. (ISI)

7 C. G. Monyei, A. O. Adewumi and K. E. H. Jenkins, "Energy (in)justice in off-grid rural electrification policy: South Africa in focus", *Energy Research and Social Science*, Volume 44, 2018, Pages 152-171. ISSN 2214-6296, *https://doi.org/10.1016/j.erss.2018.05.002*. (ISI)

The following papers were not used as chapters but were published during the PhD:

1 C. G. Monyei, A. O. Adewumi, M. O. Obolo and B. Sajou, "Nigeria's energy poverty: Insights and implications for smart policies and framework towards a smart Nigeria electricity network", *Renewable and Sustainable Energy Reviews*, Volume 81, Part 1, 2018, Pages 1582-1601. ISSN 1364-0321, *https://doi.org/10.1016/j.rser.2017.05.237*. (ISI)

2 C. G. Monyei, K. Jenkins, S. Viriri and A. O. Adewumi, "Examining energy sufficiency and energy mobility in the global south through the energy justice framework", *Energy Policy*, Volume 119, 2018, Pages 68-76. ISSN 0301-4215, *https://doi.org/10.1016/j.enpol.2018.04.026*. (ISI)

3 C. G. Monyei and K. Jenkins "Electrons have no identity: setting right misrepresentations in Google and Apples clean energy purchasing", *Energy Research and Social Science*, Volume 48, 2018, Pages 48-51. ISSN 2214-6296, *https://doi.org/10.1016/j.erss.2018.06.015*. (ISI)

4 C. G. Monyei and A. O. Adewumi, "Improving electricity grid resilience and demand response scheduling through simulated transmission line outages", *2017 CAES Research Day, University of KwaZulu-Natal, South Africa*. **1st Prize oral presentation winner for School of Mathematics, Statistics and Computer Science**.

5 C. G. Monyei and S. Viriri, “An improved comfort biased smart home load manager for grid connected homes under direct load control”, (2018), *Lecture Notes in Computer Science (Springer)*, Volume 10870. (SCOPUS)

For all the papers presented, I, Chukwuka Gideon MONYEI, conceptualised, modelled (where appropriate), wrote and communicated (excluding the paper published in Renewable and Sustainable Energy Reviews for which Prof. Aderemi was the corresponding author) with the reviewers corrections made. All the papers listed are my original idea and references have been cited where appropriate.

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CONTENTS

CHAPTER 1

INTRODUCTION

1.1 Background

The increasing need for a more integrated electricity network which has led to the widespread penetration of advanced communication and control technologies in today's electricity network is evolving a smart grid. With increase in the deployment of smart meters (that allow for bidirectional communication) [1, 2, 3, 4]; smart controls (that allow for fault detection and mitigation and also permit direct load control (DLC) [5, 6, 7, 8] of some consumer loads); dynamic pricing schemes [9, 10, 11, 12] and human computer interactive (HCI) devices (that update electricity users in [near] real time of their energy consumption pattern [13]), the electricity grid is providing a more interactive platform that is facilitating the active involvement of every participant (electricity generators/vendors, electricity users and the transmission company) in guaranteeing the optimal management of the electricity network. Furthermore, the rise of prosumers (electricity consumers who are also producers - for example grid connected houses with roof top solar photovoltaic (PV) systems and tie-grid inverters) [14] and the increasing penetration of renewable energy sources (RES) create even greater need for a smarter electricity network. This is because of the complexity introduced by the prosumers [15] and the stochasticity of the RES.

Considering the limitation of technical solutions and the inadequacy of supply side measures in mitigating the growing electricity demand/supply imbalance, solutions that target the behaviour of consumers are being exploited. These solutions seek to ensure that compromises from every electricity participant (without adversely affecting any participant or violating grid constraints) guarantee optimality in the electricity grid operation.

Demand side management (DSM) is becoming a prominent technique currently receiving acclaimed attention across the world for its ability to both influence consumer electricity behaviour and ensure demand/supply balance while providing some reprieve to the electricity utility companies (mostly from expanding electricity supply capacity) [16, 17, 18, 19, 20, 21, 22, 23]. According to [24], the concept of DSM connotes a relationship between the supply and utilization side for mutual benefit. This definition is further elaborated by [25] to be a set of flexible and interconnected programs that permit the end users of electricity (consumers) a greater role in altering their consumption profile by shifting their electricity usage from peak to off-peak periods. Generally, DSM programs are either energy efficiency (EE) based or demand response (DR) based [24, 25]. While the EE based DSM programs aim at curtailing electricity usage through the use of more energy efficient devices (use of energy saving bulbs instead of incandescent bulbs) and techniques (double glazed windows, insulation, sealing) or a compromise in comfort derived from certain electrical appliances (like reduced thermostat settings and reduced light brightness settings), the DR based programs aim at soliciting from electricity users a 'positive'[1] response due to increase in electricity rate or some other incentives [24, 25].

In South Africa, Eskom[2] began a mass EE campaign in 2008 to replace incandescent bulbs in homes with more energy efficient compact fluorescent bulbs (CFL) with about 65 million of such energy efficient bulbs installed in homes till date resulting in considerable energy savings and reduced electricity bills for homes [26]. Other associated benefits have included jobs creation and a growing culture of energy efficiency consciousness among South Africans [26].

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[1] By positive we imply an inverse relationship in which electricity users reduce their usage of electricity based on increasing electricity rate.

[2] Eskom is South Africa's major electricity utility company generating over 80% of South Africa's electricity and 40% of electricity in Africa [26].

This research work hypothesizes that energy poverty (especially for households with electricity grid/mini-grid access) can be mitigated through the incorporation of smart algorithms in the optimal operation of the electricity grid and through the active participation of households in DR. This research work thus utilizes hypothetical dynamic pricing schemes in showing the ability of the proposed artificial intelligence (AI) based techniques to mitigate energy poverty over the conventional time of use (TOU) pricing scheme. This research work further addresses energy poverty for sub-Saharan Africa (SSA) (with major emphasis on South Africa and minor emphasis on Nigeria) by showing that:

1 Despite increasing electrification exercises in South Africa and Nigeria, electricity consumption by households is on the decline.

2 Increasing electricity tariff by the utility companies deters further increase in electricity consumption by households.

3 Increasing expenditure by households on electricity leads to energy poverty and economic poverty.

4 A more integrated electricity network with active participation of electricity users through DR provides the utility an opportunity to reduce grid expansion costs, increase utilization of RES, maintain grid stability and limit tariff increase.

5 Households stand to save significantly on electricity bills by participating in DR especially DLC.

6 Emissions (especially from coal, oil and natural gas fired plants) can be greatly reduced through the incorporation of DSM (DR) which enables RES to effectively displace them without compromising on grid stability and consumer comfort.

7 At the off-grid community level, the deployment of AI techniques and the localization of smart grid concepts (DSM and DR) in managing hybrid generation schemes provides opportunity in reducing significantly emissions and energy poverty.

8 Any electricity grid infrastructure that incorporates the proposed smart AI techniques in this research work is capable of guaranteeing equity, energy mobility (the ability of households to transit from one energy level to another either by extending the usage time of already owned electrical appliances or purchasing additional electrical appliances) and offering considerable savings to both the consumers and the utility.

9 There is lacking within the literature sphere on South Africa (and by extension SSA), any comprehensive research work that holistically addresses the need for a more integrated and sustainable electricity grid by proposing smart concepts that are capable of mitigating energy poverty.

1.2 The problem statement

In South Africa, most DSM initiatives have been EE based. This is at variance with the current global trend that is experiencing a surge in the exploitation of DR based DSM initiatives with significant successes being recorded. Furthermore, the Transmission Development Plan (TDP) [27] and the Integrated Resource Plan (IRP) [28] which provide guidelines for the generation supply mix of South Africa within specified time frames show that there is growing incorporation of renewables (which in recent times has been adjudged successful). The implication of this increasing participation of renewables raises concerns as to their exploitation because consumer behaviour with regards to electricity consumption is at times uncertain. Also, proposals for more 'handshake'[3] between the participants in the electricity network has resulted in greater synergy between the utility (electricity providers) and the electricity users (consumers) with little attention on the transmission side. This can result in continuous transmission capacity expansion since static thermal line rating (STLR) is mostly used for transmission network. Furthermore, there has been a growing gap between most technical solutions and the socio-economic and environmental aspect of society. This is usually noticed in research works where beyond technical solutions, base analysis like - life cycle cost (LCC), life cycle analysis (LCA) and return on

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[3] By handshake we imply synergy between participants.

investment (RoI) are at best provided. In these technical based research works, the emerging concepts of energy justice, poverty and sustainability are hardly addressed. Such limited and 'incomplete' propositions raise serious problems as they may be incapable of addressing totally the issue of sustainable electrification for the global south (sub-Saharan Africa (SSA) and other developing regions). Technical propositions should extend their solutions by quantifying and qualifying their value addition capability in line with emerging social concepts. This is useful since we argue that most problems confronting the society at large are socially induced.

1.3 Research objectives

The main objective of this research work is to develop a smart grid framework that integrates the objective function of the home energy management systems (HEMS), supply side energy management systems (SSEMS) and transmission line management system (TLMS) for optimal operation of the electricity grid while reducing consumer costs (HEMS objective) and reducing supply cost (SSEMS objective) without violating transmission line ampacity limits[4] (TLMS objective). In achieving this objective, we aim to:

1 Evaluate electricity consumption and DSM potential across South Africa using actual household electricity consumption and a modified genetic algorithm (MGA).

2 Model a combined energy management system (CEMS) framework that integrates HEMS and SSEMS and incorporates a standard deviation biased genetic algorithm (SDBGA).

3 Model a co-ordinated centralized energy management system (ConCEMS) that integrates HEMS, SSEMS and TLMS and utilizes an externally constrained genetic algorithm (ExC-GA) for HEMS optimization, a genetic algorithm based economic and environmental dispatch algorithm (GA-EED) for optimal dispatch of generators and a dynamic thermal line rating algorithm (DTLR) for dynamically computing ampacity limits of transmission lines.

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[4] By ampacity limits we mean the current carrying capacity limits of transmission lines. Conventionally, they are determined using the static thermal line rating (STLR).

4 Model a biased load manager home energy management system (BLM-HEMS) that incorporates a hopping algorithm for maximum power point tracking (MPPT).

5 Model an integrated electricity expansion model (IEEM) for South Africa that incorporates DSM and DR.

6 Model a hybrid generation scheme (HGS) for off-grid communities that utilizes AI and DSM.

Table 1 presents a fuller description of the research objectives including their scope and focus areas.

Table 1.1: Research objectives and their description

S/N	Research objectives	Focus	Scope	Main/sub/tool
1	ConCEMS	Utilization, transmission, generation	Climate change, energy burden, energy poverty, operations cost, ampacity limits, quality of life	Main objective
2	MGA	Utilization, generation	Energy burden, energy poverty, operations cost	Tool
3	CEMS	Utilization, generation	Energy burden, energy poverty, operations cost	Sub objective
4	BLM-HEMS	Utilization, generation, local generation	Energy burden, energy poverty, quality of life, climate change, return on investment, life cycle analysis	Sub objective
5	IEEM	Utilization, transmission, generation	Electricity supply expansion, demand-supply balance, capacity utilization, electricity billing, energy burden, energy poverty, quality of life	Sub objective
6	HGS	Utilization, generation	Operations cost, quality of life, climate change, energy burden, energy poverty	Sub objective

1.4 Research contributions

This research work makes enormous contributions spanning from the technical sphere (operations research, optimization, modelling) to social (energy poverty, QoL) and economic (electricity cost and policy). A summary of the contributions of this research work is presented subsequently.

1 A comprehensive evaluation of energy poverty in South Africa has been modelled and analysed using a segregated approach and actual residential electricity consumption. This research work pioneers a new approach to estimating electricity consumption in South Africa on provincial basis to show that there is a decline in electricity consumption by households.

2 This research work pioneers the integration of the SSEMS and HEMS through DR and dynamic pricing using randomly selected houses from a province to show that households

can in real terms reduce their electricity bills. Furthermore, this research work has been able to show that the utility can also minimize reserve margins, improve capacity utilization and reduce operations cost through DLC.

3 In this research work, the evaluation of how varying operational limits (in terms of hours within which participating loads must be dispatched) of households participating in DR and DLC affects their electricity cost reduction and the generation operation profile of the utility has been successfully modelled.

4 This research work further pioneers the complete integration of the HEMS, TLMS and SSEMS along with DR and a dynamic pricing scheme through ConCEMS framework (which extends contribution 2) to show that while energy poverty can be mitigated on the utilization end, the utility can also significantly reduce its operations cost through the smart dispatch of generators at the lowest cost without compromising the network limits (TLMS constraint).

5 The robustness of the proposed ConCEMS framework for integrating HEMS, TLMS and SSEMS has been evaluated in this research work. This has been achieved by benchmarking supporting algorithms of ConCEMS with standard test functions and algorithms.

6 The surrounding issues of household utilization of rooftop solar photovoltaic (PV) systems with battery storage have been addressed in this research work. This has been achieved by a biased load manager home energy management system (BLM-HEMS) framework that localizes DSM at the household level for optimal operation while guaranteeing households a reduction in electricity costs, minimized emissions and improved comfort.

7 This research work performs sensitivity analysis on the proposed BLM-HEMS framework to show how electricity users can be encouraged to key into the global trend of adopting renewable energy technologies into their electricity supply mix through competitive electricity pricing tariffs that guarantee a quick RoI on such investments.

8 The issue of failed off-grid electrification projects for South Africa and increasingly ru-

ral marginalization has been sufficiently addressed in this research work. This has been achieved through a modelled hybrid generation scheme that incorporates DR and has been exhaustively shown to meet with most of the principles of the energy justice framework. Furthermore, the proposed hybrid generation scheme is also shown to offer considerable reductions in emissions and energy poverty.

9 This research work further extends the proposed technical solutions for off-grid electrification by proposing policy frameworks that are interoperable and show in real terms how the proposed technical solutions can mitigate energy poverty and improve QoL.

1.5 Thesis layout

This research work adopts the thesis by publication style. In exhaustively investigating smart grids and its concepts (especially for South Africa), this research work addresses the social, technical, economic, policy and environmental impacts of incorporating AI techniques in smart grid optimisation (especially with regards to mitigating poverty). The general layout and thesis structure is shown subsequently.

Literature review

Chapter two presents the first paper entitled ***A just and sustainable smart grid approach for mitigating energy poverty and reducing climate change in South Africa*** which provides an exhaustive, comprehensive and critical review of up to date literature on DSM, smart grid and energy poverty for South Africa, highlighting the gap this research aims at addressing.

Social investigation - electricity consumption, energy poverty and DSM potential

Chapter three presents the second paper entitled ***Demand Side Management potentials for mitigating energy poverty in South Africa***. This paper presents the state of electricity consumption in South Africa by evaluating electricity consumption (kWh/capita) across the provinces for certain years to show that electricity consumption is declining. Furthermore, this paper presents DSM potentials in South Africa and presents its capability in mitigating poverty. A modified genetic algorithm (MGA) is developed and utilized in this paper.

Technical investigation - CEMS, ConCEMS, BLM-HEMS

Chapter four presents the third paper. This paper proposes a standard deviation biased genetic algorithm (SDBGA) and a combined energy management system (CEMS) for integrating HEMS and SSEMS. This paper fully exploits DR for 100, 000 randomly selected homes in the Limpopo region. Utilizing the Medupi power plant, two pricing schemes (dynamic pricing and TOU pricing) and two DLC schemes Option 2 (in which the utility controls the dispatch time of the participating DR loads) and Option 1 (in which the household oversees controlling the dispatch time of the participating DR loads), the trade-offs in terms of minimized consumer cost, minimized supply cost and supply capacity utilization is shown in this chapter.

Chapter five presents the fourth paper entitled ***A smart grid framework for optimally integrating supply-side, demand-side and transmission line management systems***. This chapter extends research on Chapter four by proposing ConCEMS that incorporates TLMS. Furthermore, this chapter presents the development of an externally constrained genetic algorithm (ExC-GA) for HEMS load optimisation, two AI based algorithms GA-EED and MEED for the economic dispatch of the supply side generators and a dynamic thermal line rating (DTLR) algorithm for dynamically computing the ampacity limits of the transmission line in real time. The proposed framework (ConCEMS) is evaluated to show its ability to guarantee households a reduction in their electricity bill without adversely compromising on their comfort, while still meeting the objectives of SSEMS and TLMS. This is tested using three dynamic pricing schemes and 1 TOU pricing scheme as a benchmark. The proposed GA-EED is benchmarked using standard functions.

Chapter six presents the fifth paper entitled ***A Biased Load Manager Home Energy Management System for Low-cost Residential Building Low-income Occupants***. This chapter localizes DSM to the household level by designing a load manager (BLM-HEMS) for a grid connected low/middle income household with a solar PV/battery system. Beyond the higher-level optimisation (CEMS and ConCEMS), BLM-HEMS ensures that households adopting RES into their energy mix can derive optimum benefits of overall electricity cost reduction and RoI. Sensitivity analysis is further carried out for varying electricity tariff to inform policy decision on electricity pricing that will provide households a motivation to adopt RES into their electricity supply mix.

Economic investigation and policy recommendations - IEEM

Chapter seven presents the sixth paper entitled ***Policy discussion for sustainable integrated electricity expansion in South Africa***. This chapter harmonizes DSM and the proposed ConCEMS in presenting an integrated electrification and expansion model (IEEM) for South Africa. The proposed IEEM provides a sustainable pathway for generation and transmission capacity expansion across South Africa and provides the utility and the electricity regulator NERSA (National Energy Regulator of South Africa) an avenue to observe the impact of pricing tariff increase and emissions penalty on consumer expenditure. Also, the proposed IEEM offers the utility a platform to evaluate the impact of various DSM initiatives on network performance. The findings from this chapter provide further policy discussions especially on poverty mitigation.

Environmental and energy justice investigation - hybrid generation scheme

Chapter eight presents the seventh paper entitled ***Energy (in)justice in off-grid rural electrification policy: South Africa in focus***. This chapter addresses exhaustively the problem of failed off-grid electrification projects in South Africa (and by extension SSA) by proposing a hybrid generation scheme that localizes smart grid concepts (DSM, DR), utilises smart load distribution boards and incorporates MGA in optimally scheduling the dispatch of connected loads. A major result from this chapter is the fact that the proposed hybrid generation scheme which incorporates diesel generator as backup is capable of reducing carbon emissions by over 70% under certain conditions. In further evaluating the potential of the proposed hybrid generation scheme to guarantee equivalent quality and quantity of electricity as obtainable from grid electricity and also mitigate energy poverty, principles from the energy justice framework are exhaustively used in critically evaluating the hybrid generation scheme.

Summary and conclusion

Chapter nine presents a summary of key findings from this research and provides insights into other areas that can be researched upon to improve on this thesis.

1.6 Summary of chapter

This chapter has introduced the problem statement including the motivation for this research. Furthermore, this chapter has briefly summarized the contributions of all the chapters that make up this thesis. The next chapter (***chapter two***) provides an in-depth literature analysis of relevant and pertinent literature that address issues of DSM, smart grid and poverty while establishing the gap in literature that this research addresses. Interest is placed on literature with focus on South Africa.

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CHAPTER 2

PAPER 1 - LITERATURE REVIEW

Brief summary

This section presents an exhaustive, comprehensive and critical review of existing literature on smart grid - its conceptualization and development for South Africa. Further review is also conducted on smart grid initiatives especially DSM for both residential and industrial applications in South Africa. A primary goal for this exhaustive survey is to determine the potential of existing proposed smart grid initiatives to mitigate poverty, precipitate economic growth and combat climate change especially for South Africa and further underscore the importance of this research work.

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A just and sustainable smart grid approach for mitigating energy poverty and reducing climate change in South Africa

Monyei, C. G.[1,2,4], Viriri, S.[1] and Jenkins, K.[3]

[1]School of Mathematics, Statistics and Computer Science, University of KwaZulu-Natal,
Westville Campus, Private Bag X54001, Durban 4000, South Africa

[2]Gidia Oaks Centre for Energy Research, Lagos, Nigeria

[3]School of Environment and Technology, University of Brighton, Cockcroft Building,
Moulsecoomb, Brighton, BN2 4GJ, United Kingdom

[4]Corresponding author

Abstract

South Africa finds itself on the brink of a major dilemma, mitigating climate change *and* poverty. With a history fraught with excess electricity supply followed by a major power crisis in 2008, projections point to a repeat of excess electricity supply again. Overcompensation for the 2008 supply deficit has led to the recommissioning of decommissioned power plants, the construction of additional power plants, and a vigorous pursuit of renewable energy projects. All are geared towards ensuring energy security and availability and diversifying the supply mix to reduce carbon emissions. Yet, recent research findings demonstrate a supply glut that is expected to persist to the near future, alongside declining electricity consumption. Thus, the logic of such action can be questioned. Fears also arise over the sustainability and viability of South Africa's smart grid vision 2030 considering the effects of revenue deficit caused by reduced electricity purchases. Acknowledging already unbearable tariff rates, high poverty rates, weakened economic growth forecasts, the planned introduction of carbon tax, and the huge investments in the electricity sector, this research presents both a critique of current policy arguments and a proposal to improve South Africa's smart grid roll out.

Keywords: supply glut; tariff rates; poverty; climate change; smart grid; energy policy

Highlights

- Investigates the Smart Grid 2030 Vision for South Africa.
- Findings reveal insufficient smart grid research for South Africa.
- Identifies pertinent concerns of sustainability and justice.
- Proposes policy recommendations for Vision improvement.

1. **Introduction**

What constitutes a “smart grid” can vary according to disciplinary perspective. However, it is generally agreed that smart grids encompass a framework to increase the participation of all active players in the electricity sector, as well as some degree of technological innovation. According to Bayindir et al. (2016), smart grids refer to the next-generation grid networks that enable the synergy and integration of information technology into the existing electricity network, the purpose of which is to improve efficiency. Smart grids were also presented by Choi and Do (2016) as self-sufficient systems capable of finding and resolving network problems, supporting quality electricity delivery to customers through sustainable, reliable, and safe approaches. Thus, smart grids can be presented as an “ally”, especially for countries seeking to reduce their greenhouse gas emissions (Ponce-Jara et al. 2017).

Across the world, the reasons for the development of smart grids and their associated technologies fluctuate. They have been instrumental in the integration of renewable energy sources (RES) into the conventional power grid (see Abdmouleh et al. 2018; Baekovi and Stergaard 2018). Smart grids have also played an important role in the increasing integration of electric vehicles (EV’s) for optimal operation, as shown in Rahbari et al. (2017) and Mwasilu et al. (2014). Moreover, the growing presence of prosumers – electricity consumers who are also producers, as is the case with grid connected households that have rooftop Solar Home Systems (SHS) – has been facilitated greatly by their implementation (Zafar et al. 2018), with smart grids playing greater role in improving the quality of electricity delivery through voltage stabilization and efficient energy utilization (Gandoman et al. 2018). Finally, but perhaps not exclusively, they present a major environmental gain, enabled by a shift from a dependence on fossil fuels to increasing exploitation of lower carbon RES (Bayindir et al. 2016).

Yet despite positive strides, there are two flaws in smart research to date. Firstly, with the exception of a few notable studies, little research has comprehensively considered the social justice implications of their development (see Welsch et al. 2013; Wolsink, 2012;

Goulden et al. 2014). Secondly, research on the impacts and acceptance of smart grid development has mainly been concentrated in the affluent or developed economies of the world. Abdmouleh et al. (2018) undertook a survey in Qatar to gauge public perception on smart grids among other initiatives. Similarly, in Kktrk and Toku (2017), smart grid technology was investigated for the integration of wind energy in Izmir, Turkey. Smart grid research is also evidenced for Denmark (Schick and Gad, 2015), the USA and Canada (Meadowcroft et al., 2018), South Korea (Choi and Do, 2016), China (Yuan et al., 2014; Mah et al., 2017) and Pakistan (Irfan et al., 2017), where its potential and feasibility was investigated. The development of smart grids in *less* developed contexts is, in comparison, less well explored. The contribution of this research is to (partially) fill these gaps through a South Africa case study.

Explorations of smart grids in the global south and in particular, in South Africa, are particularly necessary. In this context, Welsch et al. (2013) identify that in addition to electricity grids being “smart” (e.g. existing as technologically advanced enablers of energy diversification), *socially just* power systems are also required to facilitate the promotion of access to electricity without marginalizing the poor. Table 1 shows that despite having over 90% electrification rate, South Africa still has poverty levels greater than 55%. Given the causal relationship between poverty and electricity consumption, this high rate implies limited electricity consumption, if not a decline in it (Monyei et al. 2018b). Indeed, Monyei and Adewumi (2017) evidence a decline in electricity consumption for three years across all of South Africa’s provinces. A further, crucial observation illustrated in Table 1 is that South Africa has the highest energy intensity for the countries under consideration. This high energy intensity raises questions around South Africa’s ability to combat climate change by committing to its CO_2 reduction target. South Africa thus faces a unique problem of combating climate change as a developing country while seeking to reduce poverty and inequality (INDC 2015) – a challenge that can be aided with a socially appropriate power system.

Table 1: Selected statistics and indicators for selected countries (IEA 2018)

Country	kWh/capita[*]	Population (million)[**]	Electricity access (%)[a]	Poverty (% of population)	Energy intensity[b]
Denmark	5,5859	5.73	100		3
Qatar	15,309	2.57	100		6
USA	12,987	323.13	100		6
Canada	15,546	36.29	100		8
India	806	1,324.17	79.2	21.9^{2011}	5
China	3,927	1,378.67	100		7
Brazil	2,601	297.65	99.7	8.7^{2015}	2
Russia	6,603	144.34	100	13.5^{2016}	8
South Africa	4,198	55.91	90.3	55.5^{2014}	9

* - 2014; ** - 2016; a - 2014; b - 2014; c - see Monyei and Adewumi (2017)

Against this background, this paper examines the growth of smart grid initiatives in South Africa across the residential and industrial sector. It does so in order to determine whether ongoing policy initiatives are capable of mitigating poverty *and* reducing the energy burden of households, whilst also facilitating the attainment of South Africa's envisioned emissions cap (INDC 2015). Acknowledging already unbearable tariff rates, high poverty rates, weakened economic growth forecasts, the planned introduction of carbon tax, and the huge investments in the electricity sector, this research presents both a critique of current policy arguments and a proposal to improve the approach to the smart grid roll out in South Africa. More specifically, by the end of the paper we present a concerted approach to supply capacity expansion that ensures that electricity supply security is not threatened, whilst electricity provision is fair.

2. The South African energy landscape

The text that follows outlines and critique current South African energy policy before we later go on to provide suggestions on how to improve it.

2.1. Background

In 2008, power crises plagued South Africa, leading to massive blackouts, load shedding and huge economic losses (see Kohler 2014; Shezi 2015). Since then, efforts to boost electricity supply have been ramped up, especially through the construction of new coal powered stations designed to both (1) compensate for the shortfall that led to the 2008 crisis and (2) meet anticipated growth in electricity demand. Alongside drives for energy security, climate change targets also drive South African energy policy. In committing to greenhouse gas (GHG) emissions reduction, South Africa adopts a peak, plateau and decline (PPD) approach. Its national policy targets 398-614 Mt CO_2-eq between 2025 and 2030 with a long-term aspiration of GHG emissions in the range of 212-428 Mt CO_2-eq by 2050, having declined in absolute terms from 2036 upwards (INDC 2015).

In the wake of these targets, South Africa's National Development Plan (NDP) identifies the need for investment in a strong network of economic infrastructure designed to support both the medium and long-term economic objectives of South Africa (DoE 2017). The national target is for 18,000 MW renewable energy supply capacity by 2030 (see Energy Intelligence 2016)[1], 5, 243 MW of which has already been delivered through 79 different projects (accounting for over a quarter of the 2030 target). This is happening primarily through a combination of renewable energy projects (REPs) and energy efficiency demand side management (EEDSM). According to Energy Intelligence (2016), over 17.25 Mt-CO_2 of carbon emissions has been saved from the inception of the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP), which includes onshore wind, solar photovoltaic, concentrated solar power (CSP), biomass, landfill gas, small hydropower and biogas.

The REIPPPP was developed to encourage private investment in further developing South Africa's renewable energy sector (Energy Intelligence 2016). It runs sequel to the renewable energy feed-in tariff (REFiT) program, which was scrapped in August 2011 because it violated national procurement legislation (Baker 2015). The REIPPPP is a tender system based on competitive bidding with the compliant bidder with the highest score, setting the benchmark for competition (Baker 2015).

Njobeni (2018) suggests that despite the public support for the successes of the REIPPPP, Eskom–South Africa's electricity public utility–has bemoaned the cost of connecting the independent power producers (IPPs). Njobeni (2018) further posits that Eskom is reported

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[1] Estimates as of March 2016.

to have spent R6.64 billion to purchase 3, 048 GWh of renewable energy at an average cost of R2.18/kWh. This is at variance with Eskom's levelized cost of energy (LCOE) for the Medupi and Kusile power plants of R0.71/kWh and R0.96/kWh respectively (DoE 2017). Thus, there is some dissatisfaction around the implementation of energy strategies. Indeed, even their wider motivation can be critiqued as being perverse. Monyei and Adewumi (2017) posit that ongoing supply capacity expansion was likely to exceed electricity demand by over 500% within the planning period under review (see also Eskom 2015). Lynne Brown (South Africa's minister of public enterprises from May 2014 to February 2018) shared this view and advocated for a revised energy plan to avoid surplus energy that could hurt the economy (in Njobeni 2018). Further, Monyei and Adewumi (2017) also established that electricity consumption across the provinces in South Africa has been in *decline* and that anticipated electricity demand growth has fallen short of initial projections. This decline in electricity consumption hinged on the astronomical increment in electricity cost by the utility (Eskom), which was cumulatively estimated to be about 114% between 2008-2013 (Eskom 2017).

Considering the ambitious renewable energy targets and declining electricity demand we have evidenced above; the need therefore arises for a concerted approach to supply capacity expansion that ensures that electricity supply security is not threatened. This is especially key as:

1. **Renewable energy sources (RES) (on which ongoing South African policies depend) are stochastic in nature.** This implies that accurately predicting their availability is often difficult. This stochasticity thus raises the problem of effective system planning by the utility. While much work has been conducted in synergizing RES with the grid for other countries, there has been no comprehensive research with focus on South Africa into investigating the impact of integrating large scale RES with the grid, coupled with declining electricity consumption. This investigation is necessary for ensuring optimal grid operations as well as the sustainability of Eskom's operations without adversely penalizing electricity consumers through resultant tariff hikes.

We do acknowledge major works on RES and their operations for South Africa, which have spanned surveys on potential (Jain and Jain 2017; Winkler et al. 2017), finance (Baker 2015) and policy (Onyeji-Nwogu 2017), amongst other themes. Moreover, we highlight the sensitivity analysis conducted by Eskom (2015) using various power generation scenarios as specified by the department of energy (DoE). However, the sensitivity analysis only considered the full impacts and not the phased rollout of these scenarios. The implication of this is that inherent and latent cases that arise will not be pre-empted ahead of time as is the case with supply capacity currently exceeding demand capacity and posited by Eskom to continue until 2021 (Jain and Jain 2017).

2. **The current demand-side management (DSM) initiatives in South Africa are energy efficiency based (EEDSM) and not price based** (Monyei and Adewumi 2018). While huge savings and potential exist from the deepening of energy efficiency initiatives in South Africa, like the distribution of compact fluorescent light (CFL) bulbs has shown (Eskom 2017a), the EEDSM initiatives are limited in offering flexibility to the system operator in planning and scheduling grid operations. Price based and incentive based DR programs are thus capable of improving the flexibility of the grid especially when there is a high participation of consumers in demand response (DR) and direct load control (DLC). In exploiting the benefits of RES, DR loads with varying DLC options (full/partial) offer the utility greater operational control in dispatching participating DSM loads to utilise RES without compromising on grid constraints. However, a survey on DSM literature with particular emphasis on South Africa shows that most DSM initiatives have been conducted exclusively on an aspect of the electricity grid. For example, Clark (2000) conducted early research on the barriers inhibiting DSM investment in South Africa, making recommendations on how to promote energy efficiency investments in the changing electricity markets. In Pelzer et al. (2008), DSM was investigated as a means of managing peak demand in gold mines situated in the Free State Province, while Rankin and Rousseau (2008) described the use of an in line water heating concept. Finally, in terms of our examples, a combined DSM strategy for 5 residential households in South Africa was presented in Setlhaolo and Xia (2016) and Lombard et al. (1999) investigated the application of DSM in

improving thermal efficiency in the residential sector, where energy savings of around 1000 GWh/year was computed for the promotion, loan and enforcement of minimum new housing standard scenario.

These examples serve to illustrate the limitations of current policy approaches. In addition to these broader critiques, we highlight a series of observations from DSM studies in South Africa and explore their potential impact.

1. Besides the work of Monyei and Adewumi (2017), there is little research that seeks to quantify the DSM potential in South Africa. Furthermore, where attempts have been made they have been limited. Case scenarios frequently utilized in preparing documents for energy planning such as the transmission development plan (TDP), Integrated Resource Plan (IRP) and the Integrated Energy Plan (IEP) have made use of assumptions which have not highlighted the potential for specific devices like dish washers, cloth dryers, cloth washers, heating ventilation and cooling (HVAC) loads to provide varying DSM potentials based on varying participation levels, for example.

Potential impact: The inadequacy of literature on the potential for DR in South Africa implies that the utility (Eskom) might not be able to take advantage of flexible customers in efficiently planning the downsizing of its coal generation power plants for greater integration of RES. Furthermore, with the likely growth of electric vehicles (EV's) and prosumers, the absence of comprehensive and robust literature investigating their impact on South Africa's power grid implies that projections by the utility on electricity demand and pricing would always be inaccurate[2].

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[2] By inaccurate we do not imply slight variations with minimal national implications. What we imply are projections that lead to either a large supply deficit (see Kohler 2014; Shezi 2015) or large supply glut (see Monyei and Adewumi 2017; Njobeni 2018). The impact of such variations is national in scope, leading to severe economic losses in the case of large supply deficits or steep electricity prices in the case of supply glut as an outcome of attempts to recoup investments. The steep electricity prices also affect consumption, increase the energy burden of households, increase energy poverty and affect productivity.

2. Most of the literature on DSM for South Africa does not establish the effect of the achieved savings on the grid (generation cost, ampacity implications for the transmission network etc.). A contrast to this is in Monyei and Adewumi (2018), where a framework was provided for South Africa to synergize the home energy management systems (HEMS) and the supply side energy management systems (SSEMS). The combined energy management system (CEMS) proposed, incorporated direct load control (partial/full) and achieved consumer costs savings and improved supply capacity utilization.

Potential impact: The isolation of DSM research in South Africa implies that the negative ripple effects of various schemes across the entire electricity network cannot be envisaged and compensated for. For instance, DSM research on HEMS *may* preclude investigation into the effect of incorporating tie-grid SHS on local voltage levels, reactive power compensation, frequency regulation and transmission/distribution line limits. Further, isolated research on SSEMS implies that the utility might evolve dispatch scenarios that either lead to excessive over-sizing (wide reserve margins) or supply deficits. An integrated DSM approach provides valuable information that can assist the utility (Eskom) in taking advantage of HEMS and TLMS (using dynamic thermal line rating (DTLR) for instance) in scheduling maintenance of its generation units, exploiting RES or balancing the grid in the event of a fault (with minimal economic losses).

3. Localized DSM initiatives for the residential sector in South Africa have not been able to explore the impact of tariff rates in influencing return on investment (RoI) for solar home systems (SHS), especially for off-grid SHS in reducing peak demand and household energy costs. We however note the work of Numbi and Malinga (2017) in which a comprehensive energy cost and economic analysis of a residential grid-interactive solar photovoltaic (PV) system was conducted for a site in the eThekwini municipality in South Africa. Differing from Monyei et al. (2018a), Numbi and Malinga (2017) considers the impact of variation in feed-in tariff (FiT) on RoI (payback period, PBP). However, since a grid connected PV system might not be economical to the residential sector (as observed by Numbi and Malinga 2017), the need arises for more

research into how residential billing could be used in encouraging the proliferation of RES especially at the residential level. Considering the high poverty rate in South Africa (estimated to be over 55% (STATSSA 2017)), and Eskom's electricity tariff rates which is declared by some to be among the lowest worldwide (LTE 2012), the need arises for a comprehensive techno-economic and environmental assessment of SHS (similar to Monyei et al. 2018a) on the capability of SHS in (1) improving the quality of life of households, (2) mitigating carbon emissions and (3) minimizing household electricity bill.

Potential impact: While large-scale renewable energy projects have been acclaimed within South Africa (especially through the REIPPPP) as having the potential to mitigate carbon emissions, the residential sector also has the potential of facilitating a decarbonised electricity grid. However, great care must be taken to avoid the failures of REFiT, as observed in Germany, where the hike in energy bills (over 12% between 2002 and 2006) led to as many as 800, 000 Germans having their electricity cut-off due to their inability to pay the rising costs (AEA 2015). Indeed, while Monyei et al. (2018a) show that households can have a quick RoI based on higher tariffs, we must be cautious when fixing tariff plans so as not to push more people into poverty. The government also has a great role to play in evolving smart policies that will encourage the purchase of RES for household uses especially through long term loans (at minimized interest rates) for the purchase of RES.

4. The majority of DSM studies for South Africa have concentrated on grid connected households and industrial sites. According to Mandelli et al. (2016), about 60% of additional electricity generation needed to provide universal access to energy will be generated through off-grid systems. This highlights the huge potential to localize DSM at the off-grid level to ensure that such off-grid systems are capable of providing both access and guaranteeing energy mobility[3]. Furthermore, the rising spate of unsuccessful

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[3] We define energy mobility to be the ability of households to transit from one level of energy consumption to a higher level through the extended usage of already owned electrical appliances or by purchasing additional electrical appliances (Monyei et al. 2018c).

off-grid projects in South Africa as shown in Azimoh et al. (2016) and SSA as presented in Ikejemba et al. (2017) necessitates the need for focused research into DSM initiatives capable of ensuring that off-grid electrification projects are sustainable.

Potential impact: According to Baker et al. (2015), the debt of South African households has doubled in recent years. Furthermore, Baker et al. (2015) also asserts that despite considerable progress made in electrifying households in South Africa, access remains limited and unaffordable for many. Considering the fact that over 60% of additional electricity generation needed to provide universal electricity access is expected to be from off-grid systems (Mandelli et al. 2016), the need arises for a more pragmatic approach to the free basic electricity (FBE). With the failure of the Lucingweni project as investigated by Azimoh et al. (2016), there is the need for more attention to off-grid electrification projects to ensure that they guarantee access and mobility. Localizing conventional smart grid approaches such as DSM at the off-grid level is argued by the authors to have the potential to reduce peak demand and also extend the usage of off-grid electrification projects. In addition, according to Casillas and Kammen (2010), while increased access to electricity alone will not eradicate poverty, there are immediate benefits. According to Casillas and Kammen (2010), electricity is capable of catalysing rural economic activities and increasing the quality of services available, for instance.

5. The majority of DSM research studies for South Africa have not been able to empirically show the capability of DR in mitigating energy poverty. According to DoE (2012), 47% of non-electrified households in South Africa experience energy poverty with declining electricity consumption as a result of steep electricity tariff noted in Monyei and Adewumi (2017). While it is posited that electrification alone cannot solve the entirety of the developmental problems plaguing rural households, households cannot access development assistance opportunities without having access to electricity (Azimoh et al. 2017). In addition, since productivity is linked to electricity access (Azimoh et al. 2017), there is the need for a framework[4] that enables the utility (in this

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[4] By framework we imply a set-up that allows for the interplay of policy directions from the various electricity major players (Eskom, IPP's, National Electricity Regulator of South Africa, NERSA, DoE, Ministry of Finance etc.). This set-up provides the various players

case Eskom), the regulator (in this case the National Energy Regulator of South Africa, NERSA), IPP's and other electricity players (electricity consumers, electricity vendors etc.) to harmonize their individual objectives. The overall aim is for evolving generation dispatch scenarios that (1) ensure sustainability of operations of the baseload utility company (Eskom)[5], (2) ensure high penetration and exploitation of RES for reducing carbon emissions and guaranteeing the survivability of the IPP's, (3) guarantees electricity rates and tariffs that do not increase the energy burden of households thus forcing them to reduce their electricity consumption, (4) encourages more electricity consumption from households, (5) precipitates economic growth (since productivity has been linked with electricity access in Azimoh et al. (2017)) and (6) is sustainable, just [6], secure [7], of high quality and does not violate grid technical

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with an overview of the effects of their various policy directions (electricity tariffs, carbon penalty, quantity of electricity bought from IPP's etc.) on GDP growth, poverty levels, carbon emissions, electricity consumption etc. Beyond providing an extended overview, such a framework is also capable of optimising the competing policy directions of the various players to evolve an optimal dispatch that strives to satisfy every player up to a reasonable extent. The term 'reasonable extent' as used is flux and varies based on the NDP.

[5] A major reason for this consideration is the fact that RES cannot be taken as base load electricity sources due to their stochastic and unpredictable nature. For instance, EIA (2017) shows that coal exploitation alone in electricity generation for the Organisation for Economic Co-operation and Development (OECD) countries still makes up about 31% (as at 2014) of the total generation mix, producing over 3 000 TWh of electricity (as at 2014) compared to over 2 000 TWh in 1980 representing about a 50% increase in utilization of coal between 1980-2014. This is despite significant investment in renewable energy (RE).

[6] By just, we imply a dispatch scenario that - guarantees equal quality of electricity supplied to all electricity users irrespective of their purchasing ability (egalitarianism); is secure and provides value to electricity users without blackouts or rationing (utilitarianism); evolves electricity tariffs that enable households purchase electricity in quantities that is sufficient to meet basic needs of lighting, heating, cooking, communication and entertainment (sufficientarianism) and places no constraints on how and when electricity users should use their purchased electricity (libertarianism). This is, in effect, our normative goal.

[7] By secure we imply a state of stable electricity supply in which there is always sufficient supply to meet demand. We acknowledge that continuously expanding supply capacity to match anticipated demand might not be sustainable in the long term, and moderate security within our proposed framework to be a state of balance between electricity demand and available supply that is achieved with the active participation of DR and other DSM initiatives that achieve peak demand reduction and exploitation of RES without compromising consumer comfort. We further extend security to off-grid communities and imply it to be a state where off-grid generation schemes can beyond electricity access

constraints.

Potential impact: Energy poverty remains a crisis for South Africa. With over 47% of non-electrified households in South Africa said to be energy poor (DoE 2012), the implication is that additional costs on households may further impoverish them. As such, the argument for DR must provide households with an incentive for participation such as reduced electricity bills. This is necessary to relieve energy poor homes of high energy bills which can be used in either extending the consumption of electricity or engaging in other activities capable of improving their quality of life (QoL). Furthermore, adopted tariff and billing systems must recognise energy poor homes. This is necessary to encourage electricity consumption from them. While the sustainability of the utility (Eskom) as well as the IPP's depends to a great extent on a sustainable financing, billing and cost-recovery scheme, DSM we argue is an important ally in ensuring that the utility can achieve fairness in billing with minimal capacity expansion.

Our critique so far, summarises the argument that current energy policy initiatives in South Africa may not be effective and indeed, that they *could* present numerous social burdens if not developed appropriately. We warn, for instance, of increased energy poverty burdens and restricted access and mobility. To further evidence the potential implications of these points, we now briefly highlight pertinent findings from the global north, especially relating to low-carbon energy transitions. These findings then lead us to develop cautionary tales and policy recommendations for smart grid development in the South African context.

3 Summary of findings on low-carbon transitions in the global north

Germany's *Energiewende*—their energy transition plan—has resulted in a renewables share of over 30% across the country (Matthews 2017), but at a significant price. Approximately 150 billion Euros is estimated to be have been spent on the program, with that figure expected to hit 500 billion Euros by 2025 (Becker 2017). In 2017 alone, almost *1 billion* Euro was spent stabilizing the German national electricity grid due to

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guarantee connected households' energy mobility up to a reasonable extent. The term 'reasonable extent' is flux here and varies based on the NDP.

intermittency in wind and solar availability (Green Watch 2018). Rising energy prices also mean that 300,000 houses have their electricity cut each year, with a further 44,000 households losing their gas supply (The Local 2017). Furthermore, the increasing penetration of renewable in Germany has resulted in electricity dumping, especially during excess power production. Germany's *Energiewende* has thus resulted in Germany becoming increasingly dependent on its neighbours – Czech Republic, Poland, the Netherlands, Belgium and France, in absorbing excess power generate[8]. Furthermore, despite the increasing penetration of renewables in Germany's electricity grid, there has been an increase in CO_2 emissions due to the increasing burning of *Braunkohle* (lignite), the result of which *might be* Germany's inability to meet its 2020 CO_2 emissions reduction target (Smil 2016).

Similarly, California is also experiencing negative fallout of the renewable energy transitions path. Despite a 2.6% reduction in annual electricity use compared to 2008, California residential and business customers together, pay approximately $6.8 billion *more* for their power (Penn and Menezes 2017). This means that on average, electricity rates in California are 50% more than the rest of the country. With surplus electricity exceeding 15% and further predicted surpluses of 6% in the next three years, in theory, the economic principles of demand and supply *should* mean that electricity rates fall. However, this evidence suggests that higher supply capacity may imply *even higher* electricity rates. Furthermore, California has had to pay Arizona to receive excess power generated from solar and wind (Donnelly 2017).

Although very brief, these two case studies (which echo across the global north) show that supporting electricity infrastructure to successfully integrate renewable energy can have unintended consequences, such as increasing energy bills and energy poverty. With

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[8] While it may be argued that the increasing dependence of Germany on its neighbours (especially for absorbing excess power generated) can foster an increasingly integrated EU wide electricity grid, the potential problems of energy security and conflicts of external influence with national policies are capable of complicating issues. A case in point is the immigration crisis in the EU, which has polarized member nations and threatened the Schengen arrangement.

already high incidences of both in South Africa, we therefore need a means of mitigating this potential.

4 Smart grid: conceptualization, development and management in South Africa

4.1 Background: Smart Grid 2030 Vision

According to Baker (2015), South Africa is one of the most unequal countries in the world with a Gini-coefficient of 0.69. This necessitates the need for a decarbonisation path that does not replicate South Africa’s historical inequalities (Baker 2015). South Africa also currently faces increasing economic challenges combined with a changing electricity landscape, where the drive for lower carbon generation options along with the need for greater efficiency on the demand side underscores the drive for more sophisticated and intelligent network capabilities. This sits alongside other drivers of smart grid development, including (1) the necessity of multi-directional power flow, (2) grid integration, (3) the accommodation of distributed generation from renewable sources and storage interfaces with EV’s, for instance and (4) protection from grid vulnerabilities due to attacks, natural disasters and having limited self-healing capabilities. SASGI (2017) maintains that without addressing grid intelligence, projected economic growth targets were at risk as the current grid and deployed technology were incapable of supporting projected economic growth and responding effectively to the broader dynamics affecting the grid.

In response to such challenges, the Smart grid 2030 Vision for South Africa was developed by South African Smart Grid Initiative (SASGI) through a process of careful consideration and consultation, the end result of which is a common picture of a smart grid that is relevant to South Africa and the challenges the industry faces. SASGI (2012) is an initiative of the South African National Development Institute (SANEDI) formed in 2012. It is made up of industry stakeholders within the Electricity Distribution Industry (EDI) with the main objective of drawing on industry expertise to develop a Smart Grid vision for the industry and create a platform for knowledge sharing (SASGI 2012). SASGI posits that the incorporation of smart grids in South Africa is to serve as an enabler in addressing pertinent challenges currently faced by the electricity supply industry (ESI) as shown in Figure 1.

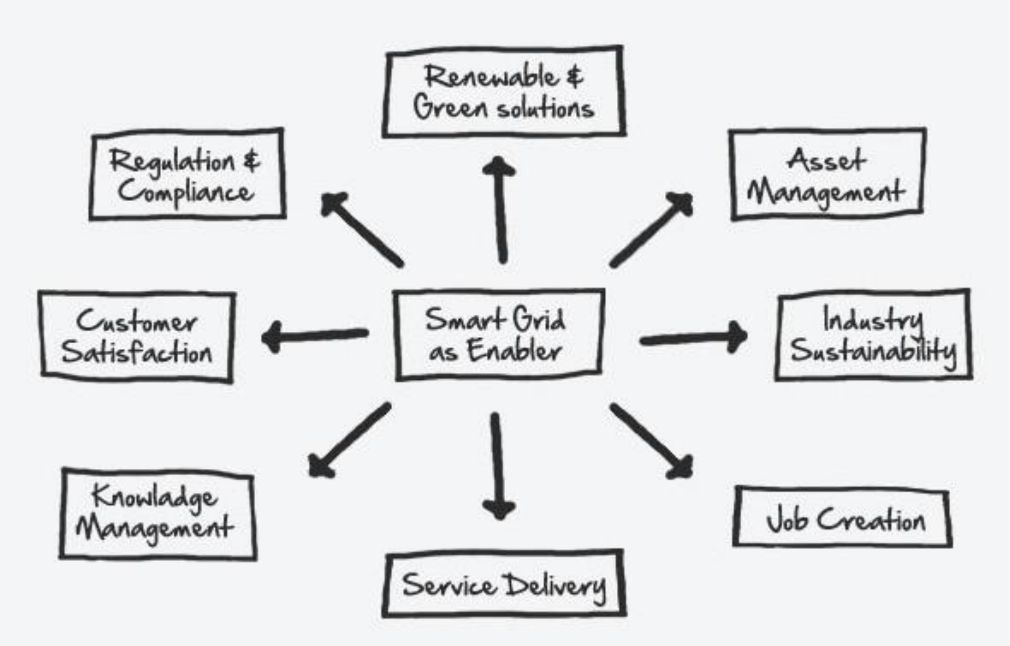

Figure 1: Smart Grid as an enabler for the ESI (SASGI 2012).

Furthermore, according to SASGI (2012), the Smart Grid Vision statement for South Africa is for an economically evolved, technology enabled, electricity system that is intelligent, interactive, flexible and efficient and will enable South Africa’s energy use to be sustainable for future generations. Clarity is further provided to key terms in the Smart Grid Vision from SASGI (2012) (the structure of which is shown in Figure 2).

- Economically evolved: affordable electricity system that meets growing needs of the country.
- Technology enabled: fit for purpose ICT, processes, sensors, systems and applications.
- Intelligent: from data to knowledge.
- Interactive: ability to monitor, control and manage using two-way communications throughout the value chain.
- Flexible: appropriate, scalable and adaptable based on common standards.

- Electricity system: the complete value chain of all interconnected equipment and components from generation to end use.
- Sustainable: optimised and affordable from environmental and economic perspectives.

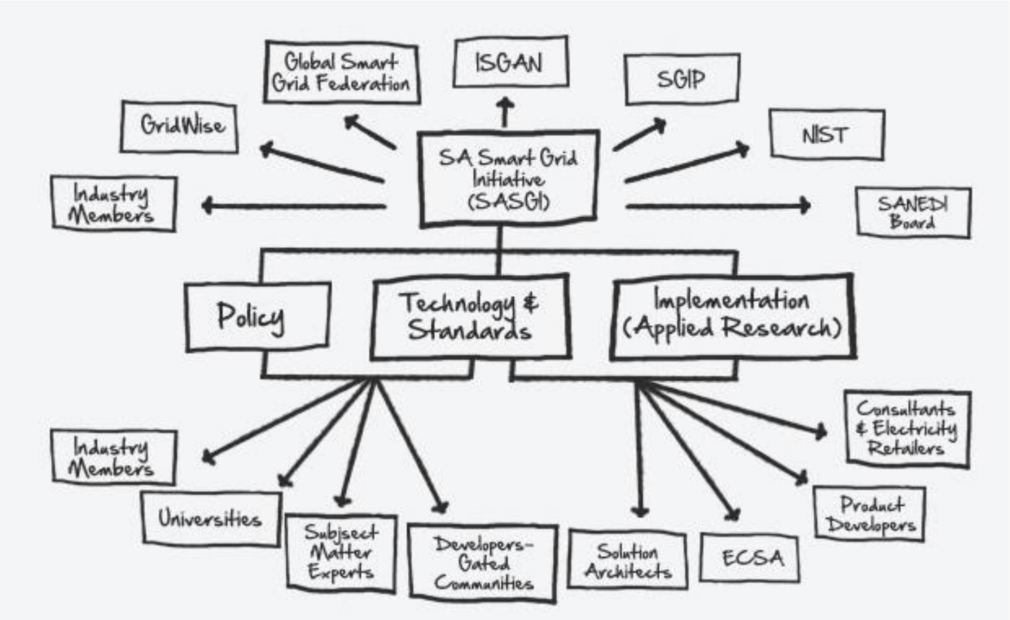

Figure 2: SASGI structure (SASGI 2012).

Yet, in keeping with the critiques presented above, the development of the Smart Grid 2030 Development is not without concern. Firstly, we must ask **what constitutes the definition for affordable electricity?** The current electricity tariff has been highlighted as being unaffordable to many and potentially damaging to the economy (Omarjee 2017). Further concerns arise over potential tariff increment to bridge Eskom's revenue shortfall (which was estimated to be R35 billion for 2014/15 in Eskom (2017)) and maintain operational status. Furthermore, considering the huge costs already expended by Eskom in integrating IPP's and the planned carbon tax, there is the possibility of the resulting cost effect being transferred to electricity consumers. With over 55% of South Africa's households poor, the possibility of driving more households further into poverty arises. In addition, the ripple effect of a poorer population does not bode well for South Africa's already struggling economy.

A second concern arises over **what constitutes an electricity system that meets growing needs of the country**? For example, the Free Basic Electrification (FBE) policy advocates 50 kWh/month for poor homes (GNESD 2018); the Non-Grid Electrification Policy advocates SHS for off-grid poor homes (DME 2009), while the Free Basic Alternative Energy (FBAE) policy is aimed at supplying indigent off-grid households without SHS limited quantities of alternative energy fuels at no cost to meet their basic energy needs (DME 2007). The failure of the Non Grid Electrification Policy has been extensively highlighted in Monyei et al. (2018d), Azimoh et al. (2016) and Azimoh et al. (2017) especially for the Lucingweni off-grid project. Considering the fact that electricity is playing a greater role in our everyday lives and its potential to significantly improve QoL, to what extent therefore does the FBAE and Non Grid Electrification Policy meet the growing needs of South Africa, considering such issues as more energy efficient systems and lower energy intensity? We further argue that the Non Grid Electrification Policy promotes rural marginalisation owing to the fact that it does not consider such pertinent factors as the stochasticity of solar irradiance, does not guarantee energy mobility, further impoverishes households and thus creates injustice[9]. Furthermore, the paucity of literature highlighting the effect of this rural marginalisation raises additional concerns and doubts as to the government's intention of stimulating economic growth and mitigating poverty.

A third and final concern emerges around the question of **what defines sustainability**? Considering South Africa's drive to mitigate carbon emissions, a key concern arises as to what extent measures are to be taken in achieving this. Considering the fact that 100% renewable might not be feasible for electrifying off-grid communities due to their already

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[9] We argue that while the FBE offers grid connected poor households quality electricity that is available, free, secure and provides for energy mobility, the Non Grid Electrification Policy creates injustice as its deployment does not abate the utilization of fuel-woods, paraffin and coal (Monyei et al. 2018d). This is due to its established failure as highlighted in Monyei et al. (2018d), Azimoh et al. (2016) and Azimoh et al. (2017). Differentiating the quality of electricity provided to poor households based on their proximity to the grid is in itself an injustice (Monyei et al. 2018c).

highlighted failures, as documented in Azimoh et al. (2016) and Azimoh et al. (2017), hybrid generation schemes[10] involving fossil fuel sources are being proposed as better alternatives to 100% renewable (Azimoh et al. 2016). This is due to their ability to counteract the effect of stochastic solar irradiance. While it may be further argued that deployed renewable energy systems could be over-sized, we also ask to what extent considering that sizing is dependent on loading and available solar irradiance. Furthermore, who bears the additional costs incurred in sizing such systems? In addition, we state that deployed SHS that are not capable of meeting the energy needs of households further impoverishes them. This is because the monthly cost (though subsidized) that is paid by the households offers no value to them. Households still continue to incur additional costs expended in purchasing paraffin, fuel-woods and coal to meet their lighting, heating and cooking needs. Furthermore, in terms of mitigating carbon emissions, the authors argue that the utilization of hybrid generation scheme offers considerable savings due to the enormous emissions saved in displacing local coal utilisation and deforestation (for fuel woods).

5. Policy discussions and recommendation

In providing guidance for an improved smart grid initiative for South Africa, we propose policy recommendations that we argue are capable of buoying the chances of success for the Smart Grid 2030 Vision. Our policy discussions center on technical expertise, flexible integration, and focused definitions of what constitutes sustainability and quality of life.

5.1 Technical expertise for a successful smart grid

South Africa currently faces severe skills shortages (Reddy et al. 2016), especially for technical disciplines. Instances of technical incompetence and a significant lack of staff (which in some cases could be as high as 50%) need to be addressed before South Africa can benefit from the untapped potentials of a smart grid (Spintelligent 2017). Spintelligent

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[10] The authors acknowledge that hybrid generation schemes might not be the best solution, but aver that they can guarantee off-grid households stable electricity supply that is sufficient (Monyei et al. 2018d). Furthermore, hybrid generation schemes offer flexibility in scaling up their size to accommodate increasing load thus guaranteeing households energy mobility.

(2017) further suggests that the smart grid is inherently characterised by information technology (IT), along with a major input from other disciplines such as systems engineering and project management, which are crucial for its success. With these skills currently lacking at the municipal level, doubts arise over the success of the Smart Grid 2030 Vision.

In addition, this paper has highlighted that there is limited research on smart grid initiatives, especially for South Africa. In particular, the significant mismatch between Eskom's projected electricity demand and actual demand which was instrumental in guiding the REIPPPP shows that there is lacking significant research on the potential impact of DSM initiatives in introducing some flexibility to the grid. The need thus arises for a concerted approach in (1) building the needed technical manpower equipped with sufficient skills to handle the demands of the envisioned smart grid (staff who are capable of using the immense information from the advanced metering infrastructure (AMI) in making (near) real time decisions) and (2) funding what may be a research body or think thank dedicated to smart grid research. This is necessary to drive research in all aspects of the smart grid and provide valuable information during smart grid policy development. Such research must comprehensively evaluate varying scenarios of RES injection, outages, DSM participation, EV's integration etc. and their overall impact on electricity cost, electricity consumption, peak demand, grid stability, loss of load probability, supply capacity utilization, energy poverty, economic growth, amongst other variables.

5.2 The flexible integration of RES

While flexibility[11] is crucial to the success of the smart grid, the need for balance arises in how much flexibility the grid can accommodate. Considering the fact that variable RES present issues of stochasticity and unpredictability, balancing the grid using generation sources that are fast in coming on-line (such as pumped hydro and open cycle gas turbines, OCGT) can be very expensive. Furthermore, the multi-directional flow of power within the smart grid on the distribution network raises issues of voltage and frequency regulation

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[11] By flexibility we imply the ability of the grid to accommodate power supply from varying independent sources. These could be rooftop SHS, wind farms, solar farms etc.

as well as reactive power compensation. Standards are thus needed that guide the size of RES and IPP’s that can be grid integrated.

5.3 Sustainability

The envisioned smart grid plays a crucial role in facilitating a balance between meeting present energy needs without adversely affecting the environment. Considering the fact that South Africa is adopting the PPD model for managing its emissions level, there is the need to take advantage of the period during which emissions is expected to peak. Here, it is possible to ensure that fossil based generation sources are used during the peak period efficiently, with particular implications for stabilizing electricity supply to off-grid communities. This is to stimulate electricity consumption and development. Furthermore, the peaking period provides an avenue to sufficiently experiment on appropriate generation mixes and their resultant effect and build sufficient case scenarios for South Africa’s electricity network without the hindrance of emissions reduction.

5.4 Quality of life

In soliciting for behavioural changes from electricity users based on incentives in DR, there is the possibility to compromise on household comfort by adversely timing the operation for participating DSM loads (late dispatch of dishwashers, cloth washers, cloth dryers etc.). Furthermore, the inclusion of HVAC loads could see consumer pre-set temperature constraints exceeded. Furthermore, deployed electrification systems might not be capable of offering quality electricity that contributes to an improvement in the QoL of households. Smart grid initiatives for South Africa must thus ensure that consumer QoL is an integral part in the deployment of electrification access and exploitation of DR. More so, considering the fact that by 2025 there will be over 1.2 billion people aged 60 and over worldwide (Yang et al. 2016), smart grid initiatives must be able to deliver reasonable cost savings without compromising on QoL for older citizens.

6 Conclusion

As South Africa gradually transits to a smarter electricity network, it is important that the mistakes made by other countries with regards to RES integration are avoided. This paper has critically examined the energy situation in South Africa and concluded that (1) we lack sufficient literature on smart grid initiatives to guide smart grid policy development, especially in the context of South Africa, (2) South Africa's smart grid initiative has the potential of driving more households into poverty due to higher electricity tariffs, (3) demand growth forecasts for South Africa are not properly conceived and will continue to lead to significant mismatch (with supply capacity) with ripple effect on the economy, (4) significant skills shortage has the potential of hindering the full delivery of smart grid potentials especially at the rural level for South Africa and (5) off-grid electrification measures are capable of increasing rural marginalisation due to their limited quality in terms of electricity delivery.

By providing policy recommendations, we assert that sufficient research needs to be undertaken on a more integrated approach to smart grid deployment for South Africa. We argue that such approach is capable of providing the utility and policy makers better insight into the effects of proposed solutions across the entire electricity value chain. Such research must investigate the potential impact of EV's, grid connected SHS, IPP's integration etc. on the network technical parameters and associated costs. Furthermore, we posit that the drive towards a more environmental friendly grid must not be at costs that are unaffordable by the consumers. We argue thus that South Africa must seek to maximize the peaking period for emissions in generally stabilizing the grid and setting the pathway to sustainable electricity development. Furthermore, we advocate for an integrated framework that provides every player in the electricity market an avenue to input their constraints and optimise the grid operations to generate dispatch scenarios and costs that will not be harmful to the economy. Lastly, we aver that skills shortage especially with experts capable of managing the smart grid operations is capable of compromising the smart grid drive. The South African Government, and indeed governments in other country contexts, must institute policy and funding that will drive interests especially in related disciplines pertinent to the smooth operations of smart grid.

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CHAPTER 3

PAPER 2 - PROVINCIAL DSM POTENTIAL INVESTIGATION

Brief summary

This chapter presents the paper entitled ***Demand Side Management potentials for mitigating energy poverty in South Africa***. This paper presents the state of electricity consumption in South Africa by evaluating electricity consumption (kWh/capita) across the provinces for certain years to show that electricity consumption is declining. Furthermore, this paper presents DSM potentials in South Africa and presents its capability in mitigating poverty. A modified genetic algorithm (MGA) is developed and utilized in this paper.

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Demand Side Management potentials for mitigating energy poverty in South Africa

C.G. Monyei[a,b,*], A.O. Adewumi[a,b]

[a] *Applied Artificial Intelligence Research Unit, School of Mathematics, Statistics and Computer Science, University of KwaZulu-Natal, Westville Campus, Private Bag X54001, Durban 4000, South Africa*

[b] *School of Mathematics, Statistics and Computer Science, University of KwaZulu-Natal, Westville Campus, Private Bag X54001, Durban 4000, South Africa*

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ABSTRACT

South Africa is severally posited to be Africa's most industrialized nation with an economy heavily reliant on energy. With depleted electricity reserve margin which led to massive load shedding and rationing of electricity in 2008, Eskom has stepped up the construction of additional power plants to cover for growing supply deficits. Emerging trends however favour Demand Side Management (DSM) initiatives as alternatives to building additional supply capacity due to environmental and economic constraints. This research evaluates the electricity per capita for 2007, 2011 and 2016 on provincial basis assuming 100% and 36.8% residential sector consumption of generated electricity to show declining electricity per capita values. A scenario simulation (for 100%, 50% and 30% household participation) of cloth washers and cloth dryers optimal dispatch is then modelled to show the enormous DSM potentials in terms of electricity cost reduction and supply flexibility. A modified genetic algorithm (MGA) is used in the dispatch of participating loads on the Medupi power plant which has been modelled to operate with carbon capture and sequestration (CCS) technology. DSM potentials of 6938.34 MW, 3469.18 MW and 2081.51 MW are computed for 100%, 50% and 30% household participation for cloth washers and cloth dryers.

1. Introduction

South Africa is one of Africa's most industrialized nation and also its highest net electricity producer (about 45%) (Eskom). Most of the electricity consumed by the nine provinces of South Africa is produced by Eskom from 27 major power stations with combined installed nominal capacity of over 42000 MW from various sources including; coal, hydro, liquid fuel, pumped storage, nuclear and wind (Where Eskom’s electricity comes from, 2015). The significant growth witnessed in South Africa's electrification drive (rural and urban) which has seen electrification rate move rapidly from less than 33% (in 1990) to 58% (1996) and 90% (2016) has been largely due to various government policy and intervention (Marquard et al., 2007).

According to Marquard et al. (2007), electrification in South Africa which was around 35% of the total population before 1990 had doubled by 2000. The 1996 census conducted revealed that about 58% of the country's population had access to electricity. Continuing, Marquard et al. (2007) further posited that only about one in four non-urban black South African households were electrified compared to 97% electrification of non-urban white South African households before 1990. It could thus be surmised that the major obstacle to increased widening access to electricity was political, which kept electricity access prior to 1990 below 40%. These dismal statistics highlighting low electrification rates for pre-1990 years were further worrisome when compared to countries with similar income levels at the beginning of the electrification program (Argentina – 88%, Venezuela – 86%, Costa Rica – 85%, Thailand – 75% and Brazil – 65%). However, the abolishment of apartheid and subsequent entrenchment of democracy has led to a steady increase in electrification rates in the country. A further observation from the report (Marquard et al., 2007) was the fact that as at 1990, South Africa had an extremely energy intensive economy and possessed in Eskom a world class electricity supply industry with a huge electricity reserve margin.

Table 1 (Where Eskom’s electricity comes from, 2015) gives a breakdown of the contribution share of each energy source to Eskom's overall capacity while Table 2 (Eskom power stations from 1926 to 2015, 2014) presents the time-line of the evolution of South Africa's power stations from 1926 to 2015 vis-a-vis their commissioning, decommissioning and recommissioning.

While government's initial efforts at boosting electricity generation

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* Corresponding author at: Applied Artificial Intelligence Research Unit,School of Mathematics, Statistics and Computer Science, University of KwaZulu-Natal, Westville Campus, Private Bag X54001, Durban 4000, South Africa.

E-mail addresses: chiejinamonyei@gmail.com (C.G. Monyei), adewumia@ukzn.ac.za (A.O. Adewumi).

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Nomenclature

$AHHS_{j,k}$	year j, province k average household size
$C_{bias}{}^{cost}$	consumer cost biased function
CCS	carbon capture and sequestration
$DEC_{j,k}^{\eta=0.368}/DEC_{j,k}^{\eta=1}$	Daily Electricity Consumption per capita (individual) for year j assuming 36.8% and 100% respectively of electricity supplied province k is consumed by the residential sector
$HEC_{j,k}^{\eta=0.368}/HEC_{j,k}^{\eta=1}$	Hourly Electricity Consumption per capita (individual) for year j assuming 36.8% and 100% respectively of electricity supplied province k is consumed by the residential sector
$HWEC_{j,k}$	Normalized value for province k households with electricity connection for year j
$MEC_{j,k}^{\eta=0.368}/MEC_{j,k}^{\eta=1}$	Monthly Electricity Consumption per capita (individual) for year j assuming 36.8% and 100% respectively of electricity supplied province k is consumed by the residential sector
$OP_t{}^{cost}$	Time t operations cost
$P_{cost}{}^{DP}$	Daily cost of electricity to consumers using dynamic pricing
$P_{cost}{}^{FP}$	Daily cost of electricity to consumers using time of use pricing
$REC_{j,k}$	Residential Electricity Consumption for province k, year j
S_{cost}	Daily operational cost of generating electricity by the utility
$THH_{j,k}$	Total households for province k, year j
$U_{bias}{}^{cost}$	Utilization cost biased function
U_{cost}	Daily cost that penalizes generator utilization outside optimal operational limits
$YEC_{j,k}^{\eta=0.368}/YEC_{j,k}^{\eta=1}$	Yearly Electricity Consumption per capita (individual) for year j assuming 36.8% and 100% respectively of electricity supplied province k is consumed by the residential sector
DLC	Direct Load Control
DSM	Demand Side Management
MGA	Modified Genetic Algorithm
QoL	Quality of Life
TOU	Time Of Use

and access led to a surplus in electricity supply in 1990 which resulted in the mothballing of the Komati, Camden and Grootvlei power stations, inconsistencies in government policies and an initial delay in the construction of additional power stations to compensate for increasing population and industrialization activities, have seen Eskom in recent times implementing load shedding (Kohler, 2014; Loadshedding) to offset supply deficits and prevent grid collapse.

Government has consistently evolved policies to guarantee energy security and sufficiency right from the National Electrification Forum of 1991–1993. Furthermore, the South Africa Government electrification thrust is service delivery based rather than on providing energy for productive services. With an increasing population and rising demand of energy for both residential and non-residential (commercial, transportation, industrial etc.) activities, building additional power plants to boost supply though logical is becoming increasingly expensive as recognised in the United Kingdom by Bradley et al. (2013), Ofgem (2015). In addition, global concerns relating to the negative contribution of fossil based electricity generation to the environment puts further constraints on the design and construction of these additional power plants. Further compounding South Africa's energy (electricity) sector drive issues is the fact that a number of South Africa's coal-powered plants will be decommissioned within the next decade. This presents a problem of energy security as planned replacements may not be able to completely cover the expected shortfalls due to delays in completion or other competing factors.

South Africa in keying into global trends has been increasing its energy base share of renewable energy. Interests has varied from solar (solar water heating) (Eskom) to wind (Eskom) to concentrating solar power (CSP) (Eskom) etc. However, despite the modest contribution of renewable energy sources (RES) to South Africa's generation mix, their availability is both stochastic (with respect to location) and probabilistic (with respect to supply) which means that exactly quantifying their real time capacity via prediction does create some disparity between predicted and actual values. This is however at variance with generation from conventional sources like coal and diesel generator power plants whose capacities are known values and provide exact figures during system operations (SO) and planning.

Table 1
Breakdown of energy category contribution to Eskom's capacity (Where Eskom's electricity comes from, 2015).

Source/Category	Number	Capacity (MW)	% of Eskom's total capacity
Coal power	13	34,952	84.85
Liquid fuel	4	2409	5.85
Nuclear power	1	1830	4.44
Pumped storage	2	1400	3.40
Hydro power	6	600	1.46
Wind power	1	3	0.01

Demand Side Management (DSM) has in recent times been gaining traction as a viable means of curtailing or modifying consumer's consumption pattern by shifting demand/supply imbalance control from the supply side to the demand (consumer) side. A reason for this is based on the fact that significant savings can be achieved from the consumer side that could eliminate the need for grid extension or additional generating capacity (Mishra et al., 2013; Pierce and Paulos, 2012). In the United Kingdom for example, the Energy Efficiency Commitment Phases 1 and 2 (EEC1) and (EEC2) programs which ran from 2002 to 2005 and 2005 to 2008 achieved energy savings of 86.8 TWh and 187 TWh respectively. Similarly, a carbon reduction of about 293MtCO_2 was achieved via the Carbon Emissions Reduction Target (CERT) and Community Energy Saving Programme (CESP) between 2008 and 2012 (Warren, 2014). In similar vein, Eskom in 2008 began a campaign to exchange incandescent bulbs in homes for more energy efficient CFL bulbs with about 65 million of such energy efficient CFL bulbs installed in South African homes to date. The result has been considerable energy savings and reduced electricity bills, job creation and a culture of greater energy efficiency among South Africans. It is estimated that about 11.8 TWh of DSM programs are currently in place in South Africa with expected cumulative savings of 466 MW by 2017/2018 from the additional Residential Mass Roll-out lighting LED program which commenced 2015/2016 (Eskom).

In a recent report SA must reduce power by up to 15: Peters (2013), it was posited that for South Africans to enjoy uninterrupted power supply, there had to be about a 10% reduction in energy consumption (from the residential sector). It can therefore be evidenced and further inferred from the report that energy efficient habits (DSM) can guarantee a balance between electricity demand and supply for residential homes. However, statistics emanating from CSIR (2016) indicate that national electricity demand using the less energy scenario modelling would increase (year-on-year) by 2.3% in 2016 and 2017, 2.5% in 2018, 2.7% in 2019 and 2.8% in 2020. To compensate for increasing electricity demand and diversify the generation mix, DOE (2016) posits that renewable energy planned capacity expansion is 2915 MW for 2016, 3799 MW for 2017, 4864 MW for 2018, 6879 MW for 2019 and

Table 2
Timeline of power plants commissioning, recommissioning and decommissioning (1926–2015) (Eskom power stations from 1926 to 2015, 2014).

Power station	Power source	Commissioned	Decommissioned	Recommissioned	Status
Witbank	Coal	1926	1963		Not operational
Colenso	Coal	1926	1985		Not operational
Salt River 1	Coal	1928	1979		Not operational
Sabie River	Hydro	1928	1964		Not operational
Congella	Coal	1928	1978		Not operational
Klip	Coal	1936	1986		Not operational
Vaal	Coal	1945	1989		Not operational
Pretoria West()	Coal	1952			Operational
Hex River	Coal	1952	1988		Not operational
Vierfontein	Coal	1953	1990		Not operational
Umgeni	Coal	1954	1989		Not operational
Taaios (+)	Coal	1954	1986; 1999	Yes	Not operational
Wilge	Coal	1954	1987		Not operational
Salt River 2	Coal	1955	1994		Not operational
West Bank 2	Coal	1956	1989		Not operational
Kelvin (*O*)	Coal	1957			Operational
Highveld (+)	Coal	1959	1986; 1999	Yes	Not operational
Komati (+,*ES*)	Coal	1961	1990	Yes	Operational
Ingagane	Coal	1963	1990		Not operational
Rooiwal()	Coal	1963			Operational
Camden (+,*ES*)	Coal	1967	1990	Yes	Operational
Grootvlei (+,*ES*)	Coal	1969	1990	Yes	Operational
Hendrina (*ES*)	Coal	1970			Operational
Gariep (*ES*)	Hydro	1971			Operational
Arnot (*ES*)	Coal	1975			Operational
Kriel (*ES*)	Coal	1976			Operational
Acacia (*ES*)	Gas	1976			Operational
Port Rex (*ES*)	Gas	1976			Operational
Vanderkloof Dam (*ES*)	Hydro	1977			Operational
Duvha (*ES*)	Coal	1980			Operational
Drakensberg (*ES*)	Hydro	1981			Operational
Matla (*ES*)	Coal	1983			Operational
Koeberg (*ES*)	Nuclear	1984			Operational
Lethabo (*ES*)	Coal	1985			Operational
Tutuka (*ES*)	Coal	1985			Operational
Kendall (*ES*)	Coal	1988			Operational
Palmiet (*ES*)	Hydro	1988			Operational
Matimba (*ES*)	Coal	1993			Operational
Majuba (*ES*)	Coal	1996			Operational
Ankerlig (*ES*)	Gas	2007			Operational
Gourikwa (*ES*)	Gas	2007			Operational
Newcastle (*)	Gas	2007			Operational
Medupi (*ES*)	Coal	2015			Operational

(*O*) – Aldwyeh International.
(+) – Mothballed.
() – City of Tshwane.
(*) – IPSA Group.
(*ES*) – Eskom.

7867 MW for 2020. Furthermore, it is also observed from the IRP report (DOE, 2016) that capacity projections for DSM techniques remain at a low 500 MW for the short to medium term projections. More emphasis is however placed on new power stations with improved efficiency and lower carbon emissions which require huge investments in construction, operations and maintenance.

A review of available literature to our knowledge has revealed the absence of any research work that has effectively quantified in real terms the contribution of applying DSM on specific household electrical devices with available pricing techniques – time of use (TOU) and a proposed dynamic pricing (DP) regime with additional constraints of peaking limits and carbon emissions for South Africa. Research conducted during the write-up of this work further indicates that majority of existing literature target such areas as efficiency in industrial sectors, renewable energy, electricity intensity, policy, review and access. Table 3 highlights the focus areas of some selected scholarly works as regards South Africa's energy (electricity) sector. From Table 3, a hierarchy of the interests sees associated statistics and policy as the major centre of focus. For example, van Blommestein and Daim (2013) evaluated the decision making process of consumers when purchasing energy efficient devices to determine if there was sync between the technology focus of consumers and current efficiency initiatives. The evaluation was carried out using a hierarchical decision model (HDM). Similarly, Amusa et al. (2009) applied bounds testing approach to co-integration with an autoregressive distributed lag framework to examine South Africa's electricity demand during the period 1960–2007 while Inglesi (2010) forecast electricity demand of South Africa up to 2030 using the Eagle-Granger methodology for co-integration and error correction models.

Works that touched on DSM include (Alix, 2000) where factors inhibiting municipalities from investing in DSM initiatives were investigated, Lombard et al. (1999) where a program for thermal efficiency in the South African residential sector was proposed and Rankin and Rousseau (2008) where the authors described how an improved in line water heating concept could achieve peak load reduction without availability compromise within the specified operating time. Pricing

Table 3
Selected literature and their focus areas relating to South Africa's Energy (electricity) Sector.

Literature	Publication year	Focus area
van Blommestein and Daim (2013)	2013	B, D, H, I
Amusa et al. (2009)	2009	D, F, I, J, K
Azimoh et al. (2015)	2015	A, C, D, I, J
Azimoh et al. (2016)	2016	A, C, D, I
Bekker et al. (2008)	2008	A, D, E, F
Bohlmann et al. (2016)	2016	D, F, H
Alix (2000)	2000	B, D, F, K, J
Inglesi (2010)	2010	B, D, F, H, I, J, K
Inglesi-Lotz and Blignaut (2011)	2011	D, E
Inglesi-Lotz (2011)	2011	D, F, H, I, K
Inglesi-Lotz and Pouris (2012)	2012	B, D, F
Inglesi-Lotz and Blignaut (2012)	2012	B, D, E, F
Inglesi-Lotz and James (2014)	2014	B, D, E, F
Kohler (2014)	2014	B, D, E, F, H
Lombard et al. (1999)	1999	B, F, I
Nakumuryango and Inglesi-Lotz (2016)	2016	D, E
Pereira et al. (2011)	2011	A, C, D, E
Rankin and Rousseau (2008)	2008	B, C
Setlhaolo and Xia (2016)	2016	B, C, G, I, K
Thondhlana and Kua (2016)	2016	B, F, I

A - Electricity access; B – DSM; C – Quality of Life (QoL); D – Associated statistics.
E – Review; F – Policy; G – Optimisation; H – Modelling.
I – Consumer side; J – Supply side; K – Pricing.

and its effect on demand was also studied in Amusa et al. (2009) where the effect of pricing policy on aggregate demand and the magnitude of demand change/response to variation in pricing policy between 1960 and 2007 for South Africa was investigated. Inglesi-Lotz (2011) also employed the Kalman filter in estimating the price elasticity of electricity in South Africa between 1980–2005.

According to Chekired et al. (2017), over 40% of global energy consumption comes from the residential and building sectors. This thus implies that households offer great potentials for DSM initiatives. This work therefore seeks to quantify in real terms the potential DSM capacity of cloth washers and cloth dryers for varying rate of household participation in South Africa. In this work, the Medupi power plant capacity is scaled between (arbitrarily selected) base loads and DSM loads. Simplified statistical derived equations are used in computing per capita electricity values for further discussions while a modified genetic algorithm (MGA) is used in allocating the evolved DSM loads (without optimising dispatch) within the allocated DSM allowance to achieve pre-determined cost functions. The evaluated and simulated results are then used in extending policy discussions on pricing, power plant capacity utilization and load dispatch.

A motivation for this work stems from the fact that in utilizing dynamic pricing schemes, households can take advantage of lower electricity prices during off-peak periods to reduce electricity bills thus freeing up resources (money) for other purposes. Similarly, Eskom using direct load control (DLC) on participating demand response (DR) loads can minimize it's operations cost and ensure a smooth grid operation.

2. Background

In providing insight into declining electricity per capita across the years under consideration, associated statistics for South Africa relating to census (population, average household number, number of houses electrified and provincial electricity supply) would be utilized.

2.1. A brief on Eskom

Eskom is South Africa's major electricity provider, generating over 95% of South Africa's electricity and 45% of Africa's electricity. Aside generation, Eskom also transmits and distributes electricity directly to the residential (5.6%), mining (14.4%), industrial (22.3%), commercial and agricultural (7%) and rail (1.4%) sectors. International exports is about 5.6% while sale to municipalities is about 42.7%. Production sources for its power generation varies from coal (83%), nuclear (5%), open-cycle gas turbine (OCGT, 3%), independent power projects (IPPS, 3%) to imports (4%) (Eskom, 2015a). Imports are from the Southern African Power Pool (SAPP) which is an inter-connected regional transmission network of the Southern African Development Community (SADC).

2.2. A brief on Medupi power station

Medupi power plant is a greenfield coal fired power plant project situated in the Limpopo province and is expected to be the fourth largest coal plant in the world. It has an installed capacity of 4764 MW from its six units each capable of outputting 794 MW. Unit 6 (the first of the 6 units) was synchronized with the grid in 2015. It has a planned operational lifetime of about 50 years (Eskom, 2015b, 2013).

2.3. A brief on data utilized and sources

Data utilized for the computation of per capita electricity consumption was primarily sourced from Statistics South Africa (STATS SA). Population, average household size and number of electrified household per province were gotten from the Community Survey (2007), Census 2011 Provinces at a glance (2012) and Community Survey (2016). Electricity supplied to each province was gotten from the P4141 series from STATS-SA and STATS-SA (2016).

Table 4 presents the population of South Africa's nine provinces from censuses conducted in 1996, 2001 and 2011 (Census 2011 Provinces at a glance, 2012) and community surveys conducted in 2007 (Community Survey, 2007) and 2016 (Community Survey, 2016). It is also observed from Table 4 the national percentage of homes with access to electricity and the growing trend in electricity access for the years under consideration. In trying to establish a justification for DSM, there is a need to present the declining electricity available to the

Table 4
Provincial census/community survey population and national electricity access (Community Survey, 2007, 2016; Census 2011 Provinces at a glance, 2012).

Province	1996	2001	2007	2011	2016
Eastern Cape	6,147,244	6,278,651	6,527,747	6,562,053	6,996,976
Free State	2,633,504	2,706,775	2,773,059	2,745,590	2,834,714
Gauteng	7,834,125	9,388,854	10,451,713	12,272,263	13,399,724
KwaZulu-Natal	8,572,302	9,584,129	10,259,230	10,267,300	11,065,240
Limpopo	4,576,566	4,995,462	5,238,286	5,404,868	5,799,090
Mpumalanga	3,123,869	3,365,554	3,643,435	4,039,939	4,335,964
Northern cape	1,011,864	991,919	1,058,060	1,145,861	1,193,780
North west	2,727,223	2,984,098	3,271,948	3,509,953	3,748,436
Western cape	3,956,875	4,524,335	5,278,585	5,822,734	6,279,730
Total	40,583,572	44,819,777	48,502,063	51,770,561	55,653,654
Household Electricity Access (%)	58.2	69.7	80.1	84.7	90.3

residential sector by computing electricity per capita (yearly, monthly, daily and hourly). This is to provide insight into the prevailing energy poverty occasioned by increasing population and increasing demand for electrical power to meet consumer needs (heating/cooling, lighting, entertainment, cooking etc.).

Table 5 presents the electricity consumed by various sector and their ranking/position. It is observed from Table 5 that the residential sector consumes on average about 36.8% of total electricity supplied and comes second behind the industrial sector (40.9%) (Modise and Mahotas).

Table 6 (STATS-SA) further presents the supply of electricity to the nine provinces for three years (2007, 2011 and 2016) and the residential component of the electricity consumed for each province using the fraction (36.8%) as obtained from Table 5. The provision of this additional column (residential component – YREC) is necessary in obtaining a more accurate value for per capita electricity consumption rather than a generalized value which assumes that 100% of electricity generated is consumed by the residential sector. Furthermore, the computation of the per capita values for electricity consumption also utilizes actual electrified households and the average household size for each province to obtain more accurate results. The method of computing electricity per capita thus employed in this research work is at variance with the generally established norm, as this employed method aims at showing the variation in electricity per capita across the different provinces.

The number of households for years 2007, 2011 and 2016 for each province alongside the average household size and percentage of provincial households with access to electricity is presented in Table 7 (Community Survey, 2007, 2016; Census 2011 Provinces at a glance, 2012).

3. Per capita electricity computation and its implications

The computation of the per capita electricity consumption for each of the nine provinces is shown subsequently. By per capita electricity consumption, we imply the average electricity consumption (Wh/kWh) computed for an individual (hourly, daily, monthly and yearly) based on the total electricity supplied to a province, number of electrified households and average household size. From Tables 5 – 7, the following can be obtained:

n = Residential electricity component weight (0.368) from Table 5

$REC_{j,k}$ = Residential electricity consumption for year j and province k from Table 6

$TEC_{j,k}$ = Total electricity consumption for year j and province k from Table 7

where,

j is the index of year and k is the index of the provinces. Eqs. (1) and (2) present the limits for j and k while Tables 8, 9 present the index description for j and k. That is,

$$1 \leq j \leq 3 \tag{1}$$

$$1 \leq k \leq 9 \tag{2}$$

If,

$THH_{j,k}$ is the total households for year j and province k from Table 4

$AHHS_{j,k}$ is the average household size for year j and province k from Table 4 and

$HWEC_{j,k}$ is households with electricity connection for year j and province k

Then,

$$\begin{aligned} HWEC_{j,k} &= \frac{(\%)HWEC_{j,k}}{100}, \quad 0 < HWEC_{j,k} \leq 1 \\ YEC_{j,k}^{\eta=1} &= \frac{TEC_{j,k}}{THH_{j,k} \times AHHS_{j,k}} \text{ (kWh/capita)} \end{aligned} \tag{3}$$

$$MEC_{j,k}^{\eta=1} = \frac{YEC_{j,k}^{\eta=1}}{12} \text{ (kWh/capita)} \tag{4}$$

$$DEC_{j,k}^{\eta=1} = \frac{MEC_{j,k}^{\eta=1}}{30} \text{ (kWh/capita)} \tag{5}$$

$$HEC_{j,k}^{\eta=1} = \frac{DEC_{j,k}^{\eta=1} \times 1000}{12} \text{ (Wh/capita)} \tag{6}$$

where, $YEC_{j,k}^{\eta=1}$, $MEC_{j,k}^{\eta=1}$, $DEC_{j,k}^{\eta=1}$ and $HEC_{j,k}^{\eta=1}$ are the yearly, monthly, daily and hourly provincial electricity consumption per capita (per individual) when all electricity supplied is assumed to be consumed by the residential sector ($\eta = 1$) and all households are assumed to be connected to the grid ($HWEC_{j,k} = 1$).

The result obtained from the computation of $YEC_{j,k}^{\eta=1}$, $MEC_{j,k}^{\eta=1}$, $DEC_{j,k}^{\eta=1}$ and $HEC_{j,k}^{\eta=1}$ for the years 2007, 2011 and 2016 for the nine provinces is shown in Table 10.

Similarly, the computation of the yearly ($YEC_{j,k}^{\eta=0.368}$), monthly ($MEC_{j,k}^{\eta=0.368}$), daily ($DEC_{j,k}^{\eta=0.368}$) and hourly ($HEC_{j,k}^{\eta=0.368}$) provincial electricity consumption per capita when actual residential electricity consumed is taken into consideration ($\eta = 0.368$) with grid connected households ($HWEC_{j,k\neq 1}$) is shown in Eqs. (7)–(10).

$$YEC_{j,k}^{\eta=0.368} = \frac{TEC_{j,k}}{THH_{j,k} \times AHHS_{j,k}} \text{ (kWh/capita)} \tag{7}$$

$$MEC_{j,k}^{\eta=0.368} = \frac{YEC_{j,k}^{\eta=0.368}}{12} \text{ (kWh/capita)} \tag{8}$$

$$DEC_{j,k}^{\eta=0.368} = \frac{MEC_{j,k}^{\eta=0.368}}{30} \text{ (kWh/capita)} \tag{9}$$

$$HEC_{j,k}^{\eta=0.368} = \frac{DEC_{j,k}^{\eta=0.368} \times 1000}{12} \text{ (Wh/capita)} \tag{10}$$

Table 11 similar to Table 10 presents the results obtained from the computation of $YEC_{j,k}^{\eta=0.368}$, $MEC_{j,k}^{\eta=0.368}$, $DEC_{j,k}^{\eta=0.368}$, and $HEC_{j,k}^{\eta=0.368}$ for the years 2007, 2011 and 2016 for the nine provinces.

Given $TEC_{j,k}$ as the total electricity supplied province k for year j in GWh, then $YEC_{j,k}^{\eta=1}$ and $YEC_{j,k}^{\eta=0.368}$ are the average yearly electricity (kWh/capita) consumed by an individual, with 100% and 36.8% consumption of electricity supplied province k for $\eta = 1$ and $\eta = 0.368$ respectively by the residential sector. $MEC_{j,k}^{\eta=1}$ and $MEC_{j,k}^{\eta=0.368}$ are the average monthly electricity (kWh/capita) consumption per capita for 100% and 36.8% residential consumption of province k supplied electricity. $HEC_{j,k}^{\eta=1}$ and $HEC_{j,k}^{\eta=0.368}$ are the average hourly electricity (Wh/capita) consumption per capita for province k.

A basis for the evaluation of the values presented in Tables 10, 11 is to highlight the following:

(a) That while electricity access might have been increasing, electricity available for consumption by the residential sector has been decreasing rapidly across the years under consideration. For example, in Table 11, $HEC_{j,k}^{\eta=0.368}$ for Eastern Cape has declined from 72.42 Wh (in 2007) to 66.67 Wh (in 2011) and 63.39 Wh (in 2016). This trend is witnessed in all the provinces (except for Limpopo) for the years under consideration.

(b) That the evaluation of electricity consumption per capita for each

Table 5
Electricity usage/consumption by sector (Modise and Mahotas).

Sector	Percentage of total consumption (%)	Position/Ranking
Residential	36.8	2nd
Commercial	11.4	3rd
Transport	2.7	5th
Others	8.1	4th
Industrial segment	40.9	1st

Table 6
Provincial yearly electricity consumption (GWh) and residential component (STATS-SA).

	2007		2011		2016	
Province	TYEC	YREC	TYEC	YREC	TYEC	YREC
Eastern Cape	7290	2682.72	7726	2843.168	8790	3234.72
Free State	10,446	3844.128	9765	3593.52	10,240	3768.32
Gauteng	62,549	23,018.03	62,113	22,857.58	57,106	21,015.01
KwaZulu-Natal	47,271	17,395.73	46,150	16,983.2	41,336	15,211.65
Limpopo	12,306	4528.608	13,904	5116.672	13,514	4973.152
Mpumalanga	34,072	12,538.5	33,704	12,403.07	34,049	12,530.03
Northern cape	5243	1929.424	5330	1961.44	5114	1881.952
North west	30,606	11,263.01	30,573	11,250.86	28,944	10,651.39
Western cape	23,836	8771.648	23,495	8646.16	22,516	8285.888

TYEC – Total yearly electricity consumed (GWh).
YREC – Yearly residential electricity component (GWh).

province has shown the varying disparity among the provinces which is usually masked when electricity consumption per capita is computed for the whole nation. For example, from Table 11, while Mpumalanga has $HEC_{j,k}^{\eta=0.368}$ of 370.39 Wh in 2016, Eastern Cape has $HEC_{j,k}^{\eta=0.368}$ of about 63.39 Wh for 2016. An importance of this result is the fact that it affects the ownership of electrical appliances of residential houses which is useful in evaluating the Quality of Life (QoL) of household dwellers.

From Table 11 therefore, three classes (tiers) of residential consumers can be observed from the $HEC_{j,k}^{\eta=0.368}$ column in 2016. These are:

Tier 1: this tier consists of all residential consumers of electricity whose hourly consumption $HEC_{j,k}^{\eta=0.368}$ is less than 200 Wh, i.e. $0 < HEC_{j,k}^{\eta=0.368} < 200\text{ Wh}$. It is observed from the Table 11 that in 2016, Eastern Cape, Limpopo, Western Cape, Free State and KwaZulu-Natal provinces were all tier 1 electricity consumers.

Tier 2: this tier consists of all residential electricity consumers with $200\text{ Wh} \leq HEC_{j,k}^{\eta=0.368} < 300\text{ Wh}$. It is also observed from the Table 11 that in 2016 only Gauteng and Northern Cape residences was into this category.

Tier 3: this tier consists of residential users of electricity with $HEC_{j,k}^{\eta=0.368} \geq 300\text{ Wh}$. North West and Mpumalanga residences were in this category as observed from the Table 11 in 2016.

3.1. Justification for tier classification

According to Monyei et al. (2017), there is a direct relationship between electrical appliance ownership and electrical consumption. In justifying the tier classifications (Tier 1, Tier 2 and Tier 3), Table 12 presents the ownership of electrical appliances by an individual used in meeting needs (lighting, entertainment, heating/cooling, and others). The classification of provincial residential houses into the various tiers is thus done to accurately depict the extent of ownership of electrical appliances by residences during the optimisation process of DSM.

Table 8
Index description for j.

Year	Index (j)
2007	1
2011	2
2016	3

Table 9
Index description for k.

Province	Index (k)
Eastern Cape	1
Free State	2
Gauteng	3
KwaZulu-Natal	4
Limpopo	5
Mpumalanga	6
Northern cape	7
North west	8
Western cape	9

The implication of the computed electricity per capita values for the provinces (when $\eta = 0.368$) is best evaluated using scenario planning. Based on already adopted values of average house size per province, the typical electricity consumption per household is thus determined for each province. A fraction of the values determined are optimally allocated among competing DSM needs (cloth washers and cloth dryers) for a typical urban and typical rural house (both grid connected) with the ensuing statistics (cost and utilization) computed for both cases.

Table 13 presents a quick comparison between the yearly electricity per capita for the years under consideration as presented in the Tables 10, 11 along with the World Bank value for 2007 and 2011 (IEA). The disparity across the various scenarios raises doubts as to the viability of ensuing planning done using these values. Furthermore, the declining electricity per capita concerns earlier raised is further reinforced by STATS-SA (2016). According to STATS-SA (2016), electricity consumption decreased by 1.2% and 1.5% in 2016 and 2015 respectively despite a 0.9% increase in electricity generation in 2016 over 2015.

4. The DSM optimisation process

In applying and optimising DSM, there is the need to justify its application. Fig. 1 (Save electricity, we'll show you how: Eskom) presents the distribution of South AFrica's residential electricity usage

Table 7
Provincial household electricity access indicators (Community Survey, 2007, 2016; Census 2011 Provinces at a glance, 2012).

	2007			2011			2016		
Province	THH	AHHS	%HWEC	THH	AHHS	%HWEC	THH	AHHS	%HWEC
Eastern Cape	1,586,739	4.1	65.9	1,687,385	3.9	75	1,773,395	3.9	85.4
Free State	802,872	3.5	86.6	823,316	3.3	89.9	946,639	3	93.8
Gauteng	3,263,712	3.3	83.2	3,909,022	3.1	87.4	4,951,137	2.7	89.7
KwaZulu-Natal	2,234,129	4.6	71.5	2,539,429	4	77.9	2,875,843	3.8	88.5
Limpopo	1,215,935	4.3	81.2	1,418,102	3.8	87.3	1,601,083	3.6	93
Mpumalanga	940,425	3.9	82.2	1,075,488	3.8	86.4	1,238,861	3.5	90.3
Northern Cape	264,653	4	86.8	301,405	3.8	85.4	353,709	3.4	88.8
North west	822,964	3.7	83	1,062,015	3.3	84	1,248,766	3	89
Western cape	1,369,180	3.8	93.9	1,634,000	3.6	93.4	1,933,876	3.2	96.6

THH – Total households.
AHHS – Average household size.
HWEC – Households with electricity connection.

Table 10
Computed $YEC_{j,k}^{\eta=1}$, $MEC_{j,k}^{\eta=1}$, $DEC_{j,k}^{\eta=1}$ and $HEC_{j,k}^{\eta=1}$ for 2007, 2011 and 2016.

Province	2007				2011				2016			
	$YEC_{j,k}^{\eta=1}$	$MEC_{j,k}^{\eta=1}$	$DEC_{j,k}^{\eta=1}$	$HEC_{j,k}^{\eta=1}$	$YEC_{j,k}^{\eta=1}$	$MEC_{j,k}^{\eta=1}$	$DEC_{j,k}^{\eta=1}$	$HEC_{j,k}^{\eta=1}$	$YEC_{j,k}^{\eta=1}$	$MEC_{j,k}^{\eta=1}$	$DEC_{j,k}^{\eta=1}$	$HEC_{j,k}^{\eta=1}$
Eastern Cape	1116.77	93.06	3.10	129.26	1177.38	98.11	3.27	136.27	1256.26	104.69	3.49	145.40
Free State	3766.96	313.91	10.46	435.99	3556.61	296.38	9.88	411.65	3612.36	301.03	10.03	418.10
Gauteng	5984.57	498.71	16.62	692.66	5061.25	421.77	14.06	585.79	4261.73	355.14	11.84	493.26
KwaZulu-Natal	4607.66	383.97	12.80	533.29	4494.85	374.57	12.49	520.24	3735.66	311.31	10.38	432.37
Limpopo	2349.24	195.77	6.53	271.90	2572.50	214.37	7.15	297.74	2330.37	194.20	6.47	269.72
Mpumalanga	9351.62	779.30	25.98	1082.36	8342.70	695.23	23.17	965.59	7852.69	654.39	21.81	908.88
Northern cape	4955.30	412.94	13.76	573.53	4651.52	387.63	12.92	538.37	4283.87	356.99	11.90	495.82
North west	9354.06	779.51	25.98	1082.65	8710.37	725.86	24.20	1008.15	7721.62	643.47	21.45	893.71
Western cape	4515.60	376.30	12.54	522.64	4035.05	336.25	11.21	467.02	3585.50	298.79	9.96	414.99

among various competing needs. A sector ranking of Fig. 1 shows that the Geyser, space heating, cold storage, others and the pool pump offer considerable potential for DSM application. However, DSM application is best suited for sectors that offer minimal discomfort to home owners and would not significantly impact negatively on the comfort level/QoL of home owners. Furthermore, the complexities involved in optimising user specific preferences for such complex sectors as cooling, heating etc. defeat the purpose for this research paper which is to show in simplest forms and without much significant investments the DSM potentials from residential homes. For this work therefore, two primary components of the laundry sector – cloth washer and cloth dryer would be considered in the DSM optimisation process.

4.1. *Justification for choice of sectors for DSM application*

A justification for the choice of the laundry sector for DSM application and optimisation stems from the fact that the current DSM initiatives being undertaken by Eskom are efficiency based and not price-based. For example, Eskom has already initiated DSM for the lighting sector through the distribution of energy efficient bulbs across the country (Eskom). Furthermore, the laundry sector (cloth washer and cloth dryer) has also received significant appraisal in reviewed articles (Klaassen et al., 2013; Hakimi, 2016; Shipman et al., 2013) due to its ability to have its functionality remotely monitored and controlled. Also, its operation can also be dispatched in real time without hitches. Additionally, data obtained shows that over 40% of South African homes have a washing machine (Community Survey, 2016), which cumulatively offers great potential for DSM.

Table 14 depicts the associated statistics (ratings and number) to be used in the optimisation process for both the cloth washer and the cloth dryer. For the purpose of this research, 60% of the 40% of residential homes with washing machine are assumed to have a cloth dryer. It is observed from Table 15 the possible periods of dispatch for the washing machine and cloth dryer for the week. Also observed is the fact that the washing machine and cloth dryer are capable of being dispatched all through the day. Hence, DSM would be optimally scheduling and dispatching the washing machines and cloth dryers within a 24-h period to show the flexibility of its dispatch and also achieve the aim of the

Table 12
Tier classification based on ownership.

Needs	Devices	Tier ownership			Average duration (h)	Unit rating (W)
		1	2	3		
Lighting	Light bulb	1	2	>2	8	16
Entertainment	TV	–	1	≥ 1	5	150
	Satellite decoder	–	1	1	5	10
	VCD/DVD player	1	1	1	5	35
Heating/cooling	Heater	–	1*	≥ 1**	8	1000/ 2000
	AC	–	–	≥ 1	–***	–***
Others	Dishwasher	–	–	1	1	1200
	Cloth washer	–	–	1	0.75	500
	Cloth dryer	–	–	1	1	700
	Cooker	–	–	1	2.5	750/ 1500

*– ≤ 1000 W ** – >1000 W *** – not evaluated since summer season is assumed.
AC – Air conditioner, TV – Television.
All values used are assumed for justification of Tier classification.

Table 13
Electricity per capita comparison for selected years.

Year	World Bank (IEA)	$\eta = 1$	$\eta = 0.368$
2007	4875.108	5111.308	2302.098
2011	4590.547	4733.581	2039.192
2016	–	4293.34	1750.944

Table 11
Computed $YEC_{j,k}^{\eta=0.368}$, $MEC_{j,k}^{\eta=0.368}$, $DEC_{j,k}^{\eta=0.368}$ and $HEC_{j,k}^{\eta=0.368}$ for 2007, 2011 and 2016.

Province	2007				2011				2016			
	$YEC_{j,k}^{\eta=0.368}$	$MEC_{j,k}^{\eta=0.368}$	$DEC_{j,k}^{\eta=0.368}$	$HEC_{j,k}^{\eta=0.368}$	$YEC_{j,k}^{\eta=0.368}$	$MEC_{j,k}^{\eta=0.368}$	$DEC_{j,k}^{\eta=0.368}$	$HEC_{j,k}^{\eta=0.368}$	$YEC_{j,k}^{\eta=0.368}$	$MEC_{j,k}^{\eta=0.368}$	$DEC_{j,k}^{\eta=0.368}$	$HEC_{j,k}^{\eta=0.368}$
Eastern Cape	625.75	52.15	1.74	72.42	576.05	48.00	1.60	66.67	547.66	45.64	1.52	63.39
Free State	1579.67	131.64	4.39	182.83	1471.23	122.60	4.09	170.28	1414.62	117.88	3.93	163.73
Gauteng	2568.73	214.06	7.14	297.31	2158.19	179.85	5.99	249.79	1752.54	146.02	4.87	202.84
KwaZulu-Natal	2367.39	197.28	6.58	274.00	2146.28	178.86	5.96	248.41	1572.84	131.07	4.37	182.04
Limpopo	1066.67	88.89	2.96	123.46	1087.63	90.64	3.02	125.88	927.75	77.31	2.58	107.38
Mpumalanga	4158.96	346.58	11.55	481.36	3512.58	292.72	9.76	406.55	3200.18	266.68	8.89	370.39
Northern cape	2099.77	174.98	5.83	243.03	2005.32	167.11	5.57	232.10	1762.26	146.86	4.90	203.97
North west	4456.50	371.37	12.38	515.80	3821.75	318.48	10.62	442.33	3194.58	266.22	8.87	369.74
Western cape	1795.44	149.62	4.99	207.81	1573.70	131.14	4.37	182.14	1386.06	115.51	3.85	160.42

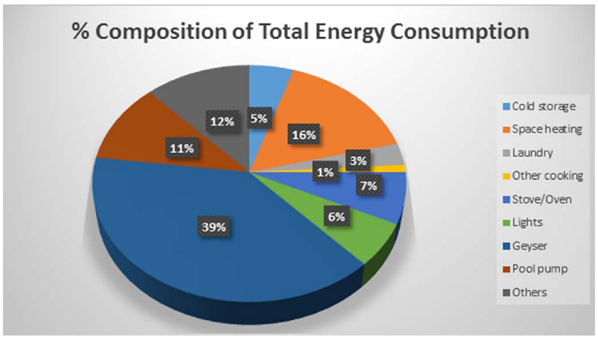

Fig. 1. Residential home electricity usage distribution among various needs (Save electricity).

Table 14
Washing machine and cloth dryer statistics.

Equipment	Device rating (W)	Number per household	Total power (W)
Washing machine	500	1	500
Cloth dryer	1000	1	1000

Table 15
Weekday dispatch of proposed DSM loads.

	Time slots		
Device	00–02	02–22	22–24
Washing machine	✓	○	✓
Cloth dryer	✓	○	✓

✓ – dispatch possible within the time slot.
○ – possible DSM window.

objective functions.

4.2. *Electrical power load optimisation and dispatch*

An electricity network broadly consists of generation (supply) stations, transmission/distribution network and the utilization/consumers. At the supply/generation side, the aim of the supply side energy management system (SSEMS) is to minimize operations and emissions cost (Gunda and Djokic, 2016). The transmission line management system (TLMS) ensures that line ampacity limits are not exceeded. Ampacity limits for transmission lines could be static or dynamic (Cong et al., 2016). Home energy management systems (HEMS) aim at reducing the electricity bills of homes (while improving their comfort) by smartly dispatching loads during periods of low electricity cost (Althaher et al., 2015). The general grid operation thus aims at optimally scheduling generation and load dispatch to ensure demand-supply balance while meeting the individual objectives of SSEMS, TLMS and HEMS.

5. Modelling and scenario description

In providing a basis for policy arguments, the Medupi power plant is modelled as to utilize carbon capture and sequestration (CCS) technology and used in dispatching the combined washing machine and cloth dryer loads for a 24-h cycle. Table 16 presents the DSM potentials for the three scenarios under consideration – 100%, 50% and 30% household participation. Furthermore, 60% of households in all three cases are assumed to own a cloth dryer. The specific modelling properties of the Medupi power plant such as its operating range, emissions value and capacity are shown in Table 17.

Table 18 presents the distribution of DSM potentials among various dispatch time schedules. It is important to point out that the values have been stochastically evaluated based on the cumulative values presented in Table 16. This has been achieved by generating random values that cumulatively add up to the total number of houses in Table 16. For example, in Table 18, 100% household participation for the cloth washer results in 1,261,518 houses for 15 min duration, 2,207,656 houses for 30 min duration, 946,138 houses for 45 min duration and 1,892,277 houses for 60 min duration. The sum of the houses adds up to 6,307,589 (as shown in Table 16).

5.1. *Cost function definition and description*

In dispatching the evaluated loads based on their dispatch time, two cost functions - the utilization biased cost function (U_{bias}^{cost}) and the consumer biased cost function (C_{bias}^{cost}) are evaluated simultaneously. While U_{bias}^{cost} aims at reducing the utilization cost which is the cost associated with operating the Medupi power plant outside its optimal operating limits as specified in Table 17, C_{bias}^{cost} aims at reducing the associated cost of electricity to the consumers using dynamic pricing. The description of the cost functions are defined as:

$$U_{bias}^{cost} = min(U_{cost}^{t}) \tag{11}$$

$$C_{bias}^{cost} = min(DP_{cost}^{t}) \tag{12}$$

where,

$$U_{bias}^{cost} = \begin{cases} 0.2 \times Op_t^{cost}; & otherwise \\ 0; & G^{norm} \leq Util^t \leq G^{max} \end{cases} \tag{13}$$

$$DP_{cost}^{t} = DP^t \times E_{MWh}^{t} \times 1000 \tag{14}$$

$$Op_t^{cost} = a + (b \times \xi^t) \tag{15}$$

${E_{MWh}}^t$ is the real time/slot (t) energy to be utilized (MWh). DP^t is the real time/slot dynamic price (ZAR/kWh). 1000 from Eq. (14) is the scaling factor for converting the price in (ZAR/kWh) to ZAR/MWh. ξ^t is the loading factor is the fraction of the power plant currently being utilized (as a percentage). a and b are defined in Table 17. G^{norm} and G^{max} are defined from Table 17 as the normal (norm) and maximum (max) operating capacity of the Medupi power plant respectively.

5.2. *Dynamic price modelling*

The computation of the dynamic price DP^t follows the time of use (TOU) pricing being used by Eskom. As seen in Fig. 2, the daily average dynamic price is equivalent to Eskom's spot price (excluding the peak

Table 16
DSM potential across various household participation rate.

	Cloth washer			Cloth dryer		
Percentage participation	100%	50%	30%	100%	50%	30%
Number of houses	6,307,589	3,153,795	1,892,277	3,784,553	1,892,277	1,135,366
DSM capacity (MW)	3153.79	1576.90	946.14	3784.55	1892.28	1135.37

Table 17
Modified Medupi power plant modelling parameters.

	LCOE model values		Operating range (%)			Carbon emissions	Capacity
Technology	a	b	min	max	norm	(kg/MWh)	(MW)
CCS	2815.21	− 14.80	66	88	85	136.2	1588

LCOE – Levelized cost of energy.
CCS – Carbon capture and sequestration.

Table 18
DSM household potential across various time schedules.

	Cloth washer			Cloth dryer		
	100%	50%	30%	100%	50%	30%
15 min	1,261,518	441,531	908,293	378,455	321,687	90,829
30 min	2,207,656	851,525	189,228	2,081,504	473,069	681,220
45 min	946,138	883,062	321,687	1,173,211	8704,47	317,902
60 min	1,892,277	977,676	473,069	151,382	227,073	45,415

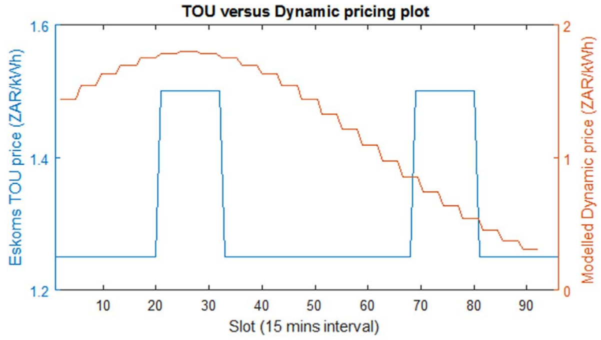

Fig. 2. TOU pricing and dynamic pricing profiles.

periods). Given FP^t as the real time TOU pricing electricity spot price, then $\frac{1}{24}\sum_{t=1}^{t=24}(DP^t) = \overline{FP^t}$.

5.3. Time of use price modelling

The selected Eskom TOU pricing scheme is for a household whose monthly electricity consumption is less than 600 kWh. The cost for off-peak periods is about ZAR 1.25/kWh and is exclusive of the peak period prices. For the purpose of this research, 20% has been added to the spot price during off-peak periods to generate the peak period (6–8 a.m. and 6–8 p.m.) TOU price. Weekdays and weekend peak periods have been assumed to be similar. The generated pricing profile is also shown in Fig. 2.

5.4. Optimisation algorithm description

The first step involved modelling the behaviour of the Medupi power plant. MANN (Monyei et al., 2014) was applied on data plot describing the evolution of the levelized cost of energy for various power plants (DOE, 2016) to generate constants a and b as shown in Table 17. The modified genetic algorithm (MGA) proposed and used in dispatching the loads to meet the already defined cost functions is described in Table 19. MGA is a variant of Monyei et al. (2014) and is modified to accommodate the variation in input data and optimisation objective. The modifications introduced include: modifying the binary strings of the population matrix to generate integer numbers that determine the start time for dispatching load and constraining dispatch of cloth washers to precede cloth dryers. This is done by scaling the start time of cloth washers and cloth dryers. The modification of the binary bits is at variance with MIGA (Monyei et al., 2014) where the binary bits are actual solutions. The cross-over employed is similar to Ogunjuyigbe et al. (2015) while the environmental cost was computed as shown in Lau et al. (2014). The prevailing exchange rate was gotten from SARB.

6. Results and discussion

In dispatching the participating DSM loads, the Medupi power plant has its capacity (power) allocated between the base loads and the DSM loads. While the base power has been arbitrarily selected to match an actual scenario, the proposed MGA dispatches the DSM loads within the DSM allowance on the power plant. In achieving an optimal allocation that meets the cost functions, the MGA ensures that the plant capacity is not over-utilized. The values chosen for the base and DSM loads allowance are shown in Table 20 for the various household participation rate. The area plot shown in Fig. 3(a) presents the 24-h (96-slots) power dispatch for the cloth washers, cloth dryers and base load demand for 100% participation of households. The real values for the cloth washer are gotten by deducting the base load value from the actual cloth washer value on the plot. Similarly, the real values for the cloth dryer are gotten by deducting the sum of the base load value and the corresponding cloth washer value (on the plot) from the actual cloth dryer value on the plot. While average utilization for both ${C_{bias}}^{cost}$ and ${U_{bias}}^{cost}$ is about 48%, over-utilization of the power plant is not observed for both cases. The ${C_{bias}}^{cost}$ option achieves a daily savings of about ZAR

Table 19
Modified genetic algorithm description.

```
Input:($P_{cost}^{DP}$, $P_{cost}^{FP}$, Tables 17, 18, $U_{bias}^{cost}$, $C_{bias}^{cost}$, limit)
Start:
Step 1: Generate MWh equivalent of Table 18
Step 2: Generate possible time slots to allocate MW and MWh vales respectively into
    time/slot matrices.
Step 3: Randomly select time slots for application of genetic algorithm
Step 4: Convert randomly selected time slots to binary equivalent
Step 5: Perform Cross-over (Monyei et al., 2014)
Step 6: Mutate random bits
Step 7: Convert mutated string to decimal values
Step 8: Update time matrix
Step 9: For each complete time allocation of MW values compute $\xi$.
Step 10: For each complete time allocation of MWh values, compute $P_{cost}^{DP}$ and $P_{cost}^{FP}$
    ($P_{cost}^{FP}$ is the equivalent fixed price cost for electricity).
Check:
For $U_{bias}^{cost}$
If current $U_{bias}^{cost}$ is smaller than preceding $U_{bias}^{cost}$,
Update $U_{bias}^{cost}$
For $C_{bias}^{cost}$
if current $P_{cost}^{DP}$ is smaller than preceding value and is greater than current $S_{cost}$,
Update $P_{cost}^{DP}$
If limit is reached, exit loop
Note:
$S_{cost}^{t} = U_{cost}^{t} + e_{cost}^{t} + Op_{t}^{cost}$
Where
$S_{cost}^{t}$ is the real time supply cost
$U_{cost}^{t}$ is the real time utilization cost
$e_{cost}^{t}$ is the real time environmental cost computed as shown in Lau et al. (2014)
End
```

Table 20
Power allocation for base and DSM loads.

Household participation (%)	Base load allowance (MW)	DSM allowance (MW)
100	588	1000
50	1000	588
30	1238	350

3,115,047 using dynamic pricing over the TOU pricing scheme for the same energy dispatch. This translates to about a 9.2% reduction in electricity cost using dynamic pricing over TOU pricing on average. The U_{bias}^{cost} option dispatch shown in Fig. 3(b) achieves a utilization cost of ZAR 5920 which is about 20% lower than the utilization cost obtained from the C_{bias}^{cost} option.

The 24-h (96-slots) power dispatch for the washing machines, cloth dryers and base load demand for a 50% participation of households is shown in the area plots depicted in Fig. 4(a and b) for both cost functions. The computation of real values for the cloth washer and cloth dryer is similar to the description provided for reading Fig. 3(a and b). Differing from the 100% household participation, convergence of values is noticed between the C_{bias}^{cost} and U_{bias}^{cost} options. With a higher average plant utilization of 68.97%, a 4.6% reduction in electricity cost for the participating households using dynamic pricing over TOU pricing is observed for both cost function options. The utilization cost for both cases is ZAR 23,794.87.

Fig. 5(a and b) presents the 24-h dispatch of the power demand from the washing machine, cloth dryers and base loads for 30% household participation for both the C_{bias}^{cost} and U_{bias}^{cost} cost functions respectively. Similar to the 50% household participation, a convergence of the dispatch allocation for both cost functions is also observed. However, a higher average utilization of the power plant (81%) is observed for both cost function options. Similar to the preceding household participation rates, electricity cost savings of about 5.1% by the dynamic pricing scheme over the TOU pricing scheme is further observed for both cost functions. The convergent utilization cost is about ZAR 29,017.88. The computation of the real cloth washer and cloth dryer values is similar to the explanation provided in reading Fig. 3(a and b).

The savings accrued from 100% household participation translates to 247 Wh/day per household. Similarly for 50% household participation it is 299 Wh/day per household and 577 Wh/day per household for 30% household participation. The implication of this is that the application of DSM is capable of extending the duration of comfort for 100% household participation by Tier 2 capacity. Similarly, 50% household participation results in the comfort of participating households being extended by Tier 2 capacity while for 30% household participation, household comfort duration is extended by Tier 3 capacity. The relevance of this stems from the fact that the contribution of electrical appliances to comfort and QoL is not only a function of ownership but also of duration of usage. In mitigating poverty, the results obtained show that on average, households' monthly electricity bill (for DSM application on cloth washer and cloth dryer only) is reduced by 1.24%, 1.5% and 2.9% for 100%, 50% and 30% household participation respectively. This implies that resources could be freed up to consume more electricity for improved QoL.

6.1. Policy discussion

Table 21 presents corresponding daily values for S_{cost}, P_{cost}^{DP}, P_{cost}^{FP} and U_{cost} for 100%, 50% and 30% household participation and C_{bias}^{cost} and U_{bias}^{cost} cost functions. In presenting policy discussions, values would be used from Table 21 to highlight alternatives on pricing, utilization and dispatch of DSM loads for the residential sector (particularly washing machines and cloth dryers).

6.1.1. Policy discussion on pricing

According to Alix (2000), Eskom's distribution tariff does not always make local sense. This is because it penalizes usage during peak periods. The consequence of this is that home owners are thus made to consciously reduce or totally avoid electricity consumption during these periods. Furthermore, this method is particularly worrisome to illiterate home owners who might have no clue as to the variation in electricity prices across the day. The proposed dynamic pricing scheme obviates the need for monitoring of price signals. With smart regulators attached to the washing machines and cloth dryers, all that home owners have to do is load their devices and indicate duration and turn over control to the utility. The utility updates its database to accommodate the new entrant and re-runs the proposed optimisation algorithm to obtain the optimal dispatch profile that meets the pre-determined cost objective. The benefits of incorporating the dynamic pricing scheme include the following:

(i) A possible reduction in household expenditure on electricity. As seen from Table 21, across all scenarios for 100%, 50% and 30% household participation, electricity cost is reduced using dynamic pricing over TOU pricing. According to Chakravarty and Massimo (2013), Kanagawa and Nakata (2007), Pachauri et al. (2004), there is a nexus between poverty and energy poverty which implies that a reduction in electricity bill for home owners frees up money that can be deployed for other activities capable of improving their QoL.
(ii) More flexibility in dispatch as the utility is able to more accurately optimise the grid and balance demand/supply. This is particularly useful in meeting grid constraints since the utility has more control over the entire electricity movement chain.
(iii) Optimisation of electrical load dispatch to meet pre-determined constraints (reduced emissions, reduced electricity cost, reduced operational costs etc.).

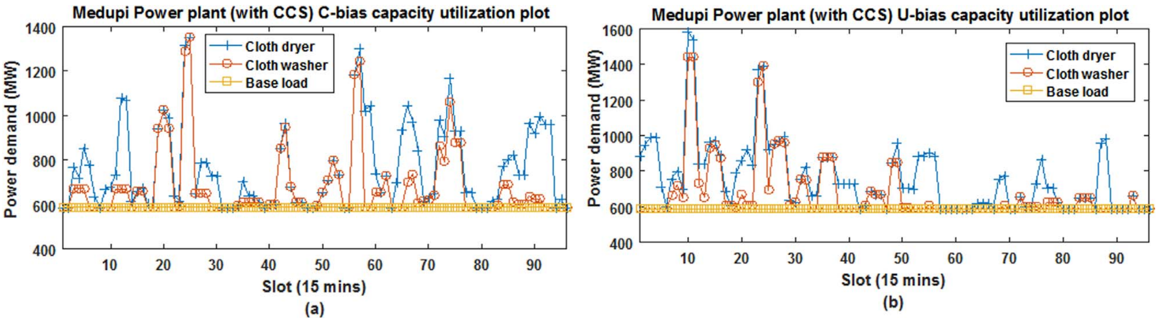

Fig. 3. 100% Household participation power dispatch for C_{bias}^{cost} and U_{bias}^{cost} options.

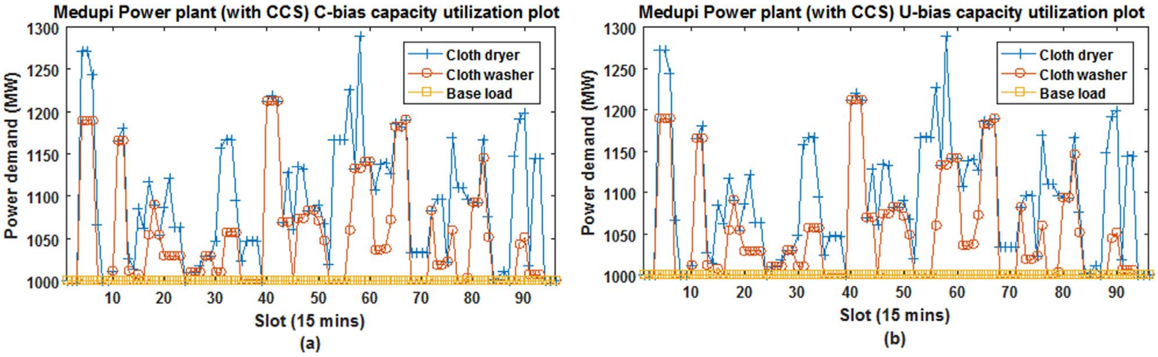

Fig. 4. 50% Household participation power dispatch for C_{bias}^{cost} and U_{bias}^{cost} options.

6.1.2. Policy discussion on utilization

Spinning and supplemental reserves are important constituents in the electricity sector as they help in preventing grid collapse in the case of sudden upsurge in electricity demand. However, lack of participation of the electricity supplier in the demand sector could lead to over-compensation and large values of spinning/supplemental reserves leading to more operational losses for non-utilization of their capacity. The incorporation of DSM however provides the electricity supplier with more information which is useful in optimally sizing spinning/supplemental reserve capacities which leads to reduced operational costs. Furthermore, the incorporation of DSM as seen from Figs. 3–5 helps in determining the optimal dispatch profile that could achieve the best average utilization of power plants. A critical observation of Table 21 shows a growing utilization cost despite increasing average utilization across the various household participation rate. This trend is due to a decreasing utilization of the allocated DSM capacity. The participation of the utility in influencing electricity end use could provide electricity demand data which can be used in optimally allocating DSM capacity for dispatch, thus freeing up more capacity for base loads.

6.1.3. Policy discussion on dispatch

A demerit of the application of Eskom's TOU pricing scheme is the fact that pseudo-peaks could be created during periods of cheaper electricity rates which is capable of disrupting the operation of the grid in case of demand exceeding supply capacity. A consequence of this has seen Eskom implementing load shedding to limit demand. Furthermore, dynamic pricing (especially when users are pre-informed of proposed spot prices) is capable of leading to pseudo-peaks (Safdarian et al., 2014). The scheme being proposed here only assures home owners of a reduction in their electricity prices (for loads participating in DSM). This thus ensures that the utility is in control of the dispatch and is capable of managing demand surge. The dispatch of the DSM loads could be classified as:

(i) Without time constraint – here, the users do not specify any constraint as to when their loads should be dispatched. The decision of the time of dispatch is entirely left to the utility. However, an override function is provided to enable the home owners remove control from the utility at any time and dispatch their loads using the current TOU spot price. A penalty could also be included to the home owners electricity bill to reduce the repetition of such actions.
(ii) With time constraint – here, the users specify a window within which their loads should be dispatched. The pricing scheme here is more rigid since the utility is given a shorter time frame for flexibility.

6.1.4. Policy discussion on energy poverty mitigation

As earlier posited, energy poverty is related to ownership of electrical appliances (Monyei et al., 2017). However, monthly electricity bill is not just a function of ownership but duration of consumption. From Table 21, the application of dynamic pricing for 100% household participation results in a daily savings of about ZAR 3,115,047 over TOU pricing. This translates to about 2.5 GWh at ZAR 1.25/kWh (247 Wh/day per household). The savings accrued can be used for extended electricity consumption or other activities that contribute to improving the QoL of the household occupants. Similarly, for 50% and 30% household participation, dynamic pricing achieves daily savings of ZAR 1,888,028 and ZAR 2,183,429 over TOU pricing. This translates to extra daily power of 299 Wh and 577 Wh respectively per household. In terms of electricity cost reduction, dynamic pricing achieves 1.24%, 1.5% and 2.9% monthly reduction per household respectively.

6.1.5. Policy discussion on supply capacity expansion

According to Eskom (2015a), plant availability for the period under review was 74.4% with average utilization of 84.77%. With a nominal

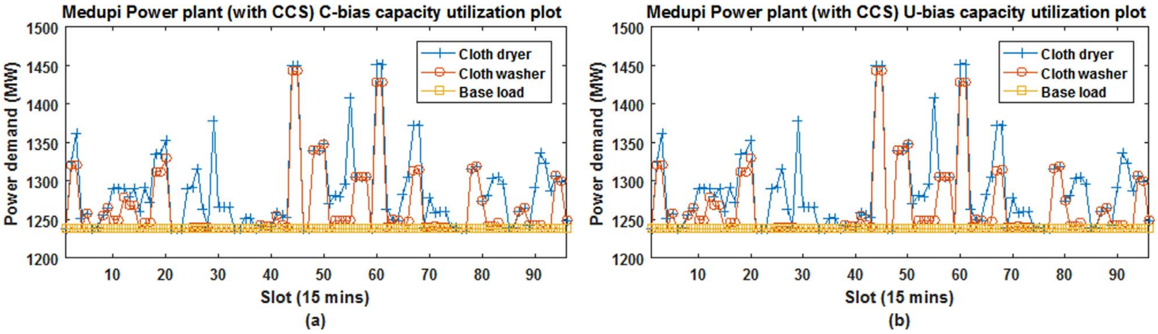

Fig. 5. 30% Household participation power dispatch for C_{bias}^{cost} and U_{bias}^{cost} options.

Table 21
Associated dispatch values for C_{bias}^{cost} and U_{bias}^{cost} options.

Household participation	100%		50%		30%	
Cost function	C_{bias}^{cost}	U_{bias}^{cost}	C_{bias}^{cost}	U_{bias}^{cost}	C_{bias}^{cost}	U_{bias}^{cost}
S_{cost}	8,442,025	8,434,699	10,239,392	10,239,392	10,922,049	10,922,049
P_{cost}^{FP}	33,869,750	33,708,250	40,397,500	40,397,500	43,007,000	43,007,000
P_{cost}^{DP}	30,754,703	34,951,081	38,509,472	38,509,472	40,823,571	40,823,571
U_{cost}	7390.13	5920	23,794.87	23,794.87	29,017.88	29,017.88

installed capacity of 42,000 MW, this translates to about 26,500 MW in terms of actual capacity utilization. According to Eskom (2016–2025), while 3516 MW is expected to be lost due to the decommissioning of ageing plants between 2021 and 2024, over 19,000 MW is expected to be added to the grid generation capacity between 2017 and 2024. This translates to a net increase of about 15,484 MW. Furthermore, additional costs are expected to be spent in increasing the transmission capacity, on reactors, capacitors and transformers, to improve electricity supply. The expected addition to the grid capacity between 2017 and 2024 is over 5 times the capacity to be lost. Demand increase within 2017 and 2024 using the high (less energy intensive) forecast from CSIR (2016) is about 55,078 GWh. Assuming a 70% utilization (of net increase) at 35% availability, this translates to a net production of about 131,106 GWh between 2017 and 2024. The huge difference between demand and supply capacity is to ensure that system operators have a wide-margin of operation allowance to accommodate for sudden increase in demand or loss of generation unit. However, an advanced metering infrastructure (AMI) that supports DSM through direct load control (DLC), provides the utility with advanced information that can enable it efficiently schedule generator and load dispatch under constraints such as maintenance and outages. This thus ensures that enormous resources do not have to be spent in over-sizing generation capacity in anticipation of an increase in demand.

7. Policy implementation and its challenges

Considering the current grid structure, a scaled-up pilot study approach is advocated for implementation of proposed policy. In the scaled-up pilot study approach, a network of willing houses cutting across the three tiers within a distribution network is established. Specific devices within the houses are then fitted with the appropriate switches and controllers for communication with the household meter which communicates with the utility. On a micro-scale level, the utility is able to evaluate response of each tier members to real-time feedback on their consumption. This is in line with Iwafune et al. (2017) where a 3.4% reduction in energy consumption was reported for households that received feedback on their electricity consumption. Some of the challenges to the proposed policy implementation include cost (due to the current grid structure which is centralized and the technical requirements for implementing an AMI), manpower (considering the high technical expertise needed and the low technical skill shortage in South Africa (Reddy et al., 2016)) and security/privacy concerns.

8. Conclusion

This research work has critically examined the electricity sector of South Africa and highlighted the fact that despite increasing investments in electricity generation, there is growing electricity poverty. Rather than taking the general approach in computing electricity per capita (assuming 100% consumption of generated electricity and using national averages), per capita electricity consumption has been computed on provincial basis taking into consideration provincial electricity supply values, residential sector consumption rate, electrified houses and average household sizes on provincial basis. The results obtained are in contrast to the usually evaluated values and show the growing disparity in electricity per capita across the various provinces. Furthermore, DSM has been thoroughly investigated for cloth washers and cloth dryers only in South Africa assuming 100%, 50% and 30% household participation for two cost functions (C_{bias}^{cost} and U_{bias}^{cost}). A major reason for this research work is to show that DSM has a huge potential in mitigating energy (electricity) poverty in South Africa by reducing electricity cost and freeing up more money for either more electricity purchases or other activities that have the potential of improving their QoL. The results obtained show first that DSM potential of 6938.34 MW, 3469.18 MW and 2081.51 MW exits for 100%, 50% and 30% household participation (for cloth washer and cloth dryers combined). Secondly, the application of DSM has been shown to mitigate poverty by reducing household electricity bills by 1.2%, 1.5% and 2.9% on monthly basis for 100%, 50% and 30% household participation. The savings accrued could then be utilized in activities that would contribute to the improvement of the household's QoL. In tackling energy poverty, the application of DSM on cloth washers and cloth dryers has shown that households' electricity consumption could be extended by 247 Wh/day, 299 Wh/day and 577 Wh/day for 100%, 50% and 30% household participation. This implies that already owned electrical appliances can have extended usage on a daily basis as a result of lower electricity bills. The dispatch of the considered DSM loads has been carried out (using the Medupi Coal Power Plant which has been modelled to include CCS technology) to show that consumers electricity cost can be reduced using dynamic pricing when compared to the existing TOU pricing scheme used by Eskom. A modified genetic algorithm (MGA) has been designed specially for this research to optimally dispatch the participating households' loads based on the earlier highlighted cost objectives. Furthermore, this research has been able to show that the incorporation of DSM into grid operation beyond electricity cost reduction, offers the utility more control in managing the grid operation due to their increased control of electricity from generation to distribution. This becomes very useful during systems operations and planning as it ensures that the utility is capable of mitigating grid collapse and reducing operational and associated expenditure costs. Other DSM potential sectors that could be exploited include heating, ventilation and cooling (HVAC), dish washers etc.

9. Future research

Considering the results obtained from the computation of electricity per capita, future work would consider electricity per capita distribution among the various population groups (blacks, coloured, Indians/coloured) across the provinces to understudy the impact of Eskom's electrification thrust in ensuring equitable energy access across the various population groups. This would be important in formulating policy on electrification that would ensure energy access for all in line with the United Nations Sustainable Development Goals (UN-SDGs) by 2030.

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CHAPTER 4

PAPER 3 - CEMS MODELLING

Brief summary

This chapter presents the paper entitled ***Integration of demand side and supply side energy management resources for optimal scheduling of demand response loads - South Africa in focus***. This paper proposes a standard deviation biased genetic algorithm (SDBGA) and a combined energy management system (CEMS) for integrating HEMS and SSEMS. This paper fully exploits DR for 100, 000 randomly selected homes in the Limpopo region. Utilizing the Medupi power plant, two pricing schemes (dynamic pricing and TOU pricing) and two DLC schemes Option 2 (in which the utility controls the dispatch time of the participating DR loads) and Option 1 (in which the household oversees controlling the dispatch time of the participating DR loads), the trade-off's in terms of minimized consumer cost, minimized supply cost and supply capacity utilization is shown in this chapter.

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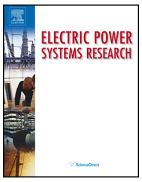

Integration of demand side and supply side energy management resources for optimal scheduling of demand response loads – South Africa in focus

C.G. Monyei[a,b,*], A.O. Adewumi[a,b]

[a] *Applied Artificial Intelligence Research Unit, School of Mathematics, Statistics and Computer Science, University of KwaZulu-Natal, Westville Campus, Private Bag X54001, Durban 4000, South Africa*
[b] *School of Mathematics, Statistics and Computer Science, University of KwaZulu-Natal, Westville Campus, Private Bag X54001, Durban 4000, South Africa*

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A B S T R A C T

The energy crisis of 2008 in South Africa, due to electricity demand surpassing supply and a depleted electricity reserve margin has exposed the need for more synergy between home energy management systems (HEMS) and supply side energy management systems (SSEMS). Demand side management (DSM) techniques have been investigated and proven to be viable means of regulating electricity demand from the consumer side. However, the viability of DSM is dependent on the participation of willing consumers. In this paper, a combined energy management system (CEMS) is proposed to provide a platform for incorporating the demands and constraints of consumers (time of dispatch, reduction of electricity costs, etc.) and suppliers (reduced operations cost, reduced emissions, etc.). The proposed CEMS utilizes dynamic pricing (DP) and a standard deviation biased genetic algorithm (SDBGA) in minimizing the DSM window to be allocated to the DSM loads of consumers based on the multi-objective constraints. The Medupi power plant which has been modelled to utilize carbon capture and sequestration (CCS) technology is used in carrying out the dispatch of the participating DSM loads (cloth washers, cloth dryers and dish washers) for 100,000 random residential customers. Results show that in dispatch option 1 (in which the user is in control of the start time), a lower cost of electricity of ZAR 373,218.40 is obtained compared to ZAR 416,280.20 by dispatch option 2 (in which the utility selects dispatch time for participating DSM loads) for the consumers. However, dispatch option 2 achieves a better minimized DSM window (14.94 MW), lower operating cost (about 1.6% lower than dispatch option 1), higher plant capacity utilization (87.92% efficiency) and a more evenly distributed profile.

1. Introduction

Generally, an electricity network consists broadly of generation (supply) stations, transmission/distribution network and the utilization/consumers side. At the supply/generation side, the objective of the supply side energy management system (SSEMS) is to minimize operations and emissions cost [24]. The transmission line management system (TLMS) ensures that line ampacity limits are not exceeded. The ampacity limits for transmission lines could either be static thermal line ratings (STLR) or dynamic thermal line ratings (DTLR) [12]. At the utilization point, home energy management systems (HEMS) aim at reducing the electricity bills of homes (while improving their comfort) by smartly dispatching loads during periods of low electricity cost [5]. The overall grid operation thus aims at optimally scheduling generation and load dispatch to ensure that there is a balance between demand and supply while meeting the individual objectives of SSEMS, TLMS and HEMS.

Integrated energy systems (IES) promote the concept of a synergized and harmonized community of energy systems based on the bi-directional flow of information (data). This synergy in terms of operation and information flow improves system's efficiency [25]. The concept of IES is however at variance with the traditional electricity grid operation which isolates the individual operations of each management system. In creating a synergy of operations, IES also provide a platform for the exploitation of such concepts as demand side management (DSM) through price based demand response (DR) and direct load control (DLC). These initia-

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[*] Corresponding author at: Applied Artificial Intelligence Research Unit, School of Mathematics, Statistics and Computer Science, University of KwaZulu-Natal, Westville Campus, Private Bag X54001, Durban 4000, South Africa.

E-mail addresses: chiejinamonyei@gmail.com (C.G. Monyei), adewumia@ukzn.ac.za (A.O. Adewumi).

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Nomenclature

C^{BL}	base load capacity for power plant
C^{DSM}	demand side management capacity for power plant
$C^{Reserve}$	reserve capacity for power plant
DP^t	hourly dynamic price electricity cost
F^{Ecost}	power plant environmental cost
F^{OPcost}	power plant operations cost
FP^t	hourly fixed price electricity cost
$\bar{FP}^t$	daily average fixed price electricity cost
P^{DP}	daily cumulative electricity cost using dynamic pricing
P^{FP}	daily cumulative electricity cost using fixed pricing
P_i^{DP}	daily electricity cost using dynamic pricing
P_i^{FP}	house *i* daily electricity cost using fixed pricing
$S_{gen}^{optimum}$	optimum solution population of dispatch values for generation *gen*
$S^{optimum}$	overall optimum best population of dispatch values after *gen* generations
sd_v	standard deviation for population v
$t_{i,j}^{start}$	house *i* specified start time for device *j*
$t_{i,j}^{dispatch}$	SDBGA generated start time for house *i* and device *j*
$t_{i,j}^{stop}$	house *i* specified maximum stop time for device *j*
$t_{i,j}^{duration}$	period of operation of device *j* for house *i*
$t'_{i,j}$	maximum possible start time for device *j* in house *i*
$t_{i,j}^{final}$	stop time of device *j* in house *i* based on $t_{i,j}^{dispatch}$
w_i	window selection set for house *i* in hours
w_i^*	window selection for house *i* in slots
k_i	class selection set for house *i*

tives become very important considering spiralling energy demand and the huge costs involved in power plant capacity expansion. For example, the energy crisis of South Africa which started in 2008 led to serious load shedding and blackouts across the country affecting homes and businesses [30,33]. Depleted reserve margins due to long years of non-investment in building additional power plants to cater for growing electricity demand was blamed for the crisis. However, the huge costs involved in building power plants and the long time frame from conceptualization to eventual completion and synchronization of the power plant output with the grid [39] have seen power shortages, loadshedding and grid interruptions extending to 2015 [33]. Furthermore, the growing population and increasing industrial activities [50] mean that other alternatives besides increasing generation capacity be exploited to guarantee electricity availability and security.

A review of existing government policy via its Integrated Resource Plan (IRP) [14] shows no significant improvement in existing DSM capacity in the short to medium term. In the same vein, Eskom's participation in the DSM sector is centred around efficiency initiatives such as distribution of energy efficient compact fluorescent lamp (CFL) bulbs [15] with moderate investments in solar water heating [21], wind [20], concentrating solar power (CSP) [16], etc. According to [23,22], Eskom plans to start decommissioning ageing power plants (Camden, Hendrina and Arnot) from 2021. While it is envisaged that ongoing construction works on Medupi, Kusile, Dedisa and Ingula power plants together with new coal independent power projects (IPP) would deliver an additional 8249 MW to the grid between 2017 and 2020 as shown in Table 1, the issue of delays due to technical constraints [17] cast huge doubts over Eskom's proposed commissioning plans. The need therefore arises for alternatives that will mitigate greatly the problems of blackouts and grid failures owing to demand exceeding supply.

Demand side management (DSM) techniques have been investigated and proven to be viable alternatives to regulating the consumption of electricity from the consumer side with applications from residential to industrial sectors [1,34,27,29,8,2]. According to [46], the two techniques for DSM from the consumer side include energy efficiency improvement programs (insulation, sealing, solar water heating systems, etc.) and demand response (DR) programs (price based and incentive based). While the energy efficiency improvement programs aim at increasing efficiency by reducing the amount of electricity required to accomplish similar tasks (with absence of supply side interference), the DR programs are initiated primarily by the supplier to influence consumer demand patterns. The home energy management systems (HEMS) [35,45,43,26,49,7] are the backbone of DR program initiatives as they provide the platform for home owners to interact with their electrical appliances and their meters [42]. On the supply side, its management system (SSEMS) refers to actions taken to ensure that electricity is generated and supplied at lowered operating costs, reduced environmental emissions and optimal system reliability [28].

A review of available literature with particular focus on South Africa's electricity sector reveals that the operations of the HEMS and SSEMS have been largely independent of each other. In attempting to extend the focus area outside of South Africa, [28] argued on the need for the integration of HEMS (DSM) and SSEMS for a realistic power system planning. The need therefore exists for a platform that is capable of harmonizing the constraints of both the supply side and demand side with the aim of:

- Reducing consumer electricity bill through the application of dynamic pricing – HEMS objective.
- Mitigating energy poverty by extending the usage of owned electrical appliances through reduced electricity bills. This is necessary since energy poverty is not only a function of ownership of electrical appliances but duration of use.
- Reducing operations and emissions cost of the supply side – SSEMS objective.

In doing so, the proposed platform must be capable of optimally scheduling DR loads (consumer controlled or utility controlled) in a DSM window (from generating capacity). This research work therefore contributes to existing DSM initiatives by:

(1) Extending the ongoing discussions on DSM initiatives by highlighting the need for synergy between HEMS and SSEMS and its benefits.
(2) Modelling and designing a centralized energy management system (CEMS) that accepts constraints and requirements from both the consumers and suppliers and optimally schedules DR loads for dispatch to meet the individual constraints.
(3) Optimally scheduling a DSM window from the generating plant overall capacity within which DSM loads can be dispatched. The DSM window is a fraction of the power plant overall capacity within which DR loads are to be dispatched based on the user requirements (time flexibility in dispatching load).

In attempting to model and design the proposed CEMS, one hundred thousand random homes in South Africa within the Limpopo province are selected. Furthermore, three deferrable loads (washing machine, cloth dryer and dish washer) are selected per house with 3 possible time-dispatch classes. Home owners are lastly provided with a control to select the time-window (2 h, 6 h or 24 h) within which dispatch of participating DDSM loads should be done. Dynamic pricing (DP) is used along with time of use (TOU) pricing for comparison. The power plant utilized in carrying out the dispatch of the participating DR loads is the Medupi power plant

Table 1
2017–2020 planned power plant capacity increment [22].

Year	Medupi		Kusile		Ingula		New coal			O&C CGT		
	Unit	MW	Unit	MW	Unit	MW	Unit	Name	MW	Unit	Name	MW
2017	3 4	738 738	2	738	4	333						
2018	5	738	3 3	738 738								
2019	6	738	5	738			1 2	Coal IPP1 Coal IPP1	200 200	3	Dedisa	237
2020			6	738			1 2	Coal IPP3 Coal IPP3	200 200	4	Dedisa	237

IPP – independent power producer.

which has been modelled to utilize carbon capture and sequestration (CCS) technology. The dispatch of the participating DSM loads is done using a standard deviation biased genetic algorithm (SDBGA).

The rest of the paper is organized as follows. Section 2 presents a review of related works and a justification for this research; Section 3 presents the case study description while CEMS is briefly modelled in Section 4. The mathematical description of the problem, pricing method adopted and SDBGA is described in Section 5. The results obtained are discussed in Section 6 while policy implications of CEMS on the consumer and supplier are briefly presented in Section 7. The work is concluded in Section 8 while Section 9 presents the general applicability of CEMS.

2. Related works

An economic model for demand response with the objective of maximizing the customer utility with constraints by either the daily budget or daily consumption was developed by [36]. The economic model was designed to explain the consumer consumption change pattern. An energy management system (EMS) that targeted average income earners in sub-Saharan Africa (SSA) was developed by [41]. The proposed EMS was capable of maximizing available capacity of a residential solar based inverter by optimally scheduling competing loads. The rule set involved in the proposed EMS did not aim at maximizing user satisfaction. In advancing the EMS design proposed by [41], [40] proposed an EMS that was capable of controlling residential loads, maximizing user satisfaction and minimizing household electricity cost. The lack of 'smartness' in pre-paid meters (common in SSA), was addressed by [42], where a smart energy management system that acted as an interface between the meter and the consumer loads was proposed. A demand side distributed and secured energy commitment framework and operations for a power producer in a deregulated environment was proposed by [9] while [1] proposed a stochastic programming model using a multi-objective particle swarm optimization method for optimizing smart grid performance, minimizing operations costs and reducing emissions with renewable sources.

Further application of DSM was done by [47] for a cement plant with a 4.2% reduction in electricity cost and [29] for cost minimization of a water supply system. A comprehensive review on demand side tools was done by [46] while the challenges of integrating HEMS with residential demand-side aggregators were addressed by [10]. An exploration of available literature was carried out by [3] and incentive-based DR programs were considered to be the most suitable solutions to addressing the problem of growing per capita electricity consumption in Kuwait. For further reading on DSM and its applications, see [4,31,48,6]. The contributions of preceding works notwithstanding, they have not been able to show the effect of DSM load control scheme (direct load control, (DLC) or consumer control) and dispatch window on energy poverty mitigation and DSM window minimization. This work extends research on DSM load dispatch by studying the effect of variable load control schemes (direct load control, (DLC) and consumer control) and dispatch window (duration within which participating DSM loads must be dispatched and completed) on the DSM load profile (DSM window minimization) and on energy poverty mitigation.

2.1. *Research motivation*

A justification for this research stems from the following:

- There has been a steady decline in electricity per capita for South African homes despite increasing generation (see [37]).
- Planned supply capacity expansion between 2017 and 2014 is over 5 times capacity loss and demand increase within the same period. According to [22], while 3516 MW is expected to be lost due to the decommissioning of ageing plants between 2021 and 2024, over 19 000 MW is expected to be added to the grid generation capacity between 2017 and 2024. This translates to a net increase of about 15 484 MW. The expected addition to the grid capacity between 2017 and 2024 is over 5 times the capacity to be lost. Demand increase within 2017 and 2024 using the high (less energy intensive) forecast from [13] is about 55 078 GWh. Assuming a 70% utilization (of net increase) at 35% availability, this translates to a net production of about 131,106 GWh between 2017 and 2024.
- Most of the homes in South Africa (based on [37]) are energy poor due to low electricity per capita that prevents extended usage of owned electrical appliances.
- According to [11], over 40% of global energy consumption comes from the residential and building sectors. This thus implies that households offer great potentials for DSM initiatives.

The computation of the electricity per capita (to show declining electricity consumption) for the nine provinces in South Africa on yearly (kWh/capita), monthly (kWh/capita), daily (kWh/capita) and hourly (Wh/capita) basis for 2007, 2011 and 2016 is shown in [37].

3. Case study description

3.1. *Consumer side problem description*

One hundred thousand residential homes are selected (for the simulation) across the Limpopo province, which is home to the Medupi power plant. Each selected home, *i*, is expected to possess at least a cloth washer, a cloth dryer and a dish washer. Each selected residential home is fitted with a HEMS and allows the home owner to:

Table 2
Class description, its dispatch time and number of slots.

Class		Cloth washer	Cloth dryer	Dish washer
1	min	75	105	105
	slots	5	7	7
2	min	60	75	75
	slots	4	5	5
3	min	30	45	60
	slots	2	3	4

Table 3
Cloth washer, cloth dryer and dish washer statistics.

Equipment	Device rating (W)	Number per household	Total power (W)
Cloth washer	500	1	500
Cloth dryer	1000	1	1000
Dish washer	1200	1	1200

(1) Select a class (k_i). A class corresponds to a pre-defined dispatch period for the participating DSM loads (cloth washer, cloth dryer and dish washer). Table 2 provides further information regarding the dispatch time and slot for each class. Three classes are offered in this modelling exercise. Thus for example, a class one choice by house 1000 (i.e. $k_{1000} = 1$) corresponds to 75 min (5 slots) duration for the cloth washer, 105 min (7 slots) duration for the cloth dryer and 105 min (7 slots) duration for the dish washer. A slot is equivalent to 15 min duration.
(2) Initialize start time ($t^{start}_{i,j}$) for each appliance j. A start time need not necessarily be the eventual dispatch time ($t^{dispatch}_{i,j}$).
(3) Select a dispatch window w_i. A dispatch window is a period from the initialized start time ($t^{start}_{i,j}$) within which the dispatch of a participating DSM load must be completed. Thus a dispatch window selection of 1 by house 1000 ($w_{1000} = 1$) means that the window within which a DSM load selected must be dispatched and dispatch completed is between $t^{start}_{i,j}$ and $t^{start}_{i,j} + 2(8\quad slots)$.

3.1.1. *Justification for choice of Limpopo Province*

A justification for the choice of the Limpopo province stems from the fact that hourly electricity consumed per person (capita) as observed from [37] as at 2016 was about 107.38 Wh which was among the lowest across the provinces. CEMS application is thus necessary to investigate its potential benefit in mitigating energy poverty among energy poor homes.

By definition,

$$1 \le i \le 100000 \tag{1}$$

$$1 \le j \le 3 \tag{2}$$

$$k_i = \{1, 2, 3\} \tag{3}$$

$$w_i = \{2, 6, 24\}\mathrm{h} \tag{4}$$

If the daily cumulative energy demand for all DSM loads in any residential house i is E^{energy}_i and P^{FP}_i and P^{DP}_i are the daily fixed price cost (electricity cost using Eskom's TOU pricing) and daily dynamic price cost (electricity cost using dynamic pricing) of DSM loads (energy) for house i, then the HEMS aims at:

(1) Minimizing P^{DP}_i such that $P^{DP}_i \le P^{FP}_i$
(2) Optimally scheduling the dispatch time $t^{dispatch}_{i,j}$ of each appliance j for house i. Where $t^{dispatch}_{i,j}$ is the final dispatch time of an appliance j for house i as evaluated by the SDBGA.

Thus,

$$t^{start}_{i,j} \le t^{dispatch}_{i,j} + t^{duration}_{i,j} \le t^{stop}_{i,j} \tag{5}$$

where $t^{duration}_{i,j}$ is the duration period for appliance j and house i as obtained from Table 2.

$$t^{stop}_{i,j} = t^{start}_{i,j} + w^*_i \tag{6}$$

Thus, the cost function associated with the HEMS is defined as

$$Z_{HEMS} = minimize(P^{DP}_i) \tag{7}$$

Table 3 presents the power rating of the participating DSM loads for each residential house.

3.1.2. *Justification for* k_i *and* w_i *pre-selection*

The pre-selected dispatch times for the cloth washer (30 min, 60 min and 75 min), cloth dryer (45 min, 75 min and 105 min) and dish washer (60 min, 75 min and 105 min) mirror conventional use time and makes for ease in simulating their use. Also, the pre-defined windows w_i are provided to offer the utility some flexibility in dispatch. While it is expected that a house that selects $w^*_i = 8$ intends for $t^{dispatch}_{i,j} = t^{start}_{i,j}$, the inconvenience in $t^{dispatch}_{i,j} > t^{start}_{i,j}$ is expected to be compensated by reduced electricity bills.

3.2. *Supply side problem description*

In dispatching the participating loads, the Medupi power plant is modelled to utilize carbon capture and sequestration (CCS) technology. From the consumer side, two kinds of loads are easily deduced - base/bulk load and the DSM load. A DSM window is to be created within the operating profile of the power plant within which loads participating in DSM would be dispatched. Furthermore, dispatch of residential loads is to be done to ensure optimal power plant utilization and reduced operations costs. The SSEMS thus aims at:

(1) Minimizing the DSM window C^{DSM} in the power plant operations profile within which the DSM loads can be dispatched. This leads to maximization of the base load capacity C^{BL}.
(2) Maximizing the utilization of the power plant capacity U^{util}.
(3) Minimizing the power plant operations cost F^{OPcost}.
(4) Minimizing the power plant emissions cost F^{Ecost}.
(5) Maximizing earnings P^{DP}_i from each household.

The relationship between the power plants reserve capacity ($C^{Reserve}$), base load capacity (C^{BL}) and DSM capacity (C^{DSM}) is shown in Eq. (8) while the operations cost of the power plant is computed as shown in Eq. (9).

$$C^{BL} + C^{DSM} + C^{Reserve} = C^{Plant} \tag{8}$$

$$F^{OPcost} = a + (b \times \varepsilon^t) \tag{9}$$

where a and b are gotten from Table 4, ε^t is the loading factor (i.e. the fraction) of the power plant currently being utilized and t is the slot being considered. In a 24-h modelling window with 15 min interval, there are four slots per hour. This translates to 96 slots for 24 h.

Assuming Z_{SSEMS} to be the cost function associated with the supply side, then its description is shown subsequently.

$$Z_{SSEMS} = \max(P^{DP}, U^{util}) + \min(F^{OPcost}, F^{Ecost}, C^{DSM}) \tag{10}$$

3.2.1. *Normalization of SSEMS associated parameters*

Z_{SSEMS} is a non-linear function and cannot be resolved using exact solutions since its optimization cuts across parameters that are of varying units. For example, while P^{DP}, F^{Ecost} and F^{OPcost} are in ZAR, U^{util} is expressed as a percentage (%) while C^{DSM} is in MW.

Table 4
Modified Medupi power plant modelling parameters.

Technology	LCOE model values		Operating range (%)			Carbon emissions	Capacity
	a	b	min	max	norm	(kg/MWh)	(MW)
CCS	2815.21	−14.80	66	88	85	136.2	1588

LCOE – levelized cost of energy.
CCS – carbon capture and sequestration.
Operating range – capacity factor range for the power plant.

Table 5
Base value for all cost component elements.

Component	Base value id	Base value	Evaluation description
P^{DP}	P^{DP}_{base}	588,000 ZAR	Evaluated by computing cost of total DSM energy E^{energy} with unit electricity price of 1.5 ZAR/kWh
P^{FP}	P^{FP}_{base}	588,000 ZAR	Evaluated by computing cost of total DSM energy E^{energy} with unit electricity price of 1.5 ZAR/kWh
U^{util}	U^{util}_{base}	100	Assumed 100% plant capacity utilization
F^{OPcost}	F^{OPcost}_{base}	145,230 ZAR	Evaluated using a and b values gotten from Table 4 and loading factor (ξ^t) of 88%
F^{Ecost}	F^{Ecost}_{base}	11,511,239 ZAR	Evaluated using emissions value from Table 10 and cost value from [32]. Conversion from Pounds to ZAR is done from [44]
C^{DSM}	C^{DSM}_{base}	30 MW	Selected by inspection
$t^{dispatch}_{i,j}$	$t^{dispatch}_{i,j,base}$	$t^{start}_{i,j}$	$t^{start}_{i,j}$ is the intended start time/reference point for $t^{dispatch}_{i,j}$

To resolve Z_{SSEMS} therefore, all associated parameters are normalized. Table 5 presents the base values used in normalizing P^{DP}, F^{Ecost}, F^{OPcost}, C^{DSM} and U^{util}. Thus, if P^{DP}_{norm}, F^{Ecost}_{norm}, F^{OPcost}_{norm}, C^{DSM}_{norm} and U^{util}_{norm} are the normalized values for P^{DP}, F^{Ecost}, F^{OPcost}, C^{DSM} and U^{util}, then $P^{DP}_{norm} = \frac{P^{DP}}{P^{DP}_{base}}$, $F^{Ecost}_{norm} = \frac{F^{Ecost}}{F^{Ecost}_{base}}$, $F^{OPcost}_{norm} = \frac{F^{OPcost}}{F^{OPcost}_{base}}$, $C^{DSM}_{norm} = \frac{C^{DSM}}{C^{DSM}_{base}}$ and $U^{util}_{norm} = \frac{U^{util}}{U^{util}_{base}}$.

3.3. DSM load dispatch options

In dispatching the participating DSM loads (cloth washer, cloth dryer and dishwasher) for the 100,000 houses in the Limpopo province, two dispatch options are modelled as follows.

3.3.1. Dispatch option 1

For dispatch option 1, the customers i are in charge of selecting k_i, w_i and their intended start time ($t^{start}_{i,j}$) for each DSM j load. In this option, the utility (Eskom) is only able to influence final dispatch time ($t^{dispatch}_{i,j}$) of the load j such that $t^{start}_{i,j} \leq t^{dispatch}_{i,j} \leq t'_{i,j}$. The flexibility of the dispatch time denoted as $f^{option1}_{i,j}|_{t^{start}_{i,j}}$ is defined as:

$$f^{Option1}_{i,j}|_{t^{start}_{i,j}} = \frac{t'_{i,j} - t^{start}_{i,j}}{t^{start}_{i,j}} \tag{11}$$

However, $t'_{i,j} = t^{stop}_{i,j} - t^{duration}_{i,j}$ and $t^{stop}_{i,j} = t^{start}_{i,j} + 4w^*_i$, $\Rightarrow t'_{i,j} = t^{start}_{i,j} + 4w^*_i - t^{duration}_{i,j}$ Hence,

$$f^{Option1}_{i,j}|_{t^{start}_{i,j}} = \frac{4w^*_i - t^{duration}_{i,j}}{t^{start}_{i,j}} \tag{12}$$

The end limits (minimum and maximum) possible selection of w_i are 2 h (8 slots) and 24 h (96 slots) respectively.

If $w^*_i = 8$, then $f^{Option1}_{i,j}|_{t^{start}_{i,j}} = \frac{8-t^{duration}_{i,j}}{t^{start}_{i,j}}$ and if $w^*_i = 96$, then $f^{Option1}_{i,j}|_{t^{start}_{i,j}} = \frac{96-t^{duration}_{i,j}}{t^{start}_{i,j}}$.

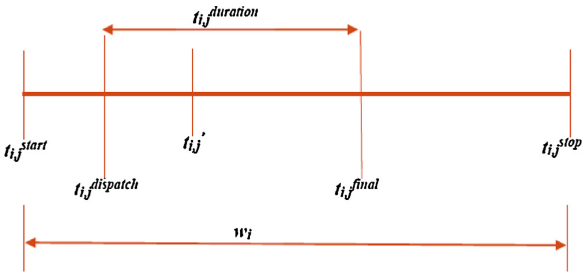

Fig. 1. A typical time progression and execution window for DSM loads.

The constraint on $f^{Option1}_{i,j}$ is given as:

$$\frac{8 - t^{duration}_{i,j}}{t^{start}_{i,j}} \leq f^{Option1}_{i,j}|_{t^{start}_{i,j}} \leq \frac{96 - t^{duration}_{i,j}}{t^{start}_{i,j}} \tag{13}$$

With the operating range of $f^{Option1}_{i,j}|_{t^{start}_{i,j}}$ given as $\frac{96-8}{t^{start}_{i,j}} = \frac{88}{t^{start}_{i,j}}$

The computation of $f^{Option1}_{i,j}|_{t^{start}_{i,j}}$ is to provide an insight into how much choice the proposed standard deviation biased genetic algorithm (SDBGA) has in optimally selecting $t^{dispatch}_{i,j}$ under the simulated options.

3.3.2. Dispatch option 2

In this option, the choice of selection of $t^{disptch}_{i,j}$ is entirely under the control of the utility, i.e. the participating DSM loads are under direct load control (DLC). Hence, under dispatch option 2, $w_i = 3$ i.e. $w^*_i = 96$. However, the consumer selects k_i. By definition, under this option, $t^{start}_{i,j} = 1$, $t^{stop}_{i,j} = 96$ and $t^{i}_{i,j} = 96 - t^{duration}_{i,j}$.

$\Rightarrow f^{Option2}_{i,j}|_{t^{start}_{i,j}} = 4w^*_i - t^{duration}_{i,j}$. Thus, the operating range of $f^{Option2}_{i,j}|_{t^{start}_{i,j}}$ is $96 - t^{duration}_{i,j}$. Fig. 1 presents the time-line progression of the various time instances ($t^{start}i$, j, $t'_{i,j}$, $t^{final}_{i,j}$, $t^{duration}_{i,j}$ and $t^{stop}_{i,j}$).

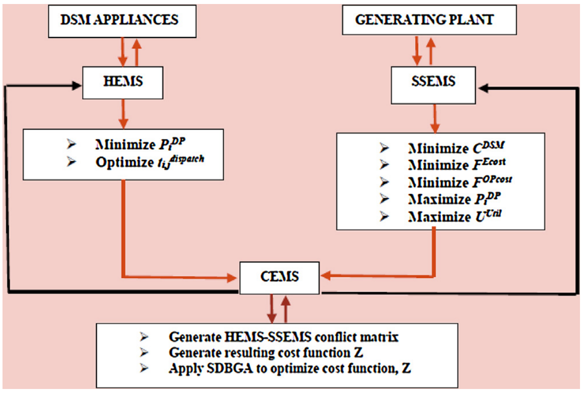

Fig. 2. Proposed CEMS infrastructure incorporating the HEMS and SSEMS.

Table 6
SSEMS-HEMS conflict matrix.

		HEMS	
		1	2
SSEMS	1		√
	2		√
	3		
	4	√	√
	5	√	

3.4. *Justification for C^{DSM} window*

As posited by [28], the integration of DSM and SSEMS is necessary for realistic system planning. Pre-selecting the DSM window C^{DSM} within which the participating DSM loads are to be dispatched provides the utility with advanced information for optimal system operation. Furthermore, the utility in pre-selecting a dispatch window C^{DSM} is able to evaluate ahead of time, the optimal generation scheduling configuration of its generators that will achieve its objectives in terms of reduced F^{Ecost} and F^{OPcost} and prevent oversizing of spinning reserves. However, in scheduling C^{DSM}, great care is taken not to under-size the window to prevent utilizing the generators beyond their normal operating range.

4. CEMS modelling

The complexity presented by the multi-objective and multi-dimensional problem is depicted in Fig. 2 where the links and connections between the proposed CEMS, HEMS and SSEMS are properly shown. Furthermore, the ensuing conflicts that may arise from the individual objectives of HEMS and SSEMS are seen. For example, while HEMS aims to minimize P_i^{DP}, SSEMS aims at maximizing P_i^{DP}. The resolution of this resulting conflict is explained subsequently.

4.1. *HEMS and SSEMS conflict matrix*

The harmonization of the household and supply requirements does reveal some conflicts. The conflict matrix shown in Table 6 presents the five major conflict spots between the HEMS and SSEMS working requirements. For example, conflict $C_{1,2}$ which is the conflict between the SSEMS constraint 1 and HEMS constraint 2 shows that in trying to minimize C^{DSM} by the SSEMS, the possibility of failing to dispatch household loads within their pre-determined window by the HEMS is possible due to reduced C^{DSM}. Also, conflict $C_{2,2}$ describes the possibility of low utilization of power plant capacity by the SSEMS due to low dispatch of residential DSM loads within certain periods owing to external constraints like line ampacity limits. The conflict $C_{4,1}$ denotes the conflict that arises in trying to reduce emissions cost by the SSEMS. The unintended consequence might be a higher cost of electricity P^{DP} for households during such periods. Similarly, conflict $C_{4,2}$ arises when SSEMS in trying to reduce F^{Ecost} selects $t_{i,j}^{dispatch}$ under dispatch option 1 that is outside the range $(t_{i,j}^{start}, t_{i,j}^{start} + w_i)$. Conflict $C_{5,1}$ denotes a direct conflict between SSEMS and HEMS in optimizing P_i^{DP}. While SSEMS strives at maximizing its value, HEMS aims at minimizing it. A platform is thus needed that is capable of addressing these constraints and optimally scheduling $t_{i,j}^{dispatch}$ of consumer DSM loads within the HEMS and SSEMS defined limits.

5. Mathematical modelling

This section presents the mathematical description for HEMS, SSEMS and SDBGA including discussions on the pricing models adopted and power plant utilized and their justification.

5.1. *HEMS constraints modelling and description*

Three classes k_i as shown in Table 2 and Eq. (3) are adopted in this research. A selection $k_{100} = 2$ implies that class 2 has been selected by house 100. A consequence of this thus implies that the dispatch time of the washing machine, cloth dryer and dish washer is 75 min (5 slots), 105 min (7 slots) and 105 min (7 slots) respectively. An initial start time $t_{i,j}^{start}$ and dispatch window w_i are selected by the user for every appliance (under dispatch option 1).

Given $t_{i,j}^{start}$, k_i and w_i, a dispatch time $t_{i,j}^{dispatch}$ is sought such that

$$t_{i,j}^{start} \le t_{i,j}^{dispatch} \le t'_{i,j} \tag{14}$$

where $t'_{i,j}$ is the final time a DSM device j for house i must be dispatched to meet with the user pre-determined window w_i selection. By dispatch, we mean “turned on.”

Thus,

$$t'_{i,j} = t_{i,j}^{stop} - t_{i,j}^{duration} \tag{15}$$

The associated cost of dispatch which is evaluated using both the time of use (TOU) pricing and dynamic pricing (DP) for comparison purposes is computed as follows: let FP^t be the TOU price and DP^t the dynamic price, then

$$P_i^{DP} = \sum \left(DP^t * E_{i,j,t}^{energy} \right), \quad t = t_{i,j}^{dispatch} : \ t_{i,j}^{final}, \quad i = 1:100000, \quad j = 1:3 \tag{16}$$

$$P_i^{FP} = \sum \left(FP^t * E_{i,j,t}^{energy} \right), \quad t = t_{i,j}^{dispatch} : t_{i,j}^{final}, \quad i = 1:100000, \quad j = 1:3 \tag{17}$$

5.2. *SSEMS constraints modelling and description*

Fig. 3 presents the typical profile of the Medupi power plant showing the base load (C^{BL}), DSM (C^{DSM}) and reserve allocations ($C^{Reserve}$). Assuming a maximum operating range (capacity factor) of 88% (as obtained from Table 4), the following is obtained:

$$C^{DSM} + C^{BL} = 1397.44 \text{ MW} \tag{18}$$

$$C^{Reserve} = 190.56 \text{ MW} \tag{19}$$

The utilization cost U^{util} is applied to utilization of the Medupi power plant capacity below 70% for any time t. This is necessary to prevent the build-up of peaks unnecessarily thus allowing for a evenly distributed dispatch profile. Thus, if $U_t^{util} \ge 70\%$, then $U_t^{util} = 0$, else $U_t^{util} = util_{cost}(t)$.

$$U^{util} = \sum_{t=1}^{96} U_t^{util} \tag{20}$$

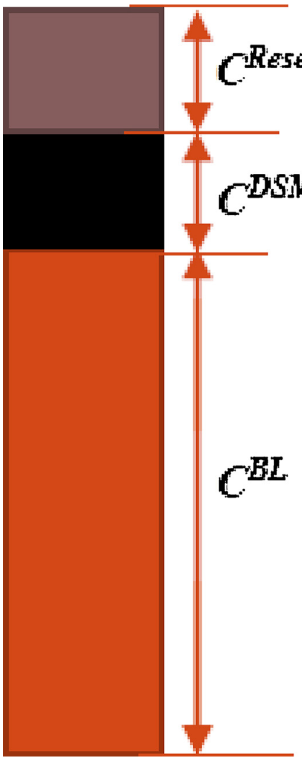

Fig. 3. A typical capacity profile of the Medupi power plant.

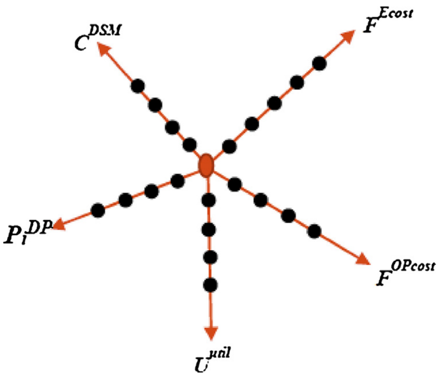

Fig. 4. SSEMS constraint wheel.

The emissions cost F^{Ecost} is computed based on the CO_2 emissions equivalent ($kgCO_2$) for energy (electricity) produced and consumed (MWh). Thus,

$$F^{Ecost} = \sum_{t=1}^{96} \left(Emi_t \times \sum_{i,j} \left(E_t^{energy} \right) \times b_1 \times b_2 \right) \tag{21}$$

where b_1 is the conversion factor to ZAR and b_2 is the conversion factor of E_t^{energy} from MW to MWh. F^{Ecost} is computed as shown in [32]. To convert to ZAR, prevailing exchange rate from [44] was used. SSEMS thus seeks to achieve an optimum operating point on its constraint wheel as shown in Fig. 4 that guarantees load dispatch at minimum costs (environment, operations) and maximized income and generator utilization. Fig. 4 presents the normalized constraint wheel for the SSEMS with each normalized factor having a range of possible selection. SSEMS thus selects points for each normalized factor that gives it the best operating conditions.

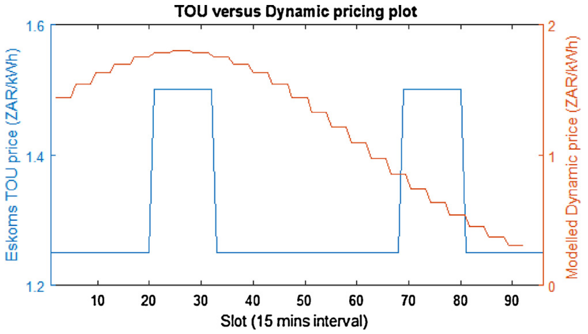

Fig. 5. TOU pricing and dynamic pricing profiles.

5.3. *Price modelling*

Two pricing schemes have been adopted for this model and they are the exiting Eskom TOU pricing scheme and a dynamic pricing scheme.

5.3.1. *Time of use pricing*

The existing TOU pricing scheme assumes a flat rate price of 1.25/kWh for off-peak periods with a 20% increment during 6 am–8 am and 6 pm–8 pm. The selected Eskom TOU pricing scheme is for a household whose monthly electricity consumption is less than 600 kWh. Weekends and weekdays have been assumed to have the same profile. The sample TOU dispatch profile for a day is shown in Fig. 5.

5.3.2. *Dynamic pricing*

The computation of the dynamic price DP^t follows the time of use (TOU) pricing being used by Eskom. As seen in Fig. 5, the daily average dynamic price is equivalent to Eskom's TOU pricing (excluding the peak periods). Given FP^t as the real time TOU pricing electricity spot price, then $\frac{1}{24}\sum_{t=1}^{t=24}(DP^t) = \bar{FP}^t$.

5.4. *Motivation for dynamic pricing model selected*

The TOU pricing scheme is adopted by Eskom to shift demand from peak periods to off-peak periods in order to prevent system collapse due to demand exceeding supply. In doing so, peak demand reduction is a motivation. However, the proposed dynamic pricing aims at:

- Improving the flexibility of the grid by offering the utility greater control of the electricity network. This is mostly the aim of dispatch option 2 in which the participating DSM loads are under DLC by the utility.
- Reducing electricity bills of consumers. The adoption of real time pricing guarantees the home-owners a reduction in their electricity bills over TOU pricing without altering their comfort level. In doing this, home-owners are able to save money that could be used in extending usage of electrical appliances.
- Reducing grid expansion investments. With the adoption of dynamic pricing and the subsequent control the utility has over the dispatch of participating DSM loads, the over-sizing of spinning reserves would be reduced since the utility can almost adequately predict the behaviour of the grid and optimize its overall operations.

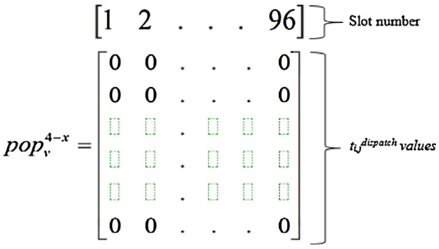

Fig. 6. pop_v^{4-x} initialization description.

5.5. SDBGA modelling

The proposed genetic algorithm (SDBGA) is a variant of MMIGA used in [42]. In differing from MMIGA, SDBGA computes the standard deviation of a generation matrix and selects the population with the highest spread. The notion behind this idea is to select the allocation that offers more spread in allocation of DSM loads dispatch time. This is to prevent the build up of multiple peaks.

5.5.1. Population initialization

pop_v^1 for start times, pop_v^2 for class selection, pop_v^3 for window selection and pop_v^4 for final dispatch time are generated as follows:

$$pop_v^1 = \left\{t_{1,1}^{start}, t_{1,2}^{start}, t_{1,3}^{start}, t_{2,1}^{start}, t_{2,2}^{start}, t_{2,3}^{start}, t_{3,1}^{start}, t_{3,2}^{start}, t_{3,3}^{start}, \ldots, t_{100000,1}^{start}, t_{100000,2}^{start}, t_{100000,3}^{start}\right\} \quad (22)$$

$$pop_v^2 = \{k_1, k_2, k_3, k_4, \ldots, k_{100000}\} \quad (23)$$

$$pop_v^3 = \{w_1^*, w_2^*, w_3^*, w_4^*, \ldots, w_{100000}^*\} \quad (24)$$

$$pop_v^4 = \left\{t_{1,1}^{dispatch}, t_{1,2}^{dispatch}, t_{1,3}^{dispatch}, t_{2,1}^{dispatch}, t_{2,2}^{dispatch}, t_{2,3}^{dispatch}, t_{3,1}^{dispatch}, t_{3,2}^{dispatch}, t_{3,3}^{dispatch}, \ldots, t_{100000,1}^{dispatch}, t_{100000,2}^{dispatch}, t_{100000,3}^{dispatch}\right\} \quad (25)$$

The selection of $t_{i,j}^{start}$ and w_i^* is either by the consumer (dispatch option 1) or the utility (dispatch option 2) while k_i selection is solely by the consumer. This then implies that $\eta(pop_v^1) = \eta(pop_v^4) = 300000$ and $\eta(pop_v^2) = \eta(pop_v^3) = 100000$. Furthermore, $t_{i,j}^{final} = t_{i,j}^{start} + w_i^* - 1$ (for dispatch option 1) and $t_{i,j}^{final} = 96$ (for dispatch option 2). The incorporation of -1 is to compensate for start position and prevent over-float. Three population matrices (pop_v^{4-x}, $x = \{1, 2, 3\}$) with dimensions $dim_1 \times dim_2$ (dim_1 = number of rows ornumber of houses and dim_2 = number of slots) are also initialized to zero as shown in Fig. 6. pop_v^{4-x} represents the matrix for $t_{i,j}^{dispatch}$ such that pop_v^{4-1} collects $t_{i,1}^{dispatch}$ values, pop_v^{4-2} collects $t_{i,2}^{dispatch}$ values while pop_v^{4-3} collects $t_{i,3}^{dispatch}$ values.

5.5.2. pop_v^{4-x} filling

The filling of pop_v^{4-x} is done based on the $t_{i,j}^{dispatch}$ stochastically evaluated for each household such that $t_{i,j}^{start} \le t_{i,j}^{dispatch} \le t'_{i,j}$. Let $pop_v^1 = \{2, 5, 5, 1, 1, 1, \ldots, 3, 3, 88\}$, $pop_v^2 = \{1, 1, \ldots, 3\}$ and $pop_v^3 = \{8, 96, \ldots, 8\}$ be the associated statistics for houses 1, 2 and 100,000. This implies that houses 1 and 100,000 are under the dispatch option 1 while house 2 is under the dispatch option 2. The description for the houses is as follows:

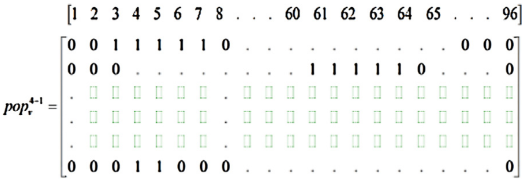

Fig. 7. pop_v^{4-1} filling.

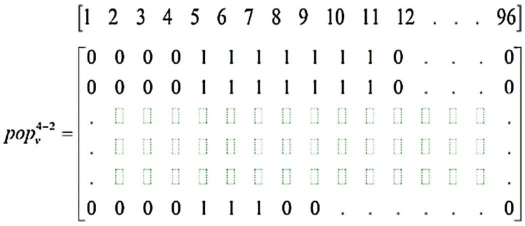

Fig. 8. pop_v^{4-2} filling.

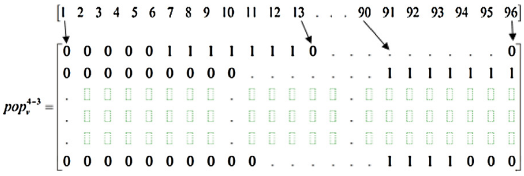

Fig. 9. pop_v^{4-3} filling.

- House 1: $t_{1,1/2/3}^{start} = \{2, 5, 5\}$, $t_{1,1/2/3}^{duration} = \{5, 7, 7\}$ while $t_{1,1/2/3}^{final} = \{9, 12, 12\}$. All values are in slots. The range of the dispatch value for the DSM loads j for house 1 is given to be $\{2, 5, 5\} \le \{t_{1,1}^{dispatch}, t_{1,2}^{dispatch}, t_{1,3}^{dispatch}\} \le \{5, 6, 6\}$. The implication of this is that $2 \le t_{1,1}^{dispatch} \le 5$, $5 \le t_{1,2}^{dispatch} \le 6$ and $5 \le t_{1,3}^{dispatch} \le 6$.
- House 2: $t_{2,1/2/3}^{start} = \{1, 1, 1\}$, $t_{2,1/2/3}^{duration} = \{5, 7, 7\}$ while $t_{2,1/2/3}^{final} = \{96, 96, 96\}$. All values are in slots. The range of the dispatch value for the DSM loads j for house 2 is given to be $\{1, 1, 1\} \le \{t_{2,1}^{dispatch}, t_{2,2}^{dispatch}, t_{2,3}^{dispatch}\} \le \{92, 90, 90\}$. The implication of this is that $1 \le t_{2,1}^{dispatch} \le 92$, $1 \le t_{2,2}^{dispatch} \le 90$ and $1 \le t_{2,3}^{dispatch} \le 90$.
- House 100000: $t_{100000,1/2/3}^{start} = \{3, 3, 88\}$, $t_{100000,1/2/3}^{duration} = \{2, 3, 4\}$ while $t_{100000,1/2/3}^{final} = \{10, 10, 95\}$. All values are in slots. The range of the dispatch value for the DSM loads j for house 100000 is given to be $\{3, 3, 88\} \le \{t_{100000,1}^{dispatch}, t_{100000,2}^{dispatch}, t_{100000,3}^{dispatch}\} \le \{9, 9, 92\}$. The implication of this is that $3 \le t_{100000,1}^{dispatch} \le 9$, $3 \le t_{100000,2}^{dispatch} \le 9$ and $88 \le t_{100000,3}^{dispatch} \le 92$.

In filling pop_v^{4-x}, SDBGA aims at varying $t_{i,j}^{dispatch}$ within its minimum ($\underline{t_{i,j}^{dispatch}}$) and maximum ($\overline{t_{i,j}^{dispatch}}$) limits to achieve the objectives of HEMS and SSEMS.

5.5.3. pop_v^{4-x} initialization

An initial allocation of $t_{i,j}^{dispatch}$ is made for all houses i and load j in pop_v^{4-x}. The values randomly generated for $t_{i,j}^{dispatch}$ are always constrained by $t_{i,j}^{start} \le t_{i,j}^{dispatch} \le t'_{i,j}$ ($\underline{t_{i,j}^{dispatch}} = t_{i,j}^{start}$ and $\overline{t_{i,j}^{dispatch}} = t'_{i,j}$). In filling pop_v^{4-x} with $t_{i,j}^{dispatch}$ values, the range $\{t^{dispatch}i, j, t_{i,j}^{dispatch} + t_{i,j}^{duration} - 1\}$ is initialized to 1. Figs. 7–9 present the initialization of

pop_v^{4-x} for houses 1, 2 and 100000. It is observed from Fig. 7 that for house 1 in pop_v^{4-1}, slots 3–7 are initialized to 1, similarly, for house 2 in pop_v^{4-1}, slots 60–64 are initialized to 1 while for house 100000 in pop_v^{4-1}, slots 4–5 are initialized to 1. The same rule is used in filling pop_v^{4-2} and pop_v^{4-3} based on each house's description given in Section 5.5.2.

5.5.4. $t_{i,j}^{dispatch}$ *variation*

For each filling of pop_v^{4-x}, E_{power}^{4-x} is computed. E_v^{4-x} is the cumulative column sum of power in pop_v^{4-x}. In generating E_{power}^{4-x}, pop_v^{4-x} is multiplied by its respective power value. From Table 3, $x = 1 \longrightarrow$ power value is 500 W. Similarly, $x = 2 \longrightarrow$ power value is 1200 W while $x = 3 \longrightarrow$ power value is 1000 W. Thus, $E_v^{4-x} = \{e_1^x, e_2^x, \ldots, e_{96}^x\}$ where $e_u^x = \sum_{u=1}^{96} pop_v^{4-x}(1:100000, u)$. The generation of E_{power}^{4-x} enables us to identify peak points and under-utilization points. These points are then isolated and used in varying $t_{i,j}^{dispatch}$. However, in the event that the constraints placed on $t_{i,j}^{dispatch}$ prevent it from being dispatched to points of under-utilization, then it is randomly computed using its constraints – $\underline{t_{i,j}^{dispatch}}$ for minimum and $\bar{t}_{i,j}^{dispatch}$ for maximum to be $round(randi \times (\bar{t}_{i,j}^{dispatch} \underline{t_{i,j}^{dispatch}}) + \underline{t_{i,j}^{dispatch}})$ where *round* is a function that converts any floating value to the nearest integer and $0 < randi < 1$.

5.5.5. *Cost computation and optimal solution selection*

For each run of pop_v^{4-x}, P_i^{DP}, P_i^{FP}, F^{OPcost}, F^{Ecost}, U^{util}, C^{DSM} and standard deviation (sd_v) are computed. Furthermore, the cost, Z_v associated with each population is calculated and used in ranking each solution. Selection of optimum solution, $S_{gen}^{optimum}$ is done as follows.

Given any pop_1^{4-x} and pop_2^{4-x} as the best population matrices per generation, *gen*, with standard deviations, sd_1 and sd_2, if $|Z_1 - Z_2| \le 1\%$ of $|Z_1 + Z_2|$ and $sd_1 < sd_2$, then $S_{gen}^{optimum} = pop_1^{4-x}$ else $S_{gen}^{optimum} = pop_2^{4-x}$.

5.6. *Medupi power plant*

The Medupi power plant is a greenfield coal fired power plant project situated in the Limpopo province. On completion, it is expected to be the fourth largest coal plant in the world. It has an installed capacity of 4764 MW from its six units each capable of outputting 794 MW. Unit 6 (the first of the 6 units) was synchronized with the grid in 2015. It has a planned operational lifetime of about 50 years [19,18]. In evaluating statistics such as loading factor, operations cost, environmental costs (ε^t, F^{OPcost}, F^{Ecost}), etc., there was the need to be able to characterize the behaviour of the Medupi power plant under varying loading conditions. A modified artificial neural network MANN [38] was applied on data plot describing the evolution of the levelized cost of energy for various power plants [14] to generate constants *a* and *b* as shown in Table 4. The choice and use of the Medupi power plant is because of its proximity to the customers being considered. Furthermore, its capacity is capable of dispatching the baseload and DSM loads of the considered consumers hence its choice.

6. Results and discussion

In modelling the allocation of consumer loads based on their selected and optimized parameters (dispatch option 1), a controlled allocation (dispatch option 2) was also done to provide a basis for comparison and standardization. The controlled allocation (dispatch option 2) assumes $w_i = 3$ (i.e. the utility selects the start time of participating DSM loads) for all customers with all other selections remaining the same (under the user's control). Table 7 presents the distribution of households across the various classes under both dispatch options (1 and 2) while Table 8 presents the distribution of houses across the various dispatch windows.

Table 7
Household class k_i distribution for the various options.

Option	Class k_i		
	1	2	3
1	24,887	50,185	24,928
2	24,887	50,185	24,928

Table 8
Household dispatch window w_i distribution for the various options.

Option	Dispatch window w_i		
	1	2	3
1	25,043	50,037	24,920
2	0	0	100,000

Table 9
Associated parameter values for the various options.

Parameters	Options	
	1	2
Baseload, C^{BL} (MW)	1356.67	1382.50
Plant utilization, U^{util}(%)[b]	86.30	87.92
Peak C^{DSM} (MW)	40.77	14.94
Cumulative energy, E^{energy} (MWh)[a]	329.31	329.31
F^{OPcost} (ZAR)[b]	147,640.50	145,329.80
F^{Ecost} (ZAR)[b]	11,288,439	11501166
P^{DP} (ZAR)[a]	373,218.40	416,280.20
P^{FP} (ZAR)[a]	438,153.40	433,185.30

[a] DSM loads only.
[b] DSM + baseloads.

Table 9 presents the values of associated parameters for both dispatch options (1 and 2). It is observed from Table 9 that dispatch option 2 achieves a better minimization of C^{DSM} of 14.94 MW compared to a peak C^{DSM} of 40.77 MW for dispatch option 1. In terms of plant utilization (U^{util}), dispatch option 2 also produces a better value of 87.92% compared to 86.30% by dispatch option 1. The operations cost (F^{OPcost}) is higher for dispatch option 1 compared to dispatch option 2 while dispatch option 1 is more environmentally friendly with F^{Ecost} of ZAR 11,288,439 compared to ZAR 11,501,166 by dispatch option 2. Dispatch option 1 was also found to be more consumer friendly from Table 10 under dynamic pricing with a total cumulative cost for the DSM loads (P^{DP}) of ZAR 373,218.40 to the residential houses. This is in contrast to a (P^{DP}) of ZAR 416,280.20 from dispatch option 2. However, dispatch option 2 provided a better fixed price cost (P^{FP}) of ZAR 433,185.30 compared to dispatch option 1's fixed price cost of ZAR 438,153.40.

The area plots shown in Figs. 10 and 11 depict the cumulative load profile (base load, cloth washer, cloth dryer and dish washer) for both dispatch options (1 and 2) respectively. The computation of the actual cloth washer value is done by deducting the read out cloth washer value from the plot and deducting the base value from it. Also, the computation of the cloth dryer value is done by deducting from the read out cloth dryer plot value the cumulative sum of the base load value and the corresponding cloth washer value. The actual dish washer value is computed by deducting from the dish washer plot value the cumulative sum of the base load value and the corresponding cloth washer and cloth dryer values. It is observed from Fig. 10 that its profile is influenced greatly by the dynamic pricing curve. With over 50% of households selecting class 2, the utility is given more leverage to shift dispatch time of DSM loads away from the early hours of the day to periods of low prices. However,

Table 10
P_i^{DP} and P_i^{FP} for selected houses under the various options for one day.

House number, i	E_i^{energy} (kWh)	k_i	w_i	Option 1			Option 2		
				P_i^{DP} (ZAR)	P_i^{FP} (ZAR)	% savings	P_i^{DP} (ZAR)	P_i^{FP} (ZAR)	% savings
1	2.2	3	2	2.57	2.75	6.46	2.14	2.81	23.8
7	3.25	2	24	4.69	4.19	−11.89	5.04	4.19	−20.25
1000	3.25	2	6	3.51	4.38	19.67	4.43	4.31	−2.69
10,000	4.475	1	2	3.82	6.28	39.16	4.87	5.81	16.14
25,000	4.475	1	2	3.53	6.31	44	3.30	6.06	45.55
33,000	2.2	3	24	2.08	3.05	31.72	3.66	2.75	−33.01
45,000	2.2	3	6	2.68	2.90	7.70	1.90	2.78	31.65
71,000	3.25	2	24	2.95	4.19	29.46	5.17	4.06	−27.38
92,000	2.2	3	6	2.57	3.05	15.73	2.14	2.81	23.90
100,000	3.25	2	6	3.50	4.36	19.80	4.60	4.81	4.52

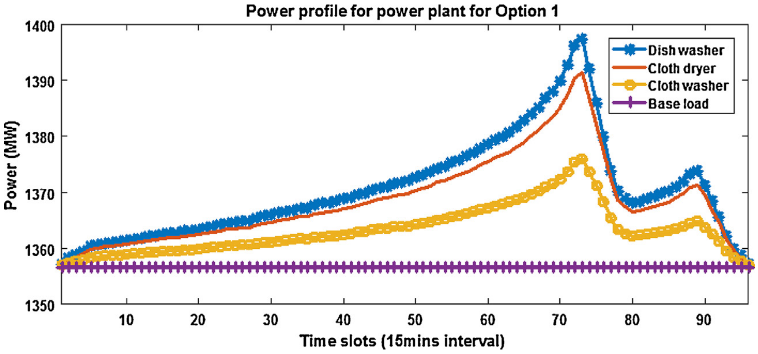

Fig. 10. Option 1 cumulative power profile.

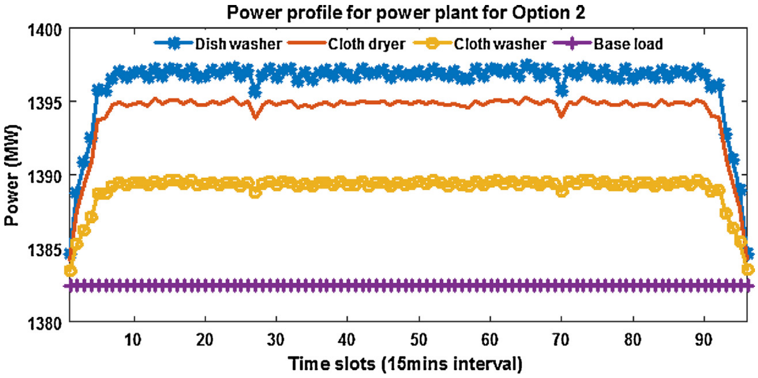

Fig. 11. Option 2 cumulative power profile.

for selections that must be done within the periods of high cost, the utility is forced to optimally schedule the DSM loads to be dispatched at periods with lower costs. This is however done within the limits allowed by the other prevailing constraining parameters (F^{Ecost}, F^{OPcost}, etc.). Fig. 11 however presents a profile which is evenly distributed across the day irrespective of the dynamic pricing profile. This explains why the P^{DP} for dispatch option 2 is higher than that for dispatch option 1 as shown in Table 9.

In evaluating the actual expenditure and potential savings (if any) for both options, the associated energy (E_i^{energy}), dynamic pricing cost (P_i^{DP}) and fixed price cost (P_i^{FP}) for selected houses for both dispatch options 1 and 2 are shown in Table 10. It is important to point out that the costs shown in the Table 10 are primarily for the DSM loads under consideration (cloth washer, cloth dryer and dish washer) and are independent of standing charges and other associated costs. From Table 10, it is noticed that dispatch option 1 achieves daily savings of 6.5%, 19.7%, 39.2%, 44%, 31.7% and 29.5% for houses 1, 1000, 10000, 25000, 33000 and 71000. Furthermore, a higher dynamic cost is observed for the house 7 under dispatch option 1 out of the ten houses under consideration. However, dispatch option 2 has more houses (4) compared to dispatch option 1 (1) incurring higher electricity cost using dynamic pricing for the houses under consideration.

Table 11 presents the disparity in dispatch time ($t_{i,j}^{dispatch}$) for each DSM appliance under both dispatch options (1 and 2) for the houses under consideration. The variation in the dispatch time evaluated for both dispatch options (1 and 2) is further depicted in Fig. 12, which presents the dispatch (power) of the three DSM appliances for house 1 for both dispatch options (1 and 2). House 1 dispatch of participating DSM loads (cloth washer, cloth dryer and dish washer) under both dispatch options (1 and 2) results in $t_{option1/option2}^{dispatch} = \{59, 25\}$ for cloth washer, $t_{option1/option2}^{dispatch} = \{85, 34\}$

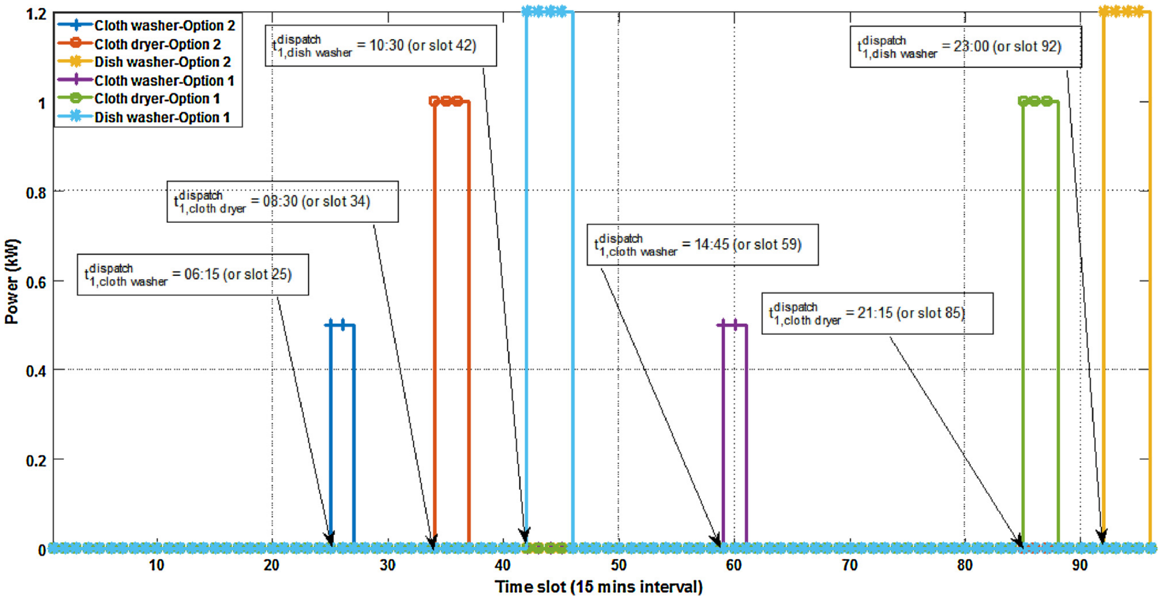

Fig. 12. Options 1 and 2 dispatch profile for house 1 DSM loads.

Table 11
$t_{i,j}^{dispatch}$ for selected houses under the various options

House number, i	Cloth washer		Cloth dryer		Dish washer	
	$t_{Option1}^{dispatch}$	$t_{Option2}^{dispatch}$	$t_{Option1}^{dispatch}$	$t_{Option2}^{dispatch}$	$t_{Option1}^{dispatch}$	$t_{Option2}^{dispatch}$
1	59	25	85	34	42	92
7	29	29	48	52	53	9
1000	46	28	73	66	56	42
10,000	76	21	60	15	72	89
25,000	33	17	78	74	74	82
33,000	33	14	60	9	76	38
45,000	58	20	38	93	67	63
71,000	71	50	5	11	87	7
92,000	33	35	40	32	73	92
100,000	55	19	56	69	68	28

for cloth dryer and $t_{option1/option2}^{dispatch} = \{42, 92\}$ for dish washer. The computation of the standard deviation for the dispatch values gives 17.68 for dispatch option 1 and 30 for dispatch option 2 which implies that the utility achieves a better spread of the dispatch times and also achieves a 23.8% savings (for dispatch option 2) compared to a 6.46% savings (for dispatch option 1).

7. Policy discussion on results

As earlier highlighted among the HEMS and SSEMS objectives, electricity cost reduction and greater system flexibility are some overarching reasons for proposing the integration of SSEMS and HEMS. Considering the implications of [37] which shows declining electricity per capita values and [13] where it can be argued that planned capacity expansion might be over-sized, we present some implications of the results obtained on the consumer and the supply side.

7.1. Policy implication of CEMS on consumers

Results obtained from CEMS modelling (that integrates HEMS and SSEMS constraints) show that averagely, reduction in electricity bills of consumers is guaranteed for CEMS platform that incorporates dynamic pricing. The introduction of dispatch windows and the incorporation of dynamic pricing mean homeowners are not forced to avoid electricity usage during peak hours due to higher electricity prices under TOU pricing. For example, results from Table 10 show that on average, dispatch option 1 saves each participating house 519.48 Wh/day with dispatch option 2 saving 135.24 Wh/day.

The benefit of this is that homeowners could either extend usage of owned electrical appliances or direct the savings to other activities that improve their Quality of Life (QoL).

7.2. Policy implication of CEMS on electricity suppliers

A major problem in electricity generation and supply is in sizing spinning reserves. Mostly, reserve margins are oversized in anticipation of demand increase which leads to higher operations cost, environmental costs and inefficiency. Providing the electricity supplier with some control over dispatch times of consumer loads (participating in DSM) offers the supply side greater flexibility in optimally scheduling generation resources. From Table 9, dispatch option 2 achieves a 1.6% reduction in operations cost over dispatch option 1 with dispatch option 2 achieving a better operations profile as shown in Fig. 11.

8. Conclusion

This research work has presented in detail the optimization of a DSM window on the Medupi power plant, for 100000 residential houses in South Africa. Using a CEMS (which incorporates a SDBGA), a synergy between HEMS and SSEMS has been established as well as the resolution of the ensuing SSEMS-HEMS conflict matrix. Two options have been modelled (with dispatch option 2 acting as a control for the standardization of the proposed model) for all residential houses and DSM loads. A critical evaluation of the two options shows that dispatch option 1 outperforms dispatch option 2 in minimizing F^{Ecost} and P^{DP}. Furthermore, dispatch option 1 has been shown to be sensitive to the dynamic pricing model adopted as it strives to shift dispatch of consumer loads from the periods of higher costs to periods of lower costs. This is at variance with dispatch option 2 which is quite insensitive to the dynamic pricing model and strives to achieve an evenly distributed profile and minimized DSM window at the expense of higher consumer and environmental costs. Average overall plant capacity utilization by dispatch option 1 has also been shown to be 86.3% which competes favourably with 87.92% obtained by dispatch option 2.

This research has thus shown that handing over total control of the dispatch time of participating DSM loads to the utility (dispatch option 2) is at variance with the aim of dynamic pricing. This is due to the reasons deduced from Table 9 where dispatch option 2 is seen to strive for a very strict minimized DSM window with the consequence of higher environmental costs and higher dynamic price cost due customers. This thus defeats the incentive behind price based demand response. However, this research has shown that the variability in consumers choice of dispatch start times and dispatch windows introduces robustness to the model and enhances its ability to search for an optimal solution with significant benefits to both the consumers and suppliers.

In extending this research, a multi-DSM window is being exploited with varying dynamic pricing schemes to see how well this proposed model performs under such multi-complex situation.

9. General applicability

While this work has utilized statistics relating to South Africa to test the proposed CEMS model, CEMS is of general application. This is because the associated statistics such as DSM loads, window, class, number of participating houses, etc. are all plug-ins and do not interfere with the model description but are rather used in optimizing the dispatch of DSM loads based on pre-determined criteria.

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CHAPTER 5

PAPER 4 - CONCEMS MODELLING

Brief summary

This chapter presents the paper entitled ***A smart grid framework for optimally integrating supply-side, demand-side and transmission line management systems***. This chapter extends research on Chapter four by proposing ConCEMS that incorporates TLMS. Furthermore, this chapter presents the development of an externally constrained genetic algorithm (ExC-GA) for HEMS load optimisation, two AI based algorithms GA-EED and MEED for the economic dispatch of the supply side generators and a dynamic thermal line rating (DTLR) algorithm for dynamically computing the ampacity limits of the transmission line in real time. The proposed framework (ConCEMS) is evaluated to show its ability to guarantee households a reduction in their electricity bill without adversely compromising on their comfort, while still meeting the objectives of SSEMS and TLMS. This is tested using three dynamic pricing schemes and 1 TOU pricing scheme as a benchmark. The proposed GA-EED is benchmarked using standard functions.

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Article

A Smart Grid Framework for Optimally Integrating Supply-Side, Demand-Side and Transmission Line Management Systems

Chukwuka Monyei [1,*], Serestina Viriri [1], Aderemi Adewumi [1], Innocent Davidson [2] and Daniel Akinyele [3]

[1] School of Mathematics, Statistics and Computer Science, University of KwaZulu-Natal, Westville Campus, Private Bag X54001, Durban 4000, South Africa; viriris@ukzn.ac.za (S.V.); adewumia@ukzn.ac.za (A.A.)
[2] Department of Electrical Power Engineering, Durban University of Technology, Durban 4001, South Africa; innocentD@dut.ac.za
[3] Department of Electrical and Computer Engineering, Elizade University, Ilara-Mokin P.M.B. 002, Ondo State, Nigeria; daniel.akinyele@elizadeuniversity.edu.ng
* Correspondence: chiejinamonyei@gmail.com

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Abstract: A coordinated centralized energy management system (ConCEMS) is presented in this paper that seeks to integrate for optimal grid operation—the supply side energy management system (SSEMS), home energy management system (HEMS) and transmission line management system (TLMS). ConCEMS in ensuring the optimal operation of an IEEE 30-bus electricity network harmonizes the individual objective function of SSEMS, HEMS and TLMS to evolve an optimal dispatch of participating demand response (DR) loads that does not violate transmission line ampacity limits (TLMS constraint) while minimizing consumer cost (HEMS constraint) and supply side operations cost (SSEMS constraint). An externally constrained genetic algorithm (ExC-GA) that is influenced by feedback from TLMS is also presented that intelligently varies the dispatch time of participating DR loads to meet the individual objective functions. Hypothetical day ahead dynamic pricing schemes (Price1, Price2 and Price3) have also been adopted alongside an existing time of use (Price0) pricing scheme for comparison and discussion while a dynamic thermal line rating (DTLR) algorithm has also been incorporated to dynamically compute power limits based on real time associated data.

Keywords: ConCEMS; demand response; ExC-GA; DTLR; dynamic pricing

1. Introduction

The traditional design of power systems has naturally isolated the sub-components from each other. Thus, an electricity network is traditionally built with pre-determined (static) constraints and minimal interaction between generation and transmission/distribution and vice versa. However, the ongoing restructuring of electricity networks is seeing a lot of interdependency among components of the electricity grid [1]. Another major contribution to the growing interdependency of sub-components is the idea of smart and connected communities that promote information exchange among integrated sub-components for efficiency and improved operations. Sensors and smart devices like smart meters and advanced metering infrastructure (AMI) are also providing a platform for real time data exchange between utilities and home devices [2].

In the construction of power systems, they are generally built to be resilient and able to withstand disturbances caused by line and/or generator outages. This thus necessitates the design of electricity grid networks to be secure for at least '$(n-1) outages$', which implies that the grid should be capable of maintaining system stability and security of supply in the event of the failure of any single associated component. The growing electricity demand coupled with the increasing penetration of renewable energy sources (RES) and stricter regulations towards emissions (CO_x and NO_x gases) is placing serious constraints on conventional grids [3]. Unplanned outages are thus not uncommon with some of the outages leading to cascading grid failure and eventual grid collapse. In mitigating grid collapse, various schemes have been proposed. The system integrity protection scheme (SIPS) according to [4] is a valuable tool for improving the security of electricity grid networks. Its design is to ensure multiple and simultaneous control of associated grid components. Demand response (DR) was also proposed as an alternative to mitigating grid collapse by [5]. Outages in a network could be planned, forced or unplanned. In the work of [6], they proposed a maintenance schedule for associated components that have been forcefully outed due to wear and tear under variable wind power while [7] presented the results of a ten year study on power outages for the Mid-Continent Area Power Pool (MAPP) for 230-, 345-, and 500 kV lines. The effect of forced distribution outage on spot electricity prices was also modelled by [8]. In South Africa, [9] presented a framework that integrates the constraints of the supply-side and the electricity end users for optimal grid operation. In the work by [9], the effect of flexible loads with varying control of dispatch times on the generation profile and associated costs was also studied. Further studies on network reliability relating to South Africa especially the Southern African Power Pool (SAPP) has been investigated by [10] where outage planning and power deficits challenges with renewable energy penetration has been addressed and [11], where the effect of high voltage direct current (HVDC) transmission of bulk electric power on grid reliability and the performance of electric power systems has been studied.

A critical observation of the foregoing shows that the provision of mitigating solutions to system reliability is mostly concerned with generation and transmission constraints. The advent and popularity of smart and interconnected systems that promote information exchange for efficiency and reliability thus necessitates the need for a system that encompasses and harmonizes the competing constraints from both the distribution/utilization end as well as the generation and transmission end of the network in ensuring optimal load flow.

In terms of layout, the control and management of the sub-components of a typical electricity network (generation, transmission/distribution and utilization) is divided into the Home Energy Management System, HEMS (for the utilization end), Supply Side Energy Management System, SSEMS (for the supply side) and Transmission Line Management System, TLMS (for the transmission side) with each management system acting independently. Furthermore, a review of available literature shows that discussions and research on these management systems are usually focused on one or at most two of the management systems with [12] considering supply and demand side management systems with a focus on generation expansion planning.

In expanding on HEMS, cost reduction and comfort of home-owners are the major focus of associated research. For example, [13] articulates on the contribution of HEMS to managing the electricity consumption and energy cost of homes while [14] proposed a system that aimed at reducing consumers' electricity bill while minimizing the daily volume of curtailed loads. In achieving most cost reductions, dynamic pricing schemes are being adopted to force consumption from peak to off-peak periods. Energy usage forecast ability is also being introduced to HEMS with [15] introducing a learning algorithm for the learning and prediction of heating, ventilation and cooling (HVAC) systems. Furthermore, [16] presented an electricity consumption-forecasting framework for industrial plants. The proposed framework was based on an Adaptive Neural Network Inference System (ANFIS) with the aim of the forecasting targeted at supporting decision making. In resolving possible conflicts for HEMS based on multiple users with conflicting preferences, [17] proposed an ontology-based framework for conflict resolution and knowledge representation in Home and Building Automation Systems (HBAS). A smart HEMS was also developed in [18] based on a limited memory algorithm for bound constrained problems (L-BFGS-B) along with a TOU pricing scheme to optimise appliance scheduling within a 24-h window. The proposed system achieved a reduction in energy consumption from 65.77 kWh to 44.295 kWh as well as a reduction in the cumulative cost of energy from US$6.50 to US$4.393 daily. Direct load control (DLC) was proposed for management of demand side loads based on a multi-objective particle swarm optimisation (MOPSO) algorithm, while [19] utilized a multi-criteria ϵ-*constraint*-based exact approach for demand side management. According to [20], SSEMS is essentially constraint-based for secure operations of power systems. Constraints are modelled in form of power flow problems to generate optimal solutions for generation dispatch/scheduling and associated technical constraints (voltage, frequency, emissions etc.). For example, [21] designed a multi agent-based controller to locate active power set points for optimal power management of electric vehicles (EV) and distributed energy resources in the microgrid to avoid worst case scenarios were all EV's to charge/discharge simultaneously. Similarly, the optimal location of distributed generators in a smart grid for reactive power management with penetration of renewable energy sources was solved by [22] utilizing genetic algorithm. An optimal coalition of formation mechanism of microgrids in a smart distribution system was presented by [23] with it its characteristics analysed from a coalitional game theoretical perspective. The proposed method which utilised a Greedy-based strategy to perform network constrained exchange (GreedEnEx) reported loss reduction ranging from 26% to 80%. TLMS aims at ensuring that the line limits in terms of the current carrying ability are not exceeded. TLMS could thus be static (i.e., static thermal line rating, STLR) where the ampacity of a transmission line is computed for the worst case scenario or dynamic (i.e., dynamic thermal line rating, DTLR) in which the computation of the ampacity of a transmission line is done in real (or near real) time [4].

Considering the diverse objectives of the various management systems, a comprehensive and smart system is thus needed that interconnects the various management systems and harmonizes their constraints for efficient operation of the power network. There is no doubt that multi-energy systems offer better perspective for achieving a sustainable energy supply and also aiding the energy transition from the traditional approach [24]. However, a comprehensive, scalable and smart system which differs from the conventional integrated energy systems (IES) [25–27] is proposed. This work thus extends the framework presented in [9] and pioneers the optimal allocation of consumer loads with the objective of meeting the individual constraints of HEMS, SSEMS and TLMS. Additionally, smart algorithms are developed and used for both optimal load dispatch of consumer loads and optimal dispatch of generators to meet the individual objectives of HEMS and SSEMS without violating the ampacity limits of the transmission network as determined by TLMS. Furthermore, this work advocates for a more integrated electricity network that gives the utility a greater role in demand side management (through DLC) to provide the utility with more allowance in balancing the grid parameters. ConCEMS thus becomes useful with growing and increasing penetration of renewable energy sources (RES) as it enables the utility mitigate against the stochastic nature of RES by dispatching participating DR loads to periods of high availability of RES while not compromising on network technical and operational constraints. In being able to efficiently and effectively utilise RES, the utility is able to minimize expansion and environmental costs (associated with the use of fossil and other dirty-based generation sources). This thus has the extended benefit of minimizing the increment in electricity costs for electricity users and ultimately minimizing energy poverty since households would not need to expend a significant proportion of their income in meeting their energy (electricity) needs. The benefits and importance of ConCEMS thus go beyond the technical advantages and extends to the socio-economic and environmental aspect of society. Figure 1 shows the conceptual design of the proposed Co-ordinated and Centralized Energy Management System (ConCEMS). This work thus extends current research on IES by proposing and applying ConCEMS to an IEEE 30-bus electricity network to dynamically dispatch consumer loads (demand response (DR) loads) to achieve the following:

- Reduce consumer electricity bill below available time of use pricing (Price0) (using day ahead dynamic pricing schemes—Price1/Price2/Price3)—HEMS constraint.
- Ensure dynamically computed ampacity limit is not violated by any line—TLMS constraint.

- Reduce operations and emissions cost of the supply side using Price1/Price2/Price3 compared to Price0—SSEMS constraint.

The labelling of the constraints in Figure 1 are as follows:

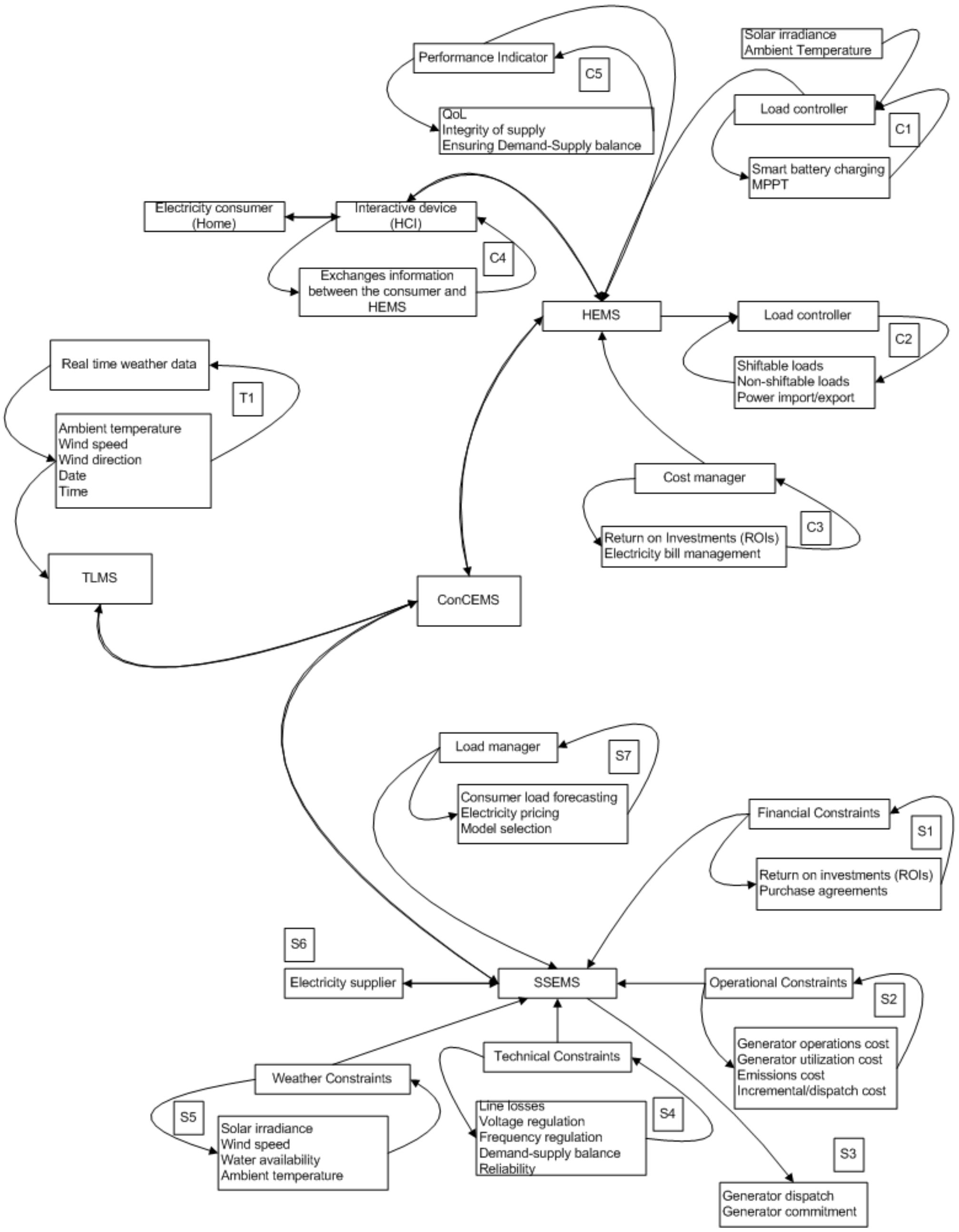

Figure 1. ConCEMS conceptual design.

- S1–S7 for SSEMS (i.e., 7 constraints) where S1 is the financial constraint (fuel costs), S2 is the operational constraint (loading limits, reliability), S3 is the generator dispatch/commitment constraint, S4 is the technical constraint (voltage, frequency, var compensation), S5 is the weather constraint, S6 deals with specific constraints from the electricity supplier and S7 is the associated constraint from electricity users on demand response loads.

- C1–C5 for HEMS (i.e., 5 constraints) where C1 deals with battery charging/feed-in-tariff, C2 handles DR loads, C3 manages household expenditure on electricity, C4 updates the household in near-real time on energy usage patterns while C5 ensures household comfort is not compromised.
- T1 for TLMS (i.e., 1 constraint) where T1 is the real time weather data (ambient temperature, wind speed and solar irradiance) that affects the computation of transmission line ampacity limits in real-time.

For the purpose of this research, Table 1 highlights which of the constraints have been considered. The rest of this article is organised as follows. Section 2 presents the case study network with the mathematical description of the utilized load flow algorithm. Section 3 presents SSEMS and a mathematical description of its generator dispatch for reduced emissions cost. Section 4 presents TLMS and the description of the DTLR algorithm utilized. HEMS is presented in Section 5 with its objective discussed while the pricing models adopted are presented in Section 6. The results are presented and discussed in Section 7 while policy discussions on the socio-economic and techno-environmental impact of ConCEMS are presented in Section 8. The paper concludes in Section 9.

Table 1. Management systems and their components considered.

HEMS		SSEMS		TLMS	
Components	**Status**	**Components**	**Status**	**Component**	**Status**
C1	XX	S1	XX	T1	√
C2	√	S2	√		
C3	XX	S3	√		
C4	√	S4	√ *		
C5	XX	S5	XX		
		S6	√		
		S7	XX		

√—component considered; XX—component not considered; *—not all parts of components considered.

2. Case Study Description

Figure 2 presents the case study network utilized for the application of the proposed ConCEMS while Figure 3 presents the gas network description. The case study network is an IEEE 30-bus network [28] which has been modelled as a closed system with 1 slack power bus (bus 1), 20 load points and 5 generation points. Each load point has both base loads and DR loads. The DR loads for each respective bus is made up of 10 clusters each of households with varying participation of DR loads. The slack power bus has been included to act as a sink/source for excess/deficit power. The test network consists of 41 lines used in moving power across the network. At the slack bus (bus 1), there are 3 generators—2 diesel generators (110 MW each) and 1 natural gas fired thermal generator (50 MW). The description of the demand side management (DSM) capabilities of the various load points is shown in Table 2 while Figure 4 presents the flow chart of the proposed working principle of ConCEMS. The description of the ConCEMS flowchart is as follows; after the computation of DLTR using hourly weather data, start time of DSM loads, $str_L^{i,j}$ is computed for all participating DSM loads. The cumulative of base load demand and DSM loads for each slot (15 min interval) is then used to optimally determine generation loading based on DTLR constraints for time t'. Load flow analysis is then done to determine the amount of power supplied from the slack bus and the appropriate costs. In computing P_T^t, DTLR could place constraints that would necessitate power import through an alternate line p to meet P_T^t and associated line losses. The computation of $str_L^{i,j}$ using ExC-GA is thus very important in determining the optimal P_T^t that would reduce power supply costs and underutilization of generated power. In addition, the computation of associated supply side costs is followed by the computation of the cost of dispatching the DSM loads using hypothetical day ahead dynamic pricing models (Price1, Price2 and Price3) which are benchmarked with a time of use pricing scheme (Price0). This is to evaluate and determine the best dynamic pricing scheme that will ensure a reduction in DSM load cost, which is the incentive for placing the eventual dispatch of participating DSM loads under direct control by the utility. In computing the associated supply costs for the gas network, ConCEMS aims to generate the least cost for operating the compressors at the various compressor stations that will guarantee the required gas flow rate at the tapoff-point while maintaining the pressure, flow rate and compressibility values within the defined constraints across the length of the pipeline. In minimizing the supply costs for the proposed electricity network, emphasis is placed on the generators in bus 1. This is due to their large size which makes them the major supplier of the bulk load for the test network. The Newton Raphson (NR) method has been adopted in attempting to solve the resulting load flow problem. The modelling of the NR operation is constrained to ensure that convergence is only possible within allowed bus voltage limits. STT and SET for this research have been taken to be 00:00 and 00:00 + 1 day while all dispatch scenarios are carried out a day ahead.

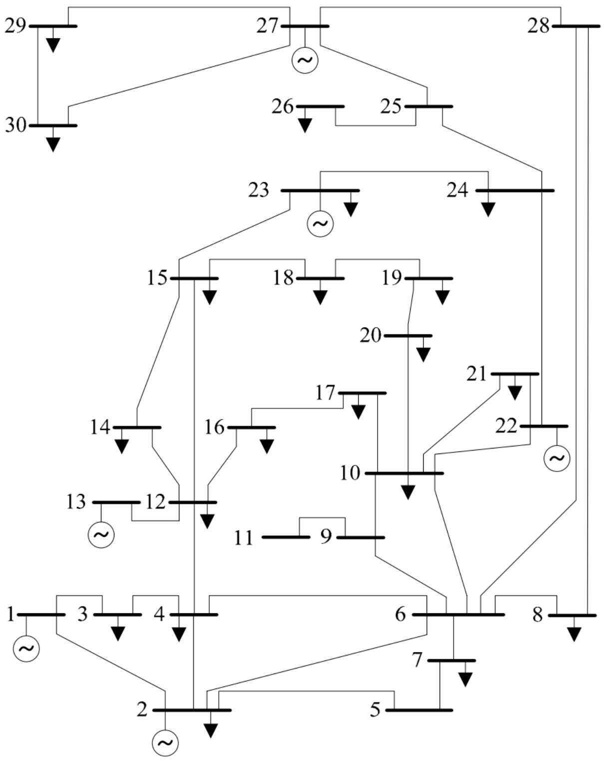

Figure 2. IEEE 30-bus electricity network [28].

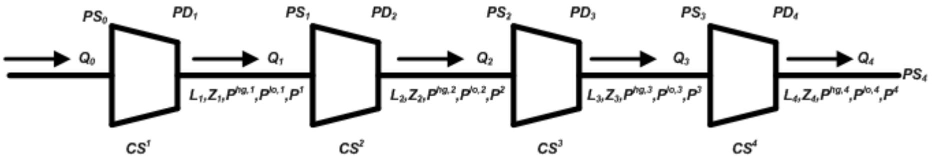

Figure 3. Hypothetical gas network.

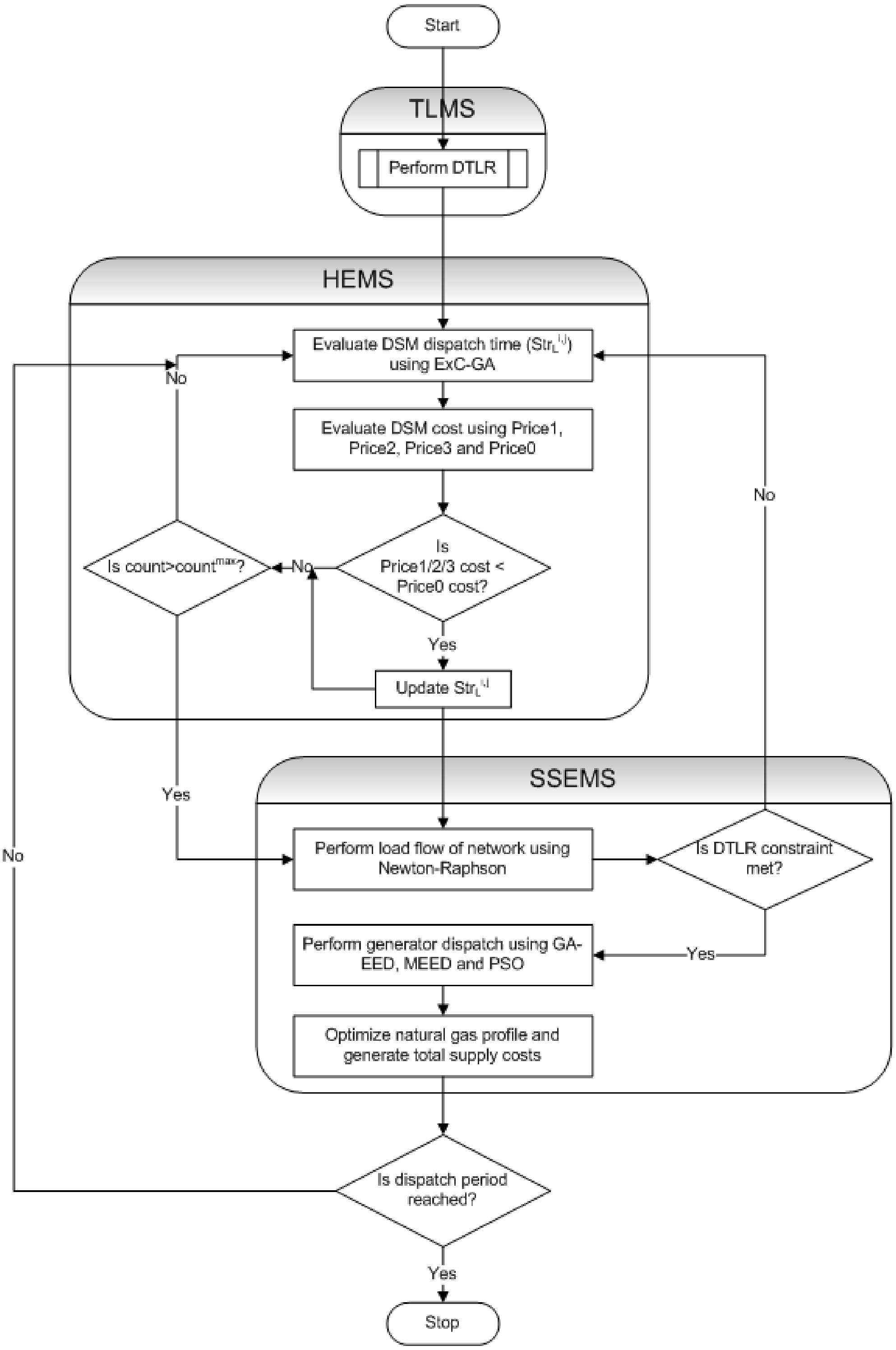

Figure 4. Flowchart of ConCEMS.

Table 2. DSM capability of load points.

Bus Number	DSM (MW)
2	39.06
3	72.58
4	13.98
7	51.98
8	61.20
10	132.08
12	21.95
14	14.63
15	17.06
16	7.56
17	19.80
18	7.17
19	14.82
20	32.70
21	37.80
23	7.04
24	18.79
26	27.54
29	5.09
30	24.17

3. SSEMS Description and Modelling

In modelling the SSEMS objective function, Z_{SSEMS}, we briefly describe the associated costs at the supply side.

Economic and Environmental Dispatch of Generators

Table 3 presents the fuel cost of each generator in bus 1 together with the power limits (lower and upper). Also shown in Table 3 is the emissions cost for each associated generator in bus 1 which has been incorporated into the fuel cost. Algorithm 1 presents the conventional economic dispatch of generators based on incremental cost which has been modified to accommodate emissions cost. The modification results in a modified economic and environmental dispatch (MEED) algorithm. Utilizing the fuel costs of the diesel generators in Table 3, the conventional incremental cost is adjusted to optimally schedule/dispatch the generators at bus 1 for the lowest economic and emissions cost. Another improvement is the compensation for under generation. This is done by optimally allocating the difference in deficit generation among the generators based on their available capacity. The need for this improvement is to reduce the time of computation spent looking for an optimal dispatch profile. Great care is however employed in setting the allowable tolerance level (deficit/surplus generation).

Table 3. Bus 1 associated data for generators.

Bus	Fuel Cost Coefficients *			Real Power Limits (MW)		Type	Emissions Cost ($/MWh)
	a	b	c	Lower	Upper		
1	0.005	35	135	20	95	Diesel	100
	0.007	39	110	40	95	Diesel	132
	0.012	23.25	200	30	50	Natural gas	53

*—Incorporates emissions cost.

The objective function Z_{SSEMS} is thus defined in Equation (1) as:

$$Z_{SSEMS} = min(OP_t^{cost}) + min(Z(t)) \tag{1}$$

Subject to:

$$1 \leq Z_\alpha \leq 1.6 \qquad \forall \alpha \tag{2}$$

$$P^{lo,\alpha} \leq P^\alpha \leq P^{hg,\alpha} \qquad \forall \alpha \tag{3}$$

$$7.5 < PS_4 \leq 9.5 \tag{4}$$

$$2.5 \leq Q_\alpha \leq 2.7 \qquad \forall \alpha \tag{5}$$

$$OP_t^{cost} = \sum (EmiC_t + F_t^{cost}) \tag{6}$$

$$Z(t) = \sum_{\theta=1}^{\theta=4} C^\theta(t) \tag{7}$$

$$EmiC_t = \sum_{x=1}^{X} (E_{x,t}^{cost}) \tag{8}$$

$$E_{x,t}^{cost} = P_{Dx}^t \times w_3 \tag{9}$$

$$Z_\alpha = \frac{PD_\alpha}{PS_{\alpha-1}} \tag{10}$$

$$F_t^{cost} = \sum_{x=1}^{X} (C_x^{cost,t}) \tag{11}$$

where θ is a compressor station, α is a pipeline section, OP_t^{cost} is the total time t cost of generation by all generators (US$), $Z(t)$ is the total cost of running all compressors at time t (US$), Z_α is the pipeline section α compressibility ratio (dimensionless), $P^{lo,\alpha}$ is the pipeline section α low pressure limits (bars), $P^{hg,\alpha}$ is the pipeline section α upper pressure limits (bars), P^α is the pipeline section α pressure (bars), PS_4 is the output pressure (bars), Q_α is the pipeline section α gas flow rate (MMSCFD), $EmiC_t$ is the total emissions cost at time t (US$), F_t^{cost} is the operations cost at time t (US$), $E_{x,t}^{cost}$ is generator x emissions cost at time t (US$), PD_α is the discharge pressure (bars) from compressor θ, $PS_{\alpha-1}$ is the suction pressure (bars) for compressor θ, $C_x^{cost,t}$ is the cost (US$/MWh) of generating P_{Dx}^t by generator x at time t while every compressor station θ lies between pipeline sections $\alpha - 1$ and α (i.e., $\alpha - 1 \leq \theta < \alpha$). Equation (2) presents the lower and upper compressibility limits for α while Equation (3) describes the lower and upper pressure limits for α. The possible range for the final discharge pressure is described in Equation (4) while Equation (5) presents the lower and upper flow rate limits for α. The evaluation of OP_t^{cost}, time t compressor cost, time t total emissions cost, time t emissions cost for generator x, α compressibility ratio and time t operations cost is shown in Equations (6)–(11).

Algorithm 1: Modified incremental generator dispatch.

```
Input: $\lambda_x^t$,$\lambda^t$, fuel cost for generators, $P_T^t$,$P_{Dx}^{t-1}$,$P_T^{t-1}$
Output: $P_{Dx}^t \ \forall x \in X(.)$

Perform normal incremental cost :
Compute $P_{Dx}^t$ such that $\sum_{x=1}^{X}(P_{Dx}^t) \simeq P_T^t$
Compute $\lambda^t$ such that $\lambda_x^t = \lambda^t \ \forall x \in X(.)$
Subject to:
$P_{Dx}^{min} \leq P_{Dx}^t \leq P_{Dx}^{max} \ \forall x \in X(.)$
if ($P_T^t \geq P_T^{t-1}$) then
    $P_{Dx}^t \geq P_{Dx}^{t-1}$
end if
if ($P_T^t < P_T^{t-1}$) then
    $P_{Dx}^t \leq P_{Dx}^{t-1}$
end if
Compute $EmiC_t$ and $F_t^{cost}$

Modifications—MEED
Set tolerance $w_4$ in MW such that $|P_T^t - \sum_{x=1}^{X}(P_{Dx}^t)| \leq w_4$
Vary $P_{Dx}^t$ using $randi$ where $0.75 \leq randi \leq 1$ to evaluate $p_{Dx,modified}^t$ where:
$P_{Dx,modified}^t = randi \times P_{Dx}^t \ \forall x \in X(.)$
Update $P_{Dx,modified}^t$ by compensating for $|P_T^t - \sum_{x=1}^{X}(P_{Dx,modified}^t)|$ by computing
$diff_x = P_{Dx}^{max} - P_{Dx,modified}^t \ \forall x \in X(.)$
Set $P_T^{t,modified} = \sum_{x=1}^{X}(P_{Dx,modified}^t)$
$P_{Dx,modified}^t = P_{Dx,modified}^t + (\frac{diff_x \times (P_T^t - P_T^{t,modified})}{\sum_{x=1}^{X}(diff_x)})$
Compute $EmiC_t^{modified}$, $F_t^{cost,modified}$ and $OP_t^{cost,modified}$
if ($OP_t^{cost,modified} \leq OP_t^{cost}$) then
    $P_{Dx}^t = P_{Dx,modified}^t \ \forall x \in X(.)$
    $OP_t^{cost} = OP_t^{cost,modified}$
end if
return $P_{Dx}^t$, $OP_t^{cost}$
```

In improving on the modified incremental generator dispatch (MEED) shown in Algorithm 1, a genetic algorithm-based economic and environmental dispatch (GA-EED) algorithm is developed and presented in Algorithm 2. The purpose for the development of GA-EED is to explore the possibility of eliminating the need for tolerance w_4 definition in Algorithm 1 to evolve dispatch options with lower operating costs.

Algorithm 2: Genetic Algorithm Economic and Environmental Dispatch (GA-EED) Algorithm.

```
Input: fuel cost for generators (Table 3), $P^t_T$,$P^{min}_{Dx}$,$P^{max}_{Dx}$
Output: $P^t_{Dx}$ $\forall x \in X(.)$
    Generate binary population matrix for each generator:
    Generate $pop_x = [dim1 \times dim2]$ for each generator $x$, where $dim1$ is the number of rows (100),
    $dim2$ is the number of columns (10) and $pop_x$ is a binary matrix.
    Perform mutation on $pop_x$:
    Mutation is performed on randomly selected bits of $pop_x$ such that
    if ($pop_x(rr, cc) == 1$) then
        $pop_x(rr, cc) = 0$
    else
        $pop_x(rr, cc) = 0$
    end if
    where $1 \leq rr \leq dim1$ and $1 \leq cc \leq dim2$ $\forall rr, cc$
    Perform conversion on $pop_x$:
    $pop_x$ is converted to its decimal equivalent matrix $pop^{'}_x = [dim1 \times 1]$ such that
    $pop^{'}_x(rr) = eval(pop_x(rr, 1 : dim2))$,
    where $eval$ is a function that converts a binary string into its decimal equivalent.
    Perform scaling on $pop^{'}_x$:
    Scaling is performed on $pop^{'}_x$ to generate the actual generator values $P^t_{Dx}$ such that
    $P^{min}_{Dx} \leq P^t_{Dx} \leq P^{max}_{Dx}$, where $P^t_{Dx} = \frac{(P^{max}_{Dx} - P^{min}_{Dx}) \times pop^{'}_x(rr)}{2^{dim2}-1} + P^{min}_{Dx}$
    Perform matching:
    In matching, a complete allocation $allot_{kk}$ is generated such that if $X = 3$,
    $allot_{kk} = [pop^{'}_1(rr_1), pop^{'}_2(rr_2), pop^{'}_3(rr_3)]$, where $rr_1, rr_2, rr_3$ are randomly selected rows of
    $pop^{'}_1, pop^{'}_2, pop^{'}_3$ respectively, such that $1 \leq (rr_1, rr_2, rr_3) \leq dim1$ and $\sum_{x=1}^{X} pop^{'}_x(rr_x) \geq P^t_T$
    Perform costing and update:
    For each $allo_{kk}$ generated, an equivalent $cost_{kk}$ is generated where $cost_{kk}$ is the cost of dispatching
    the generators at bus 1 based on the values in Table 3. In updating the optimal dispatch,
    if ($cost^{new}_{kk} < cost^{old}_{kk}$) then
        $cost^{old}_{kk} = cost^{new}_{kk}$
        $allot^{old}_{kk} = allot^{new}_{kk}$
    end if
    $OP^{cost}_t = cost^{old}_{kk}$
    return $P^t_{Dx}$, $OP^{cost}_t$
```

The degree of accuracy in terms of generating the lowest operational cost for the generators in bus 1 is dependent on the sensitivity factor sf_x. The sensitivity factor sf_x is a measure defined for each generator x as $sf_x = \frac{P^{max}_{Dx} - P^{min}_{Dx}}{2^{dim2}-1}$. Thus, as $sf_x \longrightarrow 0$, the more possible it is to evolve a wider range of possible generation values. However, care must be taken to ensure that $(2^{dim2} - 1) \gg (P^{max}_{Dx} - P^{min}_{Dx})$. Table 4 presents sf_x for each generator at bus 1.

Table 4. Generator x sensitivity factor.

x	sf_x
1	0.07
2	0.05
3	0.02

4. TLMS Modelling

The modelling of the ampacity constraints for the transmission lines was done dynamically. That is, real time (1-h interval) weather data was used in dynamically computing the limit of current that could be carried by the transmission line. The computation of the DTLR is done based on the equations described in IEEE std. 738-2006 [29]. From [29], the steady state equations are shown in Equations (12) and (13) as follows:

$$q_c + q_r = q_s + I^2 R(T_c) \tag{12}$$

such that

$$I = \sqrt{\frac{q_c + q_r - q_s}{R(T_c)}} \tag{13}$$

where q_c is heat loss from convection; q_s is the heating effect of the sun; $R(T_c)$ is the AC resistance of the conductor at temperature T_c and I is the conductor current. Out of the 14 inputs that Equations (12) and (13) depend on, five vary in real time–wind speed, wind direction, ambient temperature, time of the day and date. When these values are used without variation, Equations (12) and (13) result in STLR. For this work however, real time hourly data has been used for computing DTLR. The objective function of TLMS, Z_{TLMS} is thus described in (14) as

$$Z_{TLMS} = min(I_{line_t^p}) \tag{14}$$

subject to

$$I_{line_t^p} < Amp^t \tag{15}$$

However, an equivalent power limit has been computed based on Equation (15) and utilized in this paper.

5. HEMS Modelling

The HEMS constraint for this research work aims at achieving a reduction in consumers electricity cost for participating DR loads only. In designing the proposed electricity network, base load cost is computed using an incline block tariff (IBT) pricing scheme. However, it is not used in this paper, since emphasis is placed on the participating DR loads. The base pricing scheme utilized in measuring the performance of the dynamic pricing schemes (Price1, Price2 and Price3) is Price0 which is a time of use (TOU) pricing scheme and has a flat rate of \$0.105/kWh all through the day except for a 20% increment for the hours between 6 am–8 am and 6 pm–9 pm due to capacity constraints as a result of increased weekdays residential electricity usage during these periods. The participating DR loads are placed on direct load control (DLC) and have their dispatch time varied by the utility within the allowed time range as specified by the electricity consumer. The incentive for allowing the utility some control in varying the dispatch time of participating DR loads is to reduce the cost of these loads by using either of Price1, Price2 or Price3 to offer some minimal electricity cost differentials compared to Price0. In doing so, the utility is able to free up capacity for dispatch of base loads at critical peak demand periods and also minimize the cost of additional generation expansion. The objective function of HEMS Z_{HEMS} is described in Equation (16) as

$$Z_{HEMS} = min(dsmC_i^{h_i}) \tag{16}$$

such that

$$dsmC_i^{h_i} < touC_i^{h_i} \tag{17}$$

In achieving Equations (16) and (17), an externally constrained genetic algorithm (ExC-GA) plays a prominent role. The aim of Z_{HEMS} is to ensure that the equivalent cost of electricity using dynamic pricing ($dsmC_i^{hi}$) is always less than the equivalent cost of electricity using time of use pricing ($touC_i^{hi}$). This is achieved by comparing the difference $diff = touC_i^{hi} - dsmC_i^{hi}$. For $diff < 0$, load dispatch is recomputed. Furthermore, for any $diff_{new} > diff_{old}$ and $diff_{old} > 0$, then $diff$ is updated to $diff = diff_{new}$. The mathematical modelling of ExC-GA is presented subsequently.

5.1. *Externally Controlled Genetic Algorithm*

The proposed externally controlled genetic algorithm (ExC-GA) is a modification of the mild intrusive genetic algorithm (MIGA) proposed in [30]. Similar to MIGA, a population matrix Pop_i is generated such that the number of rows (*dim1*) of pop_i is i^{max} with the number of columns (*dim2*) given as 96 (to represent the total number of slots (a slot is a 15 min interval. For a 24 h period, there are 96 slots of 15 min interval each)). The description and working principle of ExC-GA including the modifications incorporated into MIGA is presented subsequently.

5.1.1. ExC-GA Population Matrix Filling

An initial matrix of dimension $dim1 \times dim2$ as shown in Figure 5 is created with all the values initialized to zero (i.e., $\forall P_{1,1} \quad to \quad P_{i^{max},96} \quad \in Pop_i, \quad P_{1,1} \quad to \quad P_{i^{max},96} = 0$). Since three DSM loads per household are considered for this research, three sub-populations $sub_{pop}^{i,j}$ are created. The sub-populations created are filled with the row index of pop_i as follows:

$$sub_{pop}^{i,j} = (j, incr, (i^{max} - 3 + j)) \tag{18}$$

where each $sub_{pop}^{i,j}$ is a set of values from j to $(i^{max} - 3 + j)$ with a successive difference of $incr$ between each element in $sub_{pop}^{i,j}$. $\forall \in sub_{pop}^{i,j}$, a start point $str_L^{i,j}$ and a stop point $stp_L^{i,j}$ are determined as follows:

$$\forall i, \quad and \quad j = 1, \quad \left|w^{i,j}\right| = 2 \Rightarrow 1 \leq str_L^{i,1} \leq 95 \tag{19}$$

$$\forall i, \quad and \quad j = 2, \quad \left|w^{i,j}\right| = 3 \Rightarrow 1 \leq str_L^{i,2} \leq 94 \tag{20}$$

$$\forall i, \quad and \quad j = 3, \quad \left|w^{i,j}\right| = 5 \Rightarrow 1 \leq str_L^{i,3} \leq 92 \tag{21}$$

such that

$$stp_L^{i,j} = str_L^{i,j} + w^{i,j} - 1 \quad \forall str_L^{i,j}, stp_L^{i,j} \in W(.) \tag{22}$$

The Equations (19)–(21) assume full DLC in which there are no restrictions for selection of $str_L^{i,j}$. For partial DLC, where the load cluster i specifies a range - intended start time $stt_L^{i,j}$ and latest dispatch time $std_L^{i,j}$ for a device j, then $stt_L^{i,j} \leq str_L^{i,j} \leq std_L^{i,j}$.

The incorporation of -1 in Equation (22) is to compensate for the inclusion of the start point in the counting of slots/spaces to be filled. The slots/spaces from $str_L^{i,j}$ to $stp_L^{i,j}$ are filled with the respective power values as follows:

If $j = 1, \forall i \quad DSM_j = 500$ W, similarly if $j = 2, \forall i \quad DSM_j = 700$ W and if $j = 3, \forall i \quad DSM_j = 1200$ W.

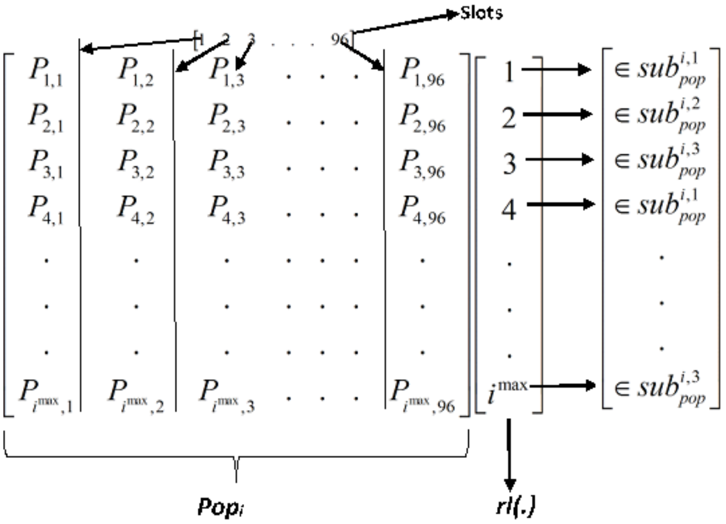

Figure 5. pop_i with its description.

5.1.2. Generation of Violation and Non-Violation Slot Sets—$stat_1^{set}$ and $stat_2^{set}$

The resulting filled population matrix pop_i as shown in Figure 6 is then cumulated column wise to obtain C_i^{DSM} for each cluster which is then added to the respective BL_i to obtain CD_i. The resulting CD_i is then passed over for load flow operations and generator scheduling operations (see Algorithms 1 and 2) to generate the violation set $stat_1^{set}$ and non-violation set $stat_2^{set}$. The violation set represents all the slots in which ampacity limit was exceeded while the non-violation set represents all the slots in which ampacity limit was not exceeded. The mathematical description of the sets is as follows:

$$stat_1^{set} = (t' | ampa_p = 1) \tag{23}$$

$$stat_2^{set} = (t' | ampa_p = 0) \tag{24}$$

Which implies that $\forall stat_1^{set}, stat_2^{set} \in W(.)$:

$$\left|stat_1^{set}\right| + \left|stat_2^{set}\right| = 96 \tag{25}$$

$$stat_1^{set} \cap stat_2^{set} = \varnothing \tag{26}$$

$$stat_1^{set} \cup stat_2^{set} = W(.) \tag{27}$$

The description of $ampa_p$ thus implies that if there is a violation of DTLR by any line p during time t' simulation, $ampa_p = 1$, with no violation implying that $ampa_p = 0$.

5.1.3. pop_i Re-Adjustments

The re-adjustments carried out on pop_i as shown in Figure 6 is based on the set to which the current t'_L belongs to. Thus, $\forall L \in rI(.)$, if $t'_L \in stat_1^{set}$, then a decision factor $decfac_{i,L}$ is determined using a random generator, $randi$, such that:

$$decfac_{i,L} = \begin{cases} 1; & if \quad randi \geq 0.2 \\ 0; & if \quad randi < 0.2 \end{cases} \tag{28}$$

Thus, for the row L with $t'_L \in stat_1^{set}$ and $decfac_{i,L} \geq 0.2$, then all elements in row L of pop_i are initialized to zero. A random start point $t'_L \in stat_2^{set}$ is selected as $str_L^{i,j}$ with $stp_L^{i,j}$ computed as shown in Equation (22). Next, the slots from $str_L^{i,j}$ to $stp_L^{i,j}$ are filled with the respective DSM_j as shown in

Figure 7 based on the $sub_{pop}^{i,j}$ to which L belongs. The resulting pop_i is then summed column-wise to compute associated costs and violations if any.

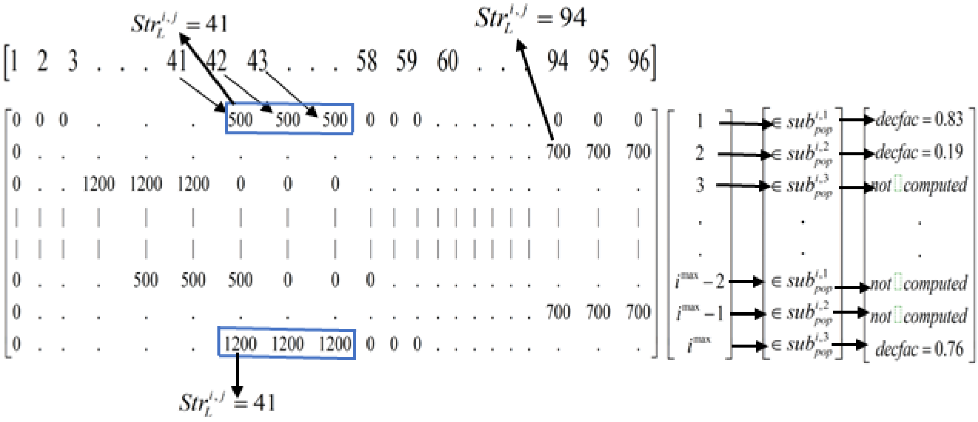

Figure 6. DSM_j load allocation in pop_i based on $str_L^{i,j}$.

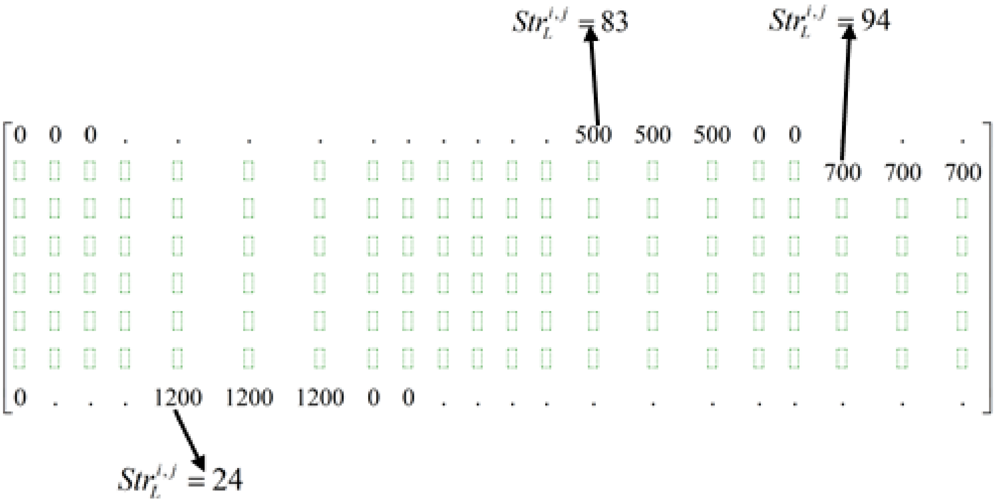

Figure 7. Re-computation of $str_L^{i,j}$ based on $stat_1^{set}$ violation.

5.2. Comfort Modelling

Given $Stt_L^{i,j}$ and $Std_L^{i,j}$ as the load cluster i intended start time and latest time for dispatch of load j, the comfort limits for these extremes are C_{max}^i and C_{min}^i. For any $Str_L^{i,j}$ such that $Stt_L^{i,j} \leq Str_L^{i,j} \leq Std_L^{i,j}$, then C^i (for any $Str_L^{i,j}$) which is the intermediate comfort and bounded as $C_{min}^i \leq C^i \leq C_{max}^i$ is defined as shown in Equation (29). For this paper, $C_{max}^i = 5$ and $C_{min}^i = 3$. The choice of C_{max}^i and C_{min}^i are arbitrary. A comfort scale from 0 to 5 is arbitrarily selected where values $0 \leq C^i < 3$ are assumed to contribute negatively to a consumer. Furthermore, for the research, $C^i \geq 3$ is assumed to be generally accepted. A reason for this assumption is to ensure that the utility in dispatching loads under DLC (full/partial) evolves $Str_L^{i,j}$ such that $|Stt_L^{i,j} - Str_L^{i,j}| \longrightarrow 0$.

$$C^i = \frac{(C^i_{max} - C^i_{min}) \times (Str_L^{i,j} - Stt_L^{i,j})}{(Std_L^{i,j} - Stt_L^{i,j})} + C^{i,j}_{min} \tag{29}$$

6. Pricing

Four pricing schemes are adopted as 'plug-ins' in this paper—1 time of use (TOU) pricing (Price0) and 3 dynamic pricing schemes (Price1, Price2 and Price3). The adopted Price0 assumes a flat rate value of US$0.105/kWh across the day with a 20% increase between the hours of 6 am–8 am and 6 pm–9 pm. Price1, Price2 and Price3 are modelled such that their daily average value is US$0.105/kWh with Price1 having peak price between 6 am–8 am, Price2 has peak price between 11 am–1 pm and Price3 has peak price between 6 pm–8 pm. The mathematical description for Price0 is shown in Equation (30) while Equation (31) is the general description for Price1, Price2 and Price3. The pricing models adopted are hypothetical and aim at curtailing demand during their peak periods. The pricing signals are further communicated to consumers within each load cluster a day ahead to enable them schedule $Stt_L^{i,j}$ for their participating DSM loads. For the purpose of this research, day ahead pricing signals is assumed to be communicated by the utility to electricity consumers via their website. The implication of this is that electricity consumers participating in DLC are assumed to be literate and familiar with information technology (IT) devices for assessing such information. This is similar to the use of the Internet in providing electricity users day ahead pricing information by ComEd in [31].

$$Price0 = \begin{cases} US\$0.126/kWh; & 6 \le t \le 8 \quad and \quad 18 \le t \le 21 \quad only \\ US\$0.105/kWh; & otherwise \end{cases} \tag{30}$$

$$\sum_{t=1}^{t=24} \frac{Price(t)}{24} = \text{US\$0.105/kWh} \tag{31}$$

Motivation for Pricing Methods Selected

The selection of Price0 is to evaluate the ability of ConCEMS in utilizing Price1, Price2 or Price3 to offer potential savings to the consumers and reduced operational costs for the electricity supplier. Furthermore, the varying pricing methods—Price1, Price2 and Price3 have been adopted to compute the extent to which savings (if any) can be offered households participating in DR when compared to Price0 option.

7. Results

The variation of ampacity for the case study network based on DTLR computations is shown for a day in Figure 8. It is seen that power (MW) equivalent of ampcity has been used. Figure 8 shows that power limit computed based on DTLR varies from about 230 MW to about 255 MW per line across the day. The variation of power in Line 1 (between bus 1 and bus 2) for all pricing options is shown in Figure 9. It is observed from Figure 9 that 1 slot (15 min) TLMS violation occurs each for both Price1 and Price0 options with no TLMS violation for Price2 and Price3 options. Assuming 50% STLR (127.5 MW limit) and utilizing Price3, violation is observed for about 74% of the slots. Similarly, for 70% STLR (178.5 MW) and using Price3, violation is observed for 25% of the slots and 9.4% of the slots for 80% STLR (204 MW) and using Price3. ConCEMS thus adopts DTLR and ensures that the transmission network can be maximized in evacuating power without the need for any significant upgrades and without any violations.

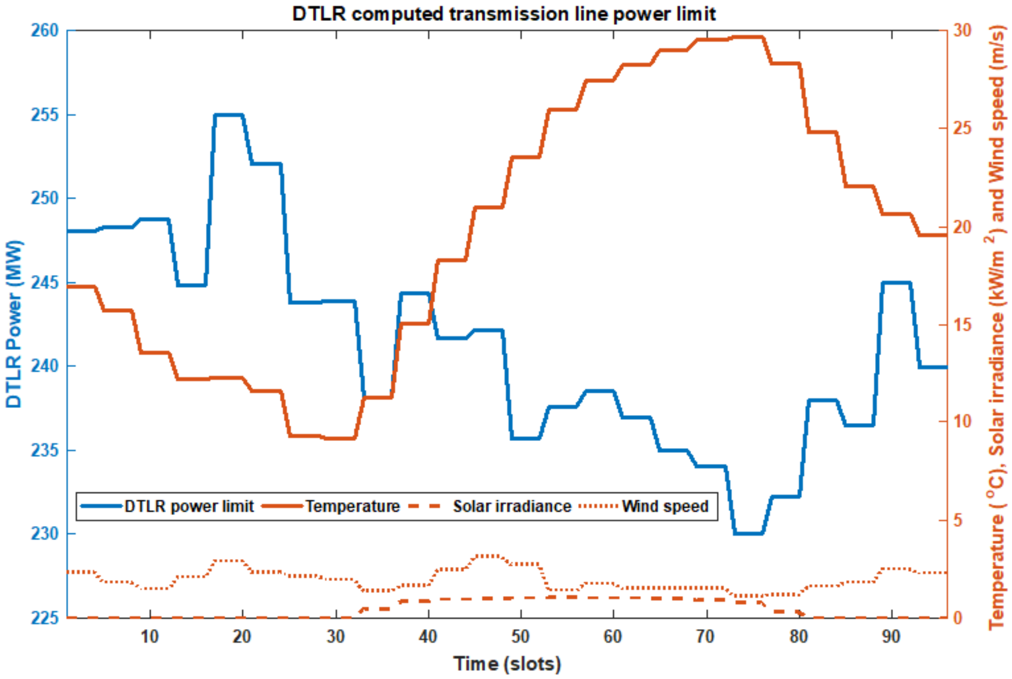

Figure 8. Dynamic thermal line power rating variation based on varying weather conditions.

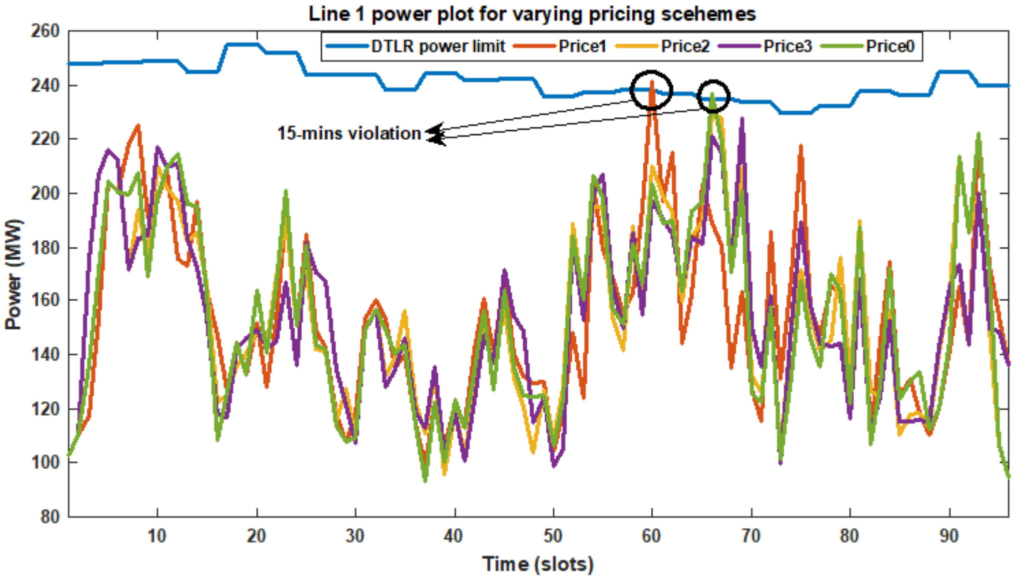

Figure 9. Line 1 power variation for all pricing options.

Figure 10 presents the various electricity pricing options adopted in this paper—Price1, Price2, Price3 and Price0 across the day While Figure 11 presents the total power supplied from the slack bus (bus 1) across the day. It is observed from Figure 11 that the total power supplied from the slack bus was within the limits set by the generators (lower limit of 90 MW and upper limit of 240 MW).

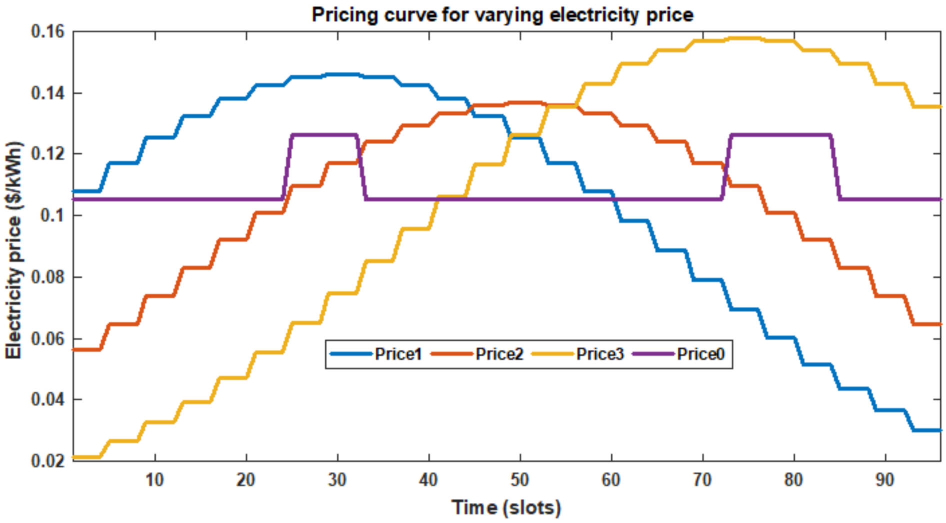

Figure 10. Daily profile for the various electricity pricing schemes.

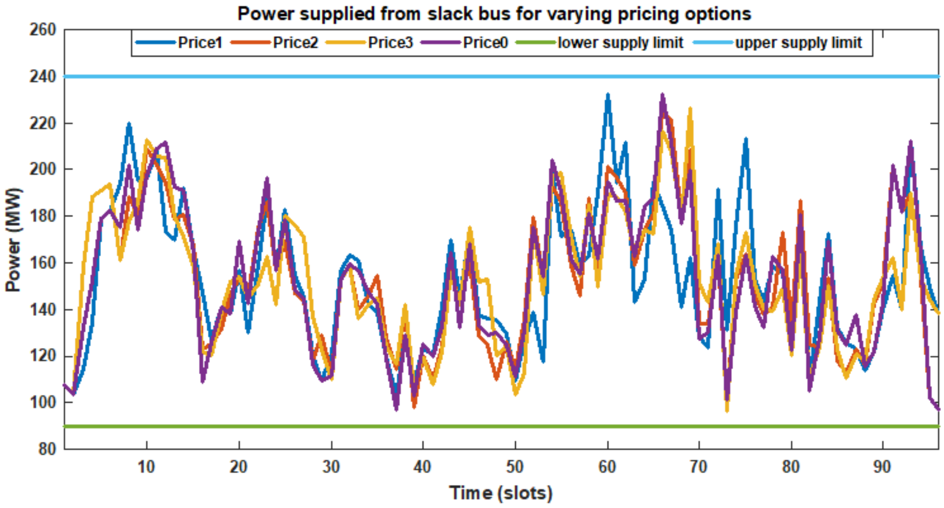

Figure 11. Daily profile for power supplied from slack bus (bus 1).

Figure 12 presents the dispatch of the DR loads under partial DLC for Price1 (DSM1), Price2 (DSM2), Price3 (DSM3) and Price0 (DSM0). It is observed that the DR loads are not able to sufficiently follow their pricing curves due to restraints placed by the users. The restraints in terms of time range within which participating DR loads must be dispatched thus limit the ability of ConCEMS to fully exploit periods of low electricity prices in dispatching participating DR loads. For the DR loads only, Price1 option billed electricity users US$67,243.10 compared with US$66,963.72, US$65,724.62 and US$68,172.06 for Price2, Price3 and Price0 respectively. The implication of this is that the Price3 option achieves a 3.6% reduction in electricity bills for the consumers over Price0 compared to 1.4% and 1.8% savings using Price1 and Price2 respectively. Furthermore, using Price3, load clusters can utilize the additional daily savings of US$2447.44 (over Price0) to purchase additional 19.42 MWh of electricity units at US$0.126/kWh. ConCEMS in utilizing Price3 thus enables consumers extend the usage of owned electrical appliances through savings earned from participating DR loads. ConCEMS also shows that further savings can be achieved for households when DR loads are placed on full DLC (as already shown in [9]), thus highlighting the ability of the proposed ConCEMS to mitigate energy poverty by reducing the energy burden of households.

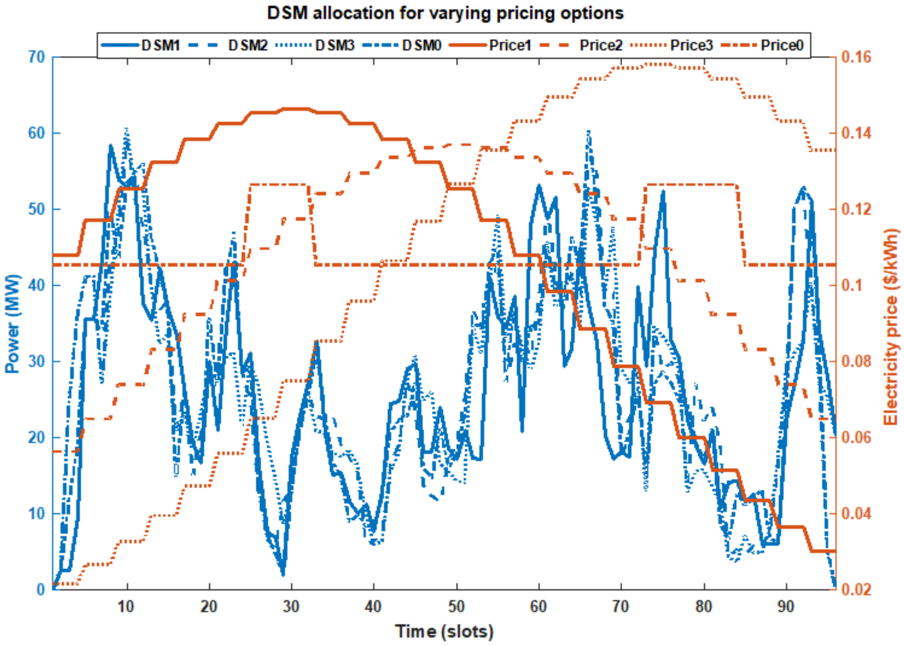

Figure 12. Price1 (DSM1), Price2 (DSM2), Price3 (DSM3) and Price0 (DSM0) DR dispatch profile.

The utilization of GA-EED and MEED algorithms shown in Algorithm 2 and Algorithm 1 respectively is to highlight the robustness of the ConCEMS framework in incorporating varying stochastic and classical optimization schemes in minimizing the associated operations and environmental costs for the supply side. However, in benchmarking the results obtained using GA-EED and MEED algorithms, a standard particle swarm optimization (PSO) algorithm is also utilized to solve a single dispatch problem with the results obtained compared with those from the proposed algorithms (GA-EED and MEED) in this paper. Table 5 presents the values obtained for each method over five trials which is then averaged. It is observed from Table 5 that the fastest algorithm is the MEED algorithm which achieves an average run time of 0.28 s compared to 3.37 s and 8.82 s for GA-EED and PSO respectively. The comparison of the total daily simulation time for Price1, Price2, Price3 and Price0 using GA-EED shows that Price1 achieves a simulation time of 14.23 s, Price2 achieves a simulation time of 13.80 s, Price3 achieves a simulation time of 11.66 s while Price0 achieves a simulation time of 13.61 s. However, GA-EED achieves the lowest operational cost of US$8224.00 compared to US$8238.60 and US$8414.81 for MEED algorithm and PSO respectively. In terms of surplus generation, MEED algorithm generates 100.01% of the required demand compared to 100.10% and 102.68% of the required demand by GA-EED and PSO.

Table 6 further presents the supply cost (the supply cost computed and shown in Table 6 incorporates the compressor cost) for the various pricing options (Price1, Price2, Price3 and Price0) and different optimisation algorithms (MEED, GA-EED and PSO). Similar to Table 5, GA-EED offers the lowest operations cost for supply side for all pricing options compared to PSO and MEED with Price3 offering the lowest cost of US$531,807.80 and US$542,361.61 for GA-EED and MEED respectively, and Price1 offering the lowest supply cost of US$532,200.80 for PSO. The utilization of the compressors at the outlet point for optimal flow of gas at reduced compressor usage cost for Price3 using GA-EED is shown in Figure 13. Also depicted in Figure 13 is the suction and discharge pressure for each slot (15 min interval) at the outlet/tapoff-point which is maintained within constrained limits.

Table 5. GA-EED, MEED and PSO dispatch profile for 225 MW.

Method	Tries	Cost (US$)	Time (S)	Surplus Generation (MW)	Dispatch Profile (MW)		
					Gen 1	Gen 2	Gen 3
GA-EED	1	8194.8	3.6209	0.19	94.63	81.4	49.16
	2	8219.67	1.6099	0.03	85.62	89.78	49.63
	3	8216.61	2.685	0.45	91.11	84.95	49.39
	4	8216.51	3.072	0.48	89.5	86.08	49.9
	5	8272.43	5.945	0.01	89.94	90	45.07
Average		8224	3.39	0.23	90.16	86.44	48.63
PSO	1	8414.81	8.7653	6.04	95	86.04	50
	2	8414.81	8.7563	6.04	95	86.04	50
	3	8414.81	8.9277	6.04	95	86.04	50
	4	8414.81	8.8108	6.04	95	86.04	50
	5	8414.81	8.8422	6.04	95	86.04	50
Average		8414.81	8.8205	6.04	95	86.04	50
MEED	1	8237.67	0.2744	0	80	95	50
	2	8238.77	0.2944	0.03	80.03	95	50
	3	8238.74	0.2784	0.03	80.03	95	50
	4	8240.13	0.2676	0.07	80.07	95	50
	5	8237.67	0.3026	0	80	95	50
Average		8238.6	0.28	0.03	80.03	95	50

Gen—Generator.

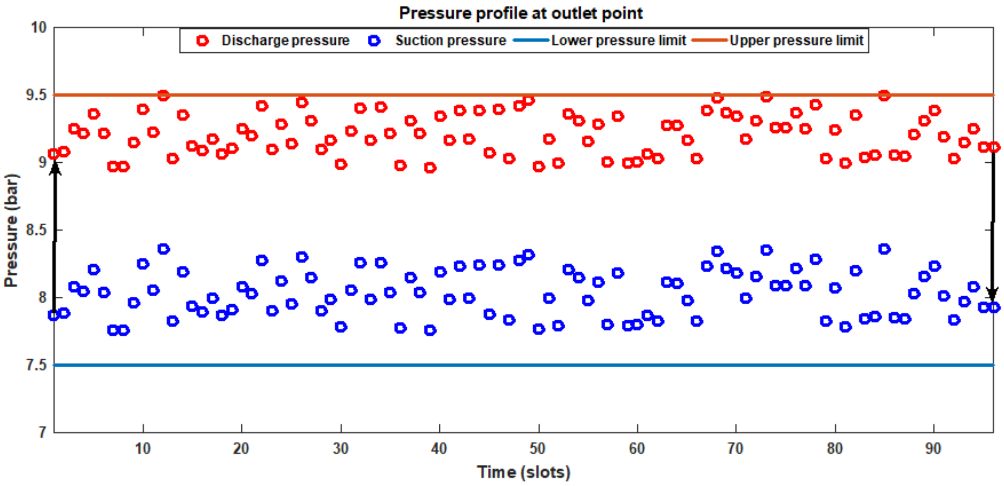

Figure 13. Price3 pipeline pressure profile at tapoff-point.

Table 6. Supply cost (US$) for various optimisation algorithms.

Option	Optimisation Algorithms			Violations	Duration (Slots)
	GA-EED	MEED	PSO		
Price1	531937.93	543211.98	532200.8	1	1
Price2	532183.92	543636.61	533491	0	- [a]
Price3	531807.8	542361.61	533032.2	0	- [a]
Price0	532717.88	544211.98	533880.3	1	1

a—Implies not applicable since no violation occurs.

A further implication of ConCEMS to the utility is that ConCEMS enables the utility reduce the associated costs of expanding generation capacity to meet demand. With ConCEMS, flexible loads can be effectively dispatched at reduced peak demand and with increased capacity utilization. Furthermore, increased flexibility in the network through DLC (full or partial) provides the utility with advanced information for system operation and planning, scheduling maintenance and dealing with outages. With increased flexible loads under DLC, the utility is able to respond better in establishing optimal grid operation in the event of faults or loss of a generating unit.

Table 7 presents $Str_L^{i,j}$ for each cluster on bus 2 and for the various pricing options while Table 8 presents the computed comfort C^i for each cluster which has been evaluated using Equation (29). It is observed from Table 8 that Price3 option offers the highest comfort of 4.21 followed by Price2 (4.19), Price0 (4.06) and Price1 (4.04). In summary therefore, Price3 utilizing GA-EED meets all the requirements by reducing the electricity cost for participating DR loads and supply cost of the supply side without violating the transmission line power limit constraint. This is shown in Table 9 where Price3 with GA-EED in addition to meeting HEMS, TLMS and SSEMS constraints further improves on the comfort of participating households by ensuring that $Str_L^{i,j}$ strives to be close to $Stt_L^{i,j}$. Table 10 presents the results obtained from further benchmarking of GA-EED against nine standard benchmarking functions from [32]. The performance of GA-EED in matching the exact solutions is also observed.

Table 7. Dispatch time $Str_L^{i,j}$ for DR loads of various pricing options on bus 2.

Bus	**Cluster**	$Stt_L^{i,j}$	$Std_L^{i,j}$	**Price1**	**Price2**	**Price3**	**Price0**
2	1	1	5	5	5	5	5
	2	89	93	91	90	90	91
	3	54	74	59	59	59	59
	4	44	64	64	64	64	64
	5	2	6	2	2	2	2
	6	46	66	52	52	52	52
	7	69	89	78	73	73	78
	8	40	84	76	76	76	76
	9	3	7	4	3	3	4
	10	4	48	14	14	9	9

Table 8. Comfort C^i for each pricing option for $Str_L^{i,j}$ on bus 2.

Bus	**Cluster**	**Price1**	**Price2**	**Price3**	**Price0**
2	1	3	3	3	3
	2	4	4.5	4.5	4
	3	4.5	4.5	4.5	4.5
	4	3	3	3	3
	5	5	5	5	5
	6	4.4	4.4	4.4	4.4
	7	4.1	4.6	4.6	4.1
	8	3.36	3.36	3.36	3.36
	9	4.5	5	5	4.5
	10	4.55	4.55	4.77	4.77
	Average	4.04	4.19	4.21	4.06

Table 9. Performance summary for various dynamic pricing options using GA-EED and MEED.

	GA-EED			**MEED**			C^i
	HEMS	**SSEMS**	**TLMS**	**HEMS**	**SSEMS**	**TLMS**	
Price1	√	√	X	√	√ ^{b}	X	X
Price2	√	√	√	√	√	√	√
Price3	√ ^{b}	√ ^{b}	√	√ ^{b}	√	√	√ ^{b}

b—Best option.

Table 10. Further benchmarking of GA-EED from [32].

Number	Name of Function	Range	D	Type	Minimum	Minimum (GA-EED)
1	Beale	[−4.5, 4.5]	2	UN	0	3.12E-05
2	Matyas	[−10, 10]	2	UN	0	3.82E-06
3	Bohachevskyl	[−100, 100]	2	MS	0	2.53E-04
4	Bohachevsky2	[−100, 100]	2	MN	0	6.99E-04
5	Bohachevsky3	[−100, 100]	2	MN	0	7.04E-04
6	Booth	[−10, 10]	2	MS	0	3.45E-05
7	Six Hump Camel Back	[−5, 5]	2	MN	−1.03163	−1.03160
8	Easom	[−100, 100]	2	UN	−1	−0.99647
9	Schaffer	[−100, 100]	2	MN	0	1.22E-07

D—Dimensions; U—unimodal; N—non-seperable; M—multimodal; S—seperable.

8. Policy Discussions

ConCEMS pioneers the full synergy of HEMS, TLMS and SSEMS by extending the model presented in [9]. As a smart grid architecture that depends on an advanced metering infrastructure (AMI), ConCEMS has benefits extending from the socio-economic to the techno-environmental aspects of society which are subsequently discussed.

8.1. Policy Discussions on the Impact of ConCEMS on the Socio-Economic Aspect of Society

A growing concern in the global south is the issue of energy poverty which presents on two frontiers—access and mobility (ability to transit from a lower energy level to a higher energy level). Furthermore, in the works of [33,34], declining electricity consumption (per capita) has been highlighted for Nigeria and South Africa respectively. A prominent reason for this has been increasing electricity tariff which has resulted in the increasing use of alternative energy sources. Furthermore, [34] has highlighted the direct link between energy poverty and economic poverty. The increasing tariffs by Eskom (Eskom is the electricity utility company for South Africa generating over 90% of electricity consumed in South Africa and 45% of electricity consumed in Africa [33]) are intended to recoup electricity network expansion costs especially in building new generation plants and improving the transmission network to prevent a repeat of the power crisis of 2008. However, according to [33], there is the possibility of planned supply capacity exceeding demand forecasts by over 500% due to declining consumption of electricity. ConCEMS obviates the need for unnecessary upgrades by ensuring that flexible consumers (DR loads) are well incorporated into the overall system mix to act as deferrable loads that offer some flexibility to the system operator in ensuring demand-supply balance. Incorporating dynamic pricing schemes (Price1, Price2 and Price3), the utility is able to guarantee households a reduction in their electricity bills. This reduced expenditure on electricity offers households the possibility of either increasing consumption of more electricity or utilizing the savings accrued on other activities capable of improving their quality of life (QoL). Overall, with increasing participation of more households in DR, the utility is able to save on expansion costs and also utilize effectively renewable energy sources (RES) by dispatching DR loads to times of high availability of RES.

8.2. Policy Discussion on the Techno-Environmental Impact of ConCEMS

The increasing complexity of electricity network raises concerns as to the ability of evolving electricity networks to handle the bi-directional flow of energy with increasing prosumers (consumers who also produce electricity through on-site mini generation schemes) and DR loads. Furthermore, the increasing participation of RES and their stochasticity raises issues of reactive power compensation and grid stability. ConCEMS in ensuring that the technical constraints are met utilizes increasing DR loads in balancing the grid. However, the extent of flexibility in ensuring grid stability through the utilization of flexible loads is based on the time allowance given the utility by the consumers. In [9], the proposed energy management system minimized peak DSM window by over 63% with an overall capacity utilization of 87.92% when the utility was fully in control of determining the start and eventual dispatch time of participating DR loads. Worldwide, there have been growing concerns to the insidious effect of fossil-based electricity generation on climate. The incorporation of GA-EED optimizes the dispatch of the participating generators to minimize the overall cost (operations and environmental). Furthermore, the increasing participation of flexible loads implies that ConCEMS in optimizing their dispatch time to periods of availability of RES can maximize the usage of available RES thus reducing environmental costs associated with conventional generation schemes.

8.3. Summary and Applicability of ConCEMS

ConCEMS has been presented as a tool capable of mitigating energy poverty and minimizing grid expansion. This is mostly important especially for developing economies (sub-Saharan Africa, SSA) where socially just power systems are required in order to facilitate the promotion of access to electricity without marginalizing the poor [35]. Considering the fact that ConCEMS integrates every aspect of the electricity network and achieves savings, the following arise:

1 The utilization of DTLR reduces transmission expansion costs which leads to stabilization of electricity tariffs for electricity users. In South Africa, Eskom's electricity tariff increment (to recoup supply capacity costs) has resulted in declining electricity consumption [33]. With stabilized electricity costs, the energy burden of households is minimized.

2 The ability of ConCEMS to guarantee savings for households participating in DR (for participation of 3 devices only) shows that more savings could be accrued when more energy consuming devices especially heating, ventilation and cooling (HVAC) devices are considered. A reduction in electricity bills for households (whose electricity bills have already been stabilized due to the incorporation of DTLR) leads to even further reduction in households energy burden.

3 ConCEMS has shown that flexible loads offer the utility great flexibility which is capable of minimizing supply capacity expansion. With greater flexibility offered the utility especially through greater participation in DR and DLC, the utility is able to minimize expansion costs and reduce spinning reserves without compromising on grid constraints (investigated in [33]). The implication of this implies that electricity tariffs remain stabilized which leads to minimized energy burden of households.

4 ConCEMS also offers a great platform for increasing the exploitation of renewable energy sources (RES) thereby leading to a reduction in emissions. With greater flexibility offered the utility in terms of controllable loads, the utility is able to effectively dispatch participating DSM loads to periods of availability of RES.

ConCEMS depends on an integrated electricity network the core of which is an advanced metering infrastructure (AMI) and a robust transmission network to guarantee its effective deployment and utilisation. For SSA, the need for infrastructure upgrades coupled with the growing calls for reduction in emissions presents an opportunity for SSA countries to develop grids that promote integration across the entire electricity chain.

9. Conclusions

ConCEMS has been presented and evaluated for an IEEE 30-bus network with an externally constrained genetic algorithm (ExC-GA) also designed and used in demand response load dispatch. Two economic and environmental dispatch algorithms for generators on bus 1—GA-EED and MEED have also been developed, applied and benchmarked using a standard PSO. In evaluating the ability of ConCEMS in meeting the objectives of HEMS, TLMS and SSEMS, three dynamic pricing schemes (Price1, Price2 and Price3) have been proposed and benchmarked with a time of use pricing scheme (Price0). Price3 has been found to reduce both the electricity cost of participating DR loads and the operational costs of the supply side without violating the transmission line power limit. Furthermore, Price3 with GA-EED has been found to ensure that the eventual dispatch time ($Str_L^{i,j}$) of participating DR loads is close to the intended start time ($Stt_L^{i,j}$) of the loads by the users. This has been verified by the high value of comfort (C^i) which is about $0.84C^i_{max}$. Policy discussions on the impact of ConCEMS on the socio-economic and techno-environmental aspect of society have also been presented to show that ConCEMS is also a capable tool in mitigating energy poverty by minimizing tariff increment through the maximized use of RES and available supply capacity, thus minimizing capacity upgrades. This has been elaborated by the ability of ConCEMS to offer the utility flexibility in varying the dispatch time of participating DR loads to reduce peak demand and maximize transmission network and supply capacity. However, it must be highlighted that ConCEMS is limited based on the degree of participation of DR loads and flexibility (in terms of dispatch time) offered the utility by the consumers. With strict time frames for load dispatch, partial DLC and the need to ensure that $|Stt^{i,j}_L - Str^{i,j}_L| \longrightarrow 0$, ConCEMS offers the utility a limited window of flexibility. However, when consumers participate in full DLC, ConCEMS is able to offer the utility higher flexibility in maximizing benefits for both the consumer and the supplier. Results obtained thus show that the extent of performance of ConCEMS in meeting the objectives of HEMS, SSEMS and TLMS is determined by the nature of the pricing profile selected and the size and flexibility of participating DR loads. In terms of general applicability, the proposed ConCEMS can be applied widely for both industrial and household DR scheduling optimisation purposes since the pricing schemes are 'plug-ins'. Furthermore, the proposed GA-EED has been benchmarked and found to outperform the contemporary MEED and conventional PSO in achieving the best results. ExC-GA has also been seen to offer $Str^{i,j}_L$ that ensure a high comfort level for consumers while guaranteeing a reduction in electricity cost for consumers.

10. Future Work

Considering the ability of ConCEMS to provide some flexibility to the utility especially in reducing peak demand and increasing utilization of the transmission network through DTLR, future research would aim at exploiting the ability of ConCEMS to still guarantee reduced electricity bills for consumers and optimal grid operation in the event of faults. Future work thus aims at determining the limit of ConCEMS to guaranteeing the objectives of HEMS, SSEMS and TLMS under dynamic network faults.

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Abbreviations

The following abbreviations are used in this manuscript:

t	hourly time
t'	quarterly hourly time
p	line number
x	index of each generator
X	total number of generators
X(.)	set of all generators index points
STT	Simulation Start Time, taken to be 00:00 i.e., midnight
SET	Simulation End Time, taken to be 00:00 + 1 day i.e., midnight of next day
w_3	conversion factor of P^t_{Dx} to energy value
w_4	tolerance for generation/demand mismatch
λ^t_x	incremental cost of generator x at time t
λ^t	incremental cost of generation at time t
randi	random number generator

k	originating node/bus point
z	connected node/bus point to k
N	total number of nodes
i	index of load cluster
i^{max}	number of demand side loads for each i load cluster
j	index of demand side load
J(.)	set of all demand side load index points
$w^{i,j}$	load j index of slots for load cluster i
W(.)	set of all slot index points
$\eta(w^{i,j})$	load j number of slots for load cluster i
$rI(.)$	set of all row index of pop_i
L	index of row of pop_i
$ampa_p$	DTLR violation status for line p
C_i^{DSM}	set of t' cumulative DR value for load cluster i
CD_i	set of t' total demand value for load cluster i
Amp^t	time t ampacity limit (A)
$I_{line_t^p}$	current through line p at time t (A)
P_{Dx}^t	generator x loading at time t (MW)
$C_x^{cost,t}$	cost of generating P_{Dx}^t by generator x at time t (US$/MWh)
Emi_x	emission rate for generator x (kg/MWh)
Emi_x^t	emission from each generator x at time t (kg)
$E_{x,t}^{cost}$	generator x emissions cost at time t (US$)
$EmiC_t$	total emissions cost at time t (US$)
F_t^{cost}	operations cost at time t (US$)
OP_t^{cost}	total time t cost of generation by all generators (US$)
P_T^t	time t total power demand (MW)
P_T^{t-1}	time (t-1) total power demand (MW)
P_{Dx}^{t-1}	time (t-1) loading on each generator x (MW)
P_{Dx}^{max}	maximum generation capacity for each generator x (MW)
P_{Dx}^{min}	minimum generation capacity for each generator x (MW)
$P_{Dx,modified}^t$	P_{Dx}^t computed when influenced with randi (MW)
$EmiC_t^{modified}$	$EmiC_t$ computed using $P_{Dx,modified}^t$ (US$)
$F_t^{cost,modified}$	F_t^{cost} computed using $P_{Dx,modified}^t$ (US$)
$OP_t^{cost,modified}$	Op_t^{cost} computed using $EmiC_t^{modified}$ and $F_t^{cost,modified}$ (US$)
DR	Demand response
DSM_j	power value (W) for DSM load j
TOU	Time of Use pricing
h_i	index of each customer for load cluster i
$dsmC_i^{h_i}$	total cost of electricity (US$) for customer h_i in load cluster i using dynamic pricing
$touC_i^{h_i}$	total cost of electricity (US$) for customer h_i in cluster i using time of use pricing
α	pipeline section
θ	compressor station
Z_α	α compressibility ratio
$P^{hg,\alpha}, P^{lo,\alpha}$	α upper and lower pressure limits (bar)
$PS_{\alpha-1}$	compressor θ suction pressure (bar)
PD_α	compressor θ discharge pressure (bar)
Q_α	α gas flow rate (MMSCFD)
$Z(t)$	Total cost of running all compressors at time t (US$)
$C^\theta(t)$	compressor θ energy cost at time t (US$)
L_α	α pipeline length (km)
$I_{line_t^p}$	current through line p at time t (A)
Z_{SSEMS}	Supply side energy management system objective function
Z_{TLMS}	Transmission line management system objective function
Z_{HEMS}	Home energy management system objective function

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CHAPTER 6

PAPER 5 - BLM-HEMS MODELLING

Brief summary

This chapter presents the paper entitled ***A Biased Load Manager Home Energy Management System for Low-cost Residential Building Low-income Occupants***. This chapter localizes DSM to the household level by designing a load manager (BLM-HEMS) for a grid connected low/middle income household with a solar PV/battery system. Beyond the higher-level optimisation (CEMS and ConCEMS), BLM-HEMS ensures that households adopting RES into their energy mix can derive optimum benefits of overall electricity cost reduction and RoI. Sensitivity analysis is further carried out for varying electricity tariff to inform policy decision on electricity pricing that will provide households a motivation to adopt RES into their electricity supply mix.

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A biased load manager home energy management system for low-cost residential building low-income occupants

Chukwuka G. Monyei [a, b, *], Aderemi O. Adewumi [a], Daniel Akinyele [c], Olubayo M. Babatunde [d], Michael O. Obolo [b], Joshua C. Onunwor [e]

[a] *Applied Artificial Intelligence Research Unit, School of Mathematics, Statistics and Computer Science, University of KwaZulu-Natal, Westville Campus, Private Bag X54001, Durban 4000, South Africa*
[b] *Gidia Oaks Centre for Energy Research, Lagos, Nigeria*
[c] *Department of Electrical and Computer Engineering, Elizade University, Ilara-Mokin, Ondo State, Nigeria*
[d] *Department of Electrical and Electronics Engineering, University of Lagos, Nigeria*
[e] *Department of Electrical and Electronics Engineering, Covenant University, Ota, Ogun State, Nigeria*

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ABSTRACT

This research paper presents the development of a biased load manager home energy management system for low-cost residential building occupants. As a smart grid framework, the proposed load manager coordinates the operation of the inverter system of a low cost residential apartment consisting of rooftop solar photovoltaic panels, converter and battery, and provides a platform for discriminating residential loads into on-grid and off-grid supply classes while maximizing solar irradiance for optimum battery charging and improving consumer comfort from base levels. Modelled in a Matlab simulation environment, the system incorporates a converter system for maximum power point tracking using a hopping algorithm, with a dedicated mechanism for smart dispatch of specified loads to meet the users' comfort based on the priority ranking of the loads. Results obtained indicate a 34% reduction in electricity cost, 26% reduction in carbon emissions and a 4% increase in comfort level for the photovoltaic/battery/utility option compared to the utility only option. The results further show that cost is a major factor affecting the users' comfort and not necessarily dispatch of appliances to meet energy needs. The research can be useful for encouraging the adoption of the photovoltaic/battery/utility option by low/middle income energy users in developing countries.

1. Introduction

Energy (electricity) access is still a major problem for over 800 million people in sub-Sahara Africa (SSA) and South Asia. In Nigeria, over 80 million people are still without access to grid electricity. Various reasons have been attributed to the inability to extend the grid and increase electricity access; cost of grid expansion, ageing transmission networks, mounting debts and poor generation. In arguing on the need for increase in electricity access, its impact on the socio-economic life of consumers has been highlighted with energy (electricity) poverty linked to actual poverty. Electricity access has also been opined to be a major factor that determines the level of success of the millennium development goals (MDGs) [1]. The sustainable development goals (SDGs) as a successor to the MDGs has goals 7 and 11 aimed at ensuring affordable and clean energy and building sustainable cities and communities. In achieving goals 7, electricity access to affordable and clean energy is being targeted to reduce emissions and make cities safe and sustainable (goal 11) by 2030 [2].

Solar home systems (SHSs) have been a much-researched alternative proposed for off-grid and on-grid homes. In Brazil for example, a study on the economic and technical advantage of domestic solar hot water systems (DSHWS) was conducted in Ref. [3] where it was discovered that annual savings on electricity bills was

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* Corresponding author. Applied Artificial Intelligence Research Unit, School of Mathematics, Statistics and Computer Science, University of KwaZulu-Natal, Westville Campus, Private Bag X54001, Durban 4000, South Africa.
E-mail addresses: chiejinamonyei@gmail.com (C.G. Monyei), adewumia@ukzn.ac.za (A.O. Adewumi), daniel.akinyele@elizadeuniversity.edu.ng (D. Akinyele), olubayobabatunde@gmail.com (O.M. Babatunde), michaeldammy@ymail.com (M.O. Obolo), joshuaonunwor@yahoo.com (J.C. Onunwor).

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Table 1
Absolute poverty measure for selected Nigeria states [7].

State	Geo-political zone	Poverty measure (%)	
		2003/2004	2009/2010
Lagos	South-west	69.4	40.3
Abia	South-east	40.9	50.2
Katsina	North-west	72.9	77.6
Edo	South-south	53.6	64.1
Kogi	North-central	91.8	67.4
Borno	North-east	59.8	60.6

Table 3
Frequency of blackouts across the geo-political zones [9].

Region	Never	Everyday	Several times a week
North-central	3.3	63.5	26.6
North-ease	1.5	71.3	23.6
North-west	5.0	71.5	17.6
South-east	1.4	60.2	29.1
South-south	3.1	49.5	26.0
South-west	4.4	49.0	41.2

about 38%. Similarly, [4] conducted a survey across Uganda and Kenya where it was discovered that the adoption of solar PV systems has led to reduced usage of kerosene (for lighting) and reduction in phone charging outside of homes. In a review work by Ref. [5], the utilization of solar thermal collectors vary across regions with major uses including district heating, process heating, swimming pool heating etc. As a scalable alternative, homes could purchase configurations of photovoltaic (PV) panels, batteries, converters and inverters that meet their specifications (cost, capacity, number of supply days without sunshine etc.). Studies have also been conducted on the integration of SHSs with the conventional grid for offsetting peak loads leading to feed-in-tariffs (FiTs) systems that compensate consumers for electricity sold to the grid [6]. In managing these SHSs, various home energy management systems (HEMs) have also been proposed. While the incorporation of SHSs in developed economies (Europe, North America, Australia, Singapore, Japan) is mainly to improve the penetration of renewable energy and robustness of the electricity grid in the developed economies, it serves a different purpose in Nigeria. Due to the peculiarity of electricity supply in Nigeria (frequent blackouts and grid collapse, low grid coverage network, ageing generation, transmission and distribution network, low number of metered households etc.), SHSs is often deployed as an alternative to grid supply.

Based on the study in Ref. [7], about 69% of Nigerians are poor (using the baseline of 55000 Naira, $180.33 yearly income). Table 1 presents the absolute poverty measure for 2003/2004 and 2009/2010 across Nigerian states cutting across the geo-political zones in Nigeria. The baseline yearly earning used in 2003/2004 was about 29000 Naira ($95.08). The breakdown of the average monthly expenditure of households in the different geo-political zones within Nigeria on gas, electricity, petrol and diesel is presented in Table 2 [8] while Table 3 presents a summary on the frequency of electricity blackouts across the geo-political zones in Nigeria [9].

Across the states of interest, expenditure on electricity monthly constitutes 4.42% (Abia), 2.03% (Borno), 4.7% (Edo), 2.78% (Katsina), 2.76% (Kogi) and 5.9% (Lagos) of the total monthly expenditure of households. The percentage values however must not be used in ranking states. This is because, in actual monetary terms, purchasing power and actual expenditure of households vary across the geo-political zones. For example, while households in Lagos spent 13105 Naira ($43) monthly on electricity, it was 9972 Naira ($33) in Abia, 8152 Naira ($27) in Edo, 5401 Naira ($18) in Kogi, 2216 Naira ($7) in Borno and 2667 Naira ($9) in Katsina. In the use of alternative electricity sources, Lagos state (considering our states of interest) has over 26% of its households having generator as an alternative [10] with only 68% of its households using the grid as their only source of electricity. Solar PV penetration for Lagos according to [10] is put at 0.2% of its population. The consequence of the high penetration of petrol and diesel generators within Lagos is high carbon footprint since it has been generally established that the residential and building sector accounts for over 40% of global energy consumption [11].

The advent of SHSs has inadvertently increased discussions and research on HEMs due to the increasing need to match supply with demand. Owing to the variability and stochastic nature of weather elements, HEMs have proven to be a viable platform for ensuring that SHSs are well utilized to guarantee consumer comfort and satisfaction. An energy flow management algorithm was presented in Ref. [11] for a grid-connected PV system that incorporated battery storage while [12] designed and tested a HEMs integrating a learning prediction algorithm that was based on neural-network for forecasting power production of a house's solar PV plant and its power consumption across a time span. The effect of sending feedback on previous energy consumption to households was also evaluated by comparing consumption drop/increase across a time frame in Ref. [13] where a 3.4% drop in energy (electricity) consumption was observed. Data error impact on HEMs was studied in Ref. [14] while [15] presented a conceptual distributed integrated energy management (diEM) system for residential buildings. The aim of [15] is to minimize operational energy cost for households through load shifting to maximize renewable energy power produced. A life cycle assessment was conducted by Ref. [16] where the environmental impact of HEMs in terms of their potential benefits and detrimental impacts was evaluated. A negative energy payback time was computed for home automation devices due to the energy consumption of smart plugs. Foresee™ was presented by Ref. [17] as a user-centred HEMs for optimizing its operations to achieve efficiency and utility cost savings. Abushnaf et al. in Ref. [18] made extensive arguments on the ability of HEMs to optimize residential building energy use especially in tackling the problems of greenhouse gas emission and energy wastage. Further reading on HEMs can be found in Ref. [19].

The objectives of HEMs vary. For example, in Ref. [20], a project is presented to increase the monetary value of photovoltaic (PV) solar production for residential application with the aims of reducing the cost of electricity and improving the local utilisation of solar PV. Also, in Ref. [21], game theory was used in formulating an energy consumption scheduling game to minimise energy costs and reduce the peak-to-average ratio of the total energy demand.

Table 2
Average monthly household expenditure (Naira) on gas, electricity, petrol and diesel by geo-political zone [8,9].

	North-central	North-east	North-west	South-east	South-south	South-west
Gas	300	103	179	807	2890	617
Electricity	5401	2216	2667	9972	8152	13105
Petrol	14233	4688	10393	10895	18019	18516
Diesel	597	351	436	787	538	2659

Similarly, in Ref. [22], the objective of HEMs was improved well-being/comfort while [23] describes the development of a control system for demand-side management in the residential sector with the incorporation of embedded generation. The utilization of car battery discharging in achieving peak shaving was studied in Ref. [24] with up to 64% reduction in peak demand achieved. In Ref. [25], the problem of optimally scheduling a set of appliances at the end user premises for a reduction in electricity cost while taking into consideration such factors as comfort and timeliness was solved, while reduced cost and optimized consumption pattern were the objectives of HEMs in Ref. [26]. Also, HEMs sought to optimize consumption and improve well-being in Ref. [27], while reduced cost, emissions and optimized consumption were the objectives of HEMs in Ref. [28]. Furthermore, various scheduling approaches have been reported in literature. For example in Ref. [29], simple linear programming was used for an optimisation model in adjusting the hourly load level for a given consumer in response to hourly electricity price. The aim was to maximize the utility derived by the consumer subject to a minimum daily energy consumption level. Also, simple linear programming was also applied in Ref. [30] to achieve a trade-off between minimizing the electricity payment and minimizing the waiting time for the operation of each appliance in a household under real time pricing. A modified and mild intrusive genetic algorithm (MMIGA) was applied in Ref. [31] for the optimal allocation of load in an off-grid household while MMIGA was applied in Ref. [32] for optimally scheduling appliances for a grid connected house considering the user preference. In Ref. [33], a constrained multi-objective optimisation problem (CMOP) is formulated and solved using evolutionary algorithms (EAs).

The localization of HEMs in Nigeria has been extensively researched in literature. In Ref. [31], the authors designed a load manager for optimizing the dispatch available solar PV power among competing loads for an off-grid house. While the proposed load manager aimed at optimizing available power, issues such as comfort and relevance of dispatched goods to overall user satisfaction were not considered. An improvement was provided in Ref. [32] where the authors developed an interface for on-grid homes in managing their electricity consumption with the influence of grid interruption and for varying daily budget. While comfort result was not evaluated in Ref. [32], user satisfaction was evaluated in Ref. [34] and used in dispatching loads. The concept of scalable SHSs for various households was also considered in Ref. [35] with various hybrid configuration of electricity sources evaluated for cost, emissions and energy dumping in Ref. [36]. A load manager utilizing mixed integer linear programming for improving the comfort level of households utilizing PV/battery under intermittent solar power was proposed in Ref. [37] while a rule based load management scheme for a stand-alone PV/battery system in a residential building was developed in Ref. [38].

A critical observation of the literature on HEMs application and management in Nigeria shows that none has been able to present a comprehensive management system for low/middle income homes, especially in addressing the issue of PV/battery sizing based on the financial level of the household and synergizing the PV/battery system operation with the grid to dispatch specific loads at specific times. Furthermore, none of the researched literature on HEMs management in Nigeria has presented a complete report on the potential payback period carbon footprint reduction (when compared with other alternatives) and energy cost/kWh utilizing PV/battery/utility for a low/middle income household.

This work thus models and investigates the PV/battery/utility option for a low-cost residential house that incorporates the BLM-HEMS for smart load dispatch, battery management and intelligent converter control, and compares its associated statistics such as electricity cost reduction, comfort/satisfaction level improvement, carbon footprint reduction and return on investment (RoI) with the Utility only option and Utility/generator option (without BLM-HEMS). In doing this, this work advocates for the adoption of the PV/battery/utility option as a viable alternative to mitigate grid interruption and improve the satisfaction level of low/middle income households with cost constraints.

In this paper, we acknowledge that the adoption and utilization of HEMs faces critical challenges in Nigeria due to the rising cost of electricity and frequent blackouts in the country. However, the high prevalence of poverty and low purchasing power of Nigerian households mean that most PV/battery systems are usually undersized for load and number of days without sunshine. The demerit of such sizing means that conventional HEMs fail to meet user expectations in terms of load management, comfort/satisfaction level, cost reduction, reduction in carbon footprint etc. Also, most HEMs are for off-grid homes or application. The disadvantage of off-grid applications means that the advantage of lower electricity cost from the utility (when available) cannot be leveraged during insufficient PV/battery capacity.

This paper presents BLM-HEMS which offers households with grid supply the opportunity of leveraging the advantage of low electricity cost from the utility in dispatching their loads along with the PV/battery. This configuration – PV/battery/utility being advocated in this paper incorporates BLM-HEMS in MPPT tracking, efficient battery management and smart load dispatch to improve household comfort, reduce electricity cost and carbon footprint and guarantee the repayment of the initial purchase and installation costs within 25 years of operation based on the evaluated yearly savings. The proposed solution aims at tackling the problem of low comfort/satisfaction level often encountered from households with undersized PV/battery systems with utility (grid) availability.

The rest of the paper is organized as follows; Section 2 presents the methods including modelling of the PV panels, converter design, battery management and load dispatch while the results and discussions including sensitivity analysis and policy recommendations are presented in Section 3. The paper is concluded in Section 4.

2. Methods

In justifying the proposed methods, we first justify its need by evaluating a comfort expenditure plot (Fig. 1) for both the use of the utility and the generator (independently) in meeting the needs of a household.

Table 4 presents the daily utilization profile of loads (LP1 – LP6). The computation of the monthly cost of dispatching loads (LP1 – LP6) assuming uninterrupted power supply is shown in equations (1)–(3). As seen from equations (1)–(3), about $14.43 representing about 33.5% of the average monthly expenditure on electricity is expended in dispatching LP1 – LP6 (if grid is assumed available throughout) monthly.

Compensating for poor power supply and frequent grid

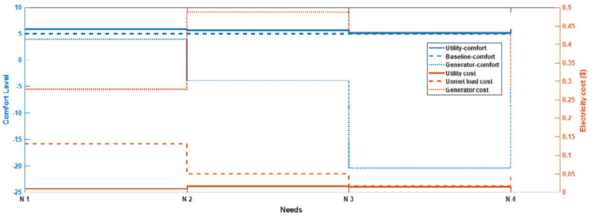

Fig. 1. The combined comfort and expenditure plot for utility and generator.

Table 4
Daily dispatch profile for considered loads.

Load point	Unit (W)	Weekday time dispatch of load																
		1	2	3	4	5	6	7	13	14	17	18	19	20	21	22	23	24
LP1	200	0	0	0	0	0	0	1	0	0	1	1	1	1	1	1	0	0
LP2	96	0	0	0	0	0	1	1	0	0	0	0	1	1	1	1	1	1
LP3	32	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1
LP4	225	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1
LP5	55	@	@	@	@	@	@	@	@	@	@	@	@	@	@	@	@	@
LP6	75	&	&	&	&	&	&	&	&	&	&	&	&	&	&	&	&	&
Total (W)		257+@+&	257+@+&	257+@+&	257+@+&	257+@+&	128+@+&	296+@+&	@+&	@+&	425+@+&	425+@+&	553+@+&	553+@+&	553+@+&	553+@+&	353+@+&	353+@+&

1 – Valid period for load point dispatch.
0 – Not a valid period for load point dispatch.
@ - Fraction of others 1 dispatched.
& - Fraction of others 2 dispatched.

Table 5
Needs – appliances matrix.

		Needs			
		N-1	N-2	N-3	N-4
Appliances (Loads)	LP1	X	X	V	X
	LP2	V	X	X	X
	LP3	V	X	X	X
	LP4	X	V	X	X
	LP5	X	X	V	V
	LP6	X	X	V	V

X – Need cannot be met by appliance.
V – Need can be met by appliance.
N-1 is Lighting need; N-2 is Cooling need.
N-3 is Entertainment need; N-4 is others.

interruptions, a fraction of $C_M^{\cos t}$ (moderated monthly electricity cost) is usually expended. Table 5 presents the Needs – Appliances Matrix for a low-cost house under consideration. The loads (appliances) under consideration (LP1 – LP6) are classified based on their ability to dispatch the need class (lighting, cooling, entertainment and others) being considered. For example, LP2 (indoor lighting) and LP3 (outdoor lighting) are the only appliances (loads) that can dispatch the lighting (indoor and/or outdoor) need of the house at any time. The associated costs of unmet hourly load due to power outage and the hourly cost of dispatching loads LP1 – LP6 using the Utility only options are presented in Table 6. Equation (4) provides the computation of the associated utility-based comfort level of the household under consideration. The next best alternative to a middle-class home electrification is the petrol generator. Table 7 presents some basic facts associated with a typical 6.5 kVA petrol generator which is predominant among homes surveyed around the low-cost housing estate.

Assuming full dispatch always for LP5 and LP6, then @ = 1 and & = 1. For hours 1–7 and 17–24 during weekdays and weekends and $df\ = 0.85$, total daily consumption (T_{DC}) without df moderation amounts to 8087 Wh.

By incorporating df,

$$T_{DC}^{M} = T_{DC} \times df \tag{1}$$

This implies that $T_{DC}^{M}\ = 8087 \times 0.85\ = 6873.95Wh/day$.

Assuming 30 days/month,

$$MC = T_{DC}^{M} \times 30 = 6873.95 \times 30 = 206218.50Wh$$

Converting to kWh results in $MC\ = 206.22kWh$

$$E_{PC} = \$0.07/kWh \tag{2}$$

This implies that $C_M^{\cos t}$ is evaluated as;

$$C_M^{\cos t} = MC(kWh) \times E_{PC} \tag{3}$$

$$C_M^{\cos t} = 206.22 \times 0.07 = \$14.40$$

where, T_{DC}^{M} is the demand factor moderated total daily consumption (Wh or kWh), MC is the monthly electricity consumption (Wh or kWh), E_{PC} is the electricity cost per unit ($/kWh) and $C_M^{\cos t}$ is the monthly cost of T_{DC}^{M} ($). j is the index of the needs-set J such that $J\ = \{N-1, N-2, N-3, N-4\}$, $H_{i,j}$ is the hour i demand for need j, $C_{i,j}^{utility}$ is the utility cost of dispatching need j for hour i and $C_{i,j}^{Total-unmet}$ is the baseline comfort cost of need j for hour i. The comfort level for dispatching need j in hour i using the utility is

Table 6
Utility based associated statistics for LP1 – LP6.

	Needs			
	N-1	N-2	N-3	N-4
$H_{i,j}$	128 Wh	225 Wh	200 Wh	130 Wh
$C_{i,j}^{utility}$	2.73 Naira (\$0.01)	4.79 naira (\$0.02)	4.26 Naira (\$0.01)	2.77 Naira (\$0.01)
$C_{i,j}^{Total-unmet}$	40 Naira (\$0.13)	15 Naira (\$0.05)	5 Naira (\$0.02)	15 Naira (\$0.05)
$U_{i,j}^{utility}$	5.93	5.68	5.15	5.82

Table 7
Petrol generator associated characteristics.

Generator characteristics	
Burn rate	1.6 L/hour
CO_2 emissions per Litre	2.392 kgCO$_2$/Litre
Hours of utilization per day	6
Monthly maintenance cost	\$4.92
Petrol cost/Litre	\$0.48

Table 8
Generator based associated statistics for LP1 – LP6.

	Needs			
	N-1	N-2	N-3	N-4
$H_{i,j}$	128 Wh	225 Wh	200 Wh	130 Wh
$C_{i,j}^{generator}$	\$0.28	\$0.49	\$0.43	\$0.28
$C_{i,j}^{unmet}$	\$0.13	\$0.05	\$0.02	\$0.05
$U_{i,j}^{generator}$	3.89	−3.90	−20.41	0.28

$U_{i,j}^{utility}$. It must be pointed out that the $C_{i,j}^{unmet}$ values for computation shown in Tables 6 and 8 assume full dispatch of all appliances related to the needs (N-1, N-2, N-3 and N-4) and is $C_{i,j}^{Total-unmet}$.

In the results, the actual values for $C_{i,j}^{unmet}$ would be computed based on the appliances selected by the user and eventually dispatched for the hour under consideration. While it is expected that the computation of $C_{i,j}^{unmet}$ would directly sum the associated comfort costs for unmet loads intended to be dispatched, $C_{i,j}^{unmet}$ sums up the comfort cost of dispatched loads. The reason for this is because the baseline comfort of the household is assumed based on all the loads associated with a need being dispatched. Thus, equations (4a) and (4b) aim at penalizing the differential established by $C_{i,j}^{Total-unmet} - C_{i,j}^{unmet}$.

The computation of $U_{i,j}^{utility}$ in the case of full dispatch is as follows:

Given baseline comfort level $U_{baseline}$ to be 5, then

$$U_{i,j}^{utility} = U_{baseline} - \frac{C_{i,j}^{utility} - C_{i,j}^{unmet}}{C_{i,j}^{unmet}} \tag{4a}$$

However, when all the appliances scheduled for dispatch in an hour to meet any need are not all dispatched eventually due to PV/battery for instance being insufficient, then equation (4a) is modified to become equation (4b) as:

$$U_{i,j}^{mtd} = U_{baseline} - \frac{C_{i,j}^{mtd} - C_{i,j}^{unmet}}{C_{i,j}^{Total-unmet}} \tag{4b}$$

Such that $C_{i,j}^{unmet} \le C_{i,j}^{Total-unmet}$ and for fixed $C_{i,j}^{mtd}$, as $C_{i,j}^{unmet} \rightarrow C_{i,j}^{Total-unmet}$, $U_{i,j}^{mtd}$ increases, where $mtd = \{utility, PV/battery/utility, utility/generator\}$, $C_{i,j}^{unmet}$ is the sum of the comfort cost of the loads dispatched for the hour and that were intended to be dispatched, $C_{i,j}^{mtd}$ is the hourly cost of dispatching electricity for any *mtd* while $C_{i,j}^{Total-unmet}$ is the cumulative/baseline comfort cost for any need (\$0.13 for N-1, \$0.05 for N-2, \$0.02 for N-3 and \$0.05 for N-4). Table 9 presents the comfort based cost for each appliance which is used in computing $C_{i,j}^{unmet}$. It is observed from Table 9 that N-1 need has the highest $C_{i,j}^{Total-unmet}$ of \$0.13 followed by N-2 (\$0.05) and N-4 (\$0.05) with N-3 having the lowest at \$0.02. The build-up of $C_{i,j}^{Total-unmet}$ for N-1, N-2 and N-4 is based on their sub-units (LP2 (1) – LP2 (6), LP3 (1) – LP3 (2), LP4 (1) – LP4 (3), LP5 (1) – LP5 (3) and LP6 (1) – LP6 (2)). We can thus infer based on $C_{i,j}^{Total-unmet}$ for the various needs (N-1, N-2, N-3, N-4) that lighting takes the most priority, followed by cooling, others and entertainment. Expanding on equations (4a) and (4b), 3 scenarios are likely to occur:

- Scenario 1: $U_{i,j}^{mtd} < U_{baseline}$, this is possible if and only if $C_{i,j}^{mtd} > C_{i,j}^{unmet}$. A possible explanation for this scenario is when no loads are dispatched to meet a need.
- Scenario 2: $U_{i,j}^{mtd} = U_{baseline}$, this is possible if and only if $C_{i,j}^{mtd} = C_{i,j}^{unmet}$. This scenario though possible is highly unlikely considering the wide disparity between $C_{i,j}^{mtd}$ and $C_{i,j}^{unmet}$.
- Scenario 3: $U_{i,j}^{mtd} > U_{baseline}$, this is possible if and only if $C_{i,j}^{mtd} < C_{i,j}^{unmet}$. This scenario is very likely especially as loads get dispatched to meet needs. Thus, an increase in $U_{i,j}^{mtd}$ is expected as $C_{i,j}^{unmet} \rightarrow C_{i,j}^{Total-unmet}$.

The computation of the associated cost of running the generator for an hour based on Table 7 is shown subsequently. Hourly fuel cost (assuming 1.6 L/hour) is \$0.76 at \$0.48/Litre while emission from the generator for the hour is evaluated to be 3.8272kgCO$_2$. Using \$0.07/kWh, the cost of emissions is computed to be \$0.69. The hourly maintenance fee (for 180 operations hours/month) translates to \$0.03. A total hourly cost (THC^{gen}) of \$1.48 is thus obtained. The computation of $C_{i,j}^{generator}$ and $U_{i,j}^{generator}$ is shown in equations (5)–(6).

$$C_{i,j}^{generator} = \frac{H_{i,j}}{\sum_i \sum_{j=1}^{4} H_{i,j}} \times THC^{gen} \tag{5}$$

$$U_{i,j}^{generator} = U_{baseline} - \frac{C_{i,j}^{generator} - C_{i,j}^{unmet}}{C_{i,j}^{Total-unmet}} \tag{6}$$

Table 8 presents the evaluated values from equations (5)–(6).

Table 9
Comfort cost breakdown for each sub load point and Need.

Needs	N-1								N-2			N-3	N-4				
Load points	LP2 (1)	LP2 (2)	LP2 (3)	LP2 (4)	LP2 (5)	LP2 (6)	LP3 (1)	LP3 (2)	LP4 (1)	LP4 (2)	LP4 (3)	LP1	LP5 (1)	LP5 (2)	LP5 (3)	LP6 (1)	LP6 (2)
Comfort cost ($)	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01
$C_{i,j}^{Total-unmet}$	0.13								0.05			0.02	0.05				

Table 10
Associated parameters for PV panel, converter, battery and inverter.

PV panel		Converter		Battery		Inverter	
Number	2	r_i	$5m\Omega$	Voltage	24 V	η_{inv}	0.9
Power	80 Wp	r_L	0.2Ω	Rating	100 Ah	Rating	1 kVA
η_{PV}	16%	R_L	15Ω	η_{batt}	0.9		
Cost	$188.12	F_s	$5000Hz$	DOD	90%		
Life cycle	25 years	k	0.5	σ	<3%/month		
V_{mp}	18 V	C_i	$200\mu F$	Life cycle	3 years		
I_{mp}	4.44 A	C_o	$333.33\mu F$	Cost	$200		
Weight	7.4 kg	L	$18.75mH$				

The plot of the various comfort levels for the utility and generator as well as the cost in dispatching needs N-1, N-2, N-3, N-4 is shown in Fig. 1.

The huge costs involved in using generator as an alternative to the utility in meeting needs thus informs the need for a more affordable alternative system that is both cost effective and environmentally friendly. Furthermore, the proposed system must incorporate smart concepts that would enhance its operation and overall performance.

2.1. The proposed alternative energy system

Fig. 2 presents the proposed alternative system for meeting electricity needs of the household under consideration. It is observed from Fig. 2 that the proposed system consists of an inverter system (1 kVA), converter system (boost), battery (100 Ah, 24 V), PV (2 × 80 Wp) panel and a smart manager BLM-HEMS. The units (number) of the battery and PV panels are the maximum that can be afforded by the household.

Table 11
Initial purchase, installation and daily operations cost for considered generation sources.

		Generation sources		
		PV/battery	Utility	Generator
Costs	Initial purchase	$486.49[*]	$163.93[++]	$574[*]
	Maintenance	$8.20/year	No maintenance fee	$4.92/month
	Hourly operations	$0[#]	\$0.07 × $D_{hour}^{k}(kWh)$	$0.09[#]

$D_i(kWh)$ is the hourly demand to be dispatched by the PV/battery.
[*]- Inclusive of installation cost.
[++] - Households were initially charged for pre-paid meters with a payment plan spread across 12 months.
[#] - Charge is flat for the hour as long as demand can be met by available generation capacity.

Table 12
Load audit of use case low-cost house.

Device	Code	Number	Unit rating (W)	Total power (W)
Television[a]	LP1	1	200	200
Indoor light[a]	LP2	6	16	96
Outdoor light[a]	LP3	2	16	32
Standing/ceiling fan[a]	LP4	3	75	225
Others 1[a]	LP5	–	55	55
Others 2[a]	LP6	–	75	75
Electric cooker[+,b]	–	1	1500	1500
Fridge/Freezer[+,b]	–	1	400	400
Electric kettle[+,b]	–	1	1000	1000
Pressing iron[+,b]	–	1	1000	1000
Total				4583

[+]- Not considered for alternative power supply.
[a] - Class one load points.
[b] Class two load points.

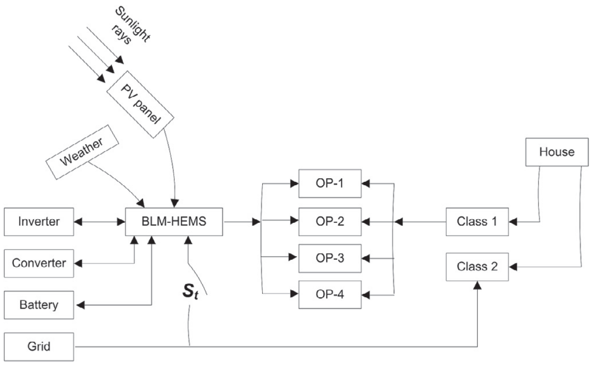

Fig. 2. Proposed alternative system.

The loads in the house are divided into two classes (Class 1 and Class 2) as shown in Table 12. BLM-HEMS provides a platform

- ✓ For measuring weather condition (real time) to determine optimum operating condition of the converter. This is achieved through a hopping algorithm that is designed to track the maximum power point (MPPT) of the PV panel in real time by sampling results from either the incremental conductance method, perturb and observe method or normal operation (fixed duty cycle). The sampling duration of the converter is thus influenced based on the method that provides the maximum power.
- ✓ For managing battery state of charge. Battery management is done to ensure that law of energy conservation is obeyed with battery discharge only allowed within the permitted limits.
- ✓ Optimally dispatching Class 1 loads. In dispatching of loads under constrained supply, the optimal dispatch profile that results in better consumer comfort is always followed.

It must however be pointed out that the grid is never used in charging the battery. The methods for implementing the proposed alternative system described in Fig. 2 involve modelling of the PV system, converter system, battery management system and load dispatch. The detailed description of each method is presented subsequently.

2.2. Photovoltaic modelling

The typical equivalent circuit of a solar cell is shown in Ref. [39] where $\boldsymbol{I_{sc}}$ is the current generated due to the photoelectric effect (i.e. solar radiation hitting the PV panel and causing electrons to be emitted and flow in the connected circuit), $\boldsymbol{I_D}$ is the current that flows from the p junction to the n junction due to the diffusion of charge carriers, and is used to represent the net drop in the photo generated short circuit current ($\boldsymbol{I_{SC}}$), $\boldsymbol{R_{sh}}$ is a resistor of high value that is used to represent losses due to defects in the PV panel, $\boldsymbol{R_s}$ is the series resistor of low value used to represent losses due to the metal contacts that convey electrons, $\boldsymbol{R_L}$ is the load resistance connected to the PV panel output, $\boldsymbol{I}$ is the load current i.e. the current that flows through the connected load $\boldsymbol{R_L}$ and $\boldsymbol{V}$ is the terminal or load voltage (i.e. voltage across the load $\boldsymbol{R_L}$). Newton-Raphson is employed in solving equation (7).

Given any $f(x) = y$, where y is a linear homogeneous equation, $if \ni any\ f(x_o) = 0$ and r is a suggested root where $x_o, r \in R$

Then, if $f(r) \neq 0$,

The distance $x_o - r = h$ can be reduced by updating r to r_{new} as follows:

$$r_{new} = r - \frac{f(r)}{f'(r)}, \quad r = r_{new} \quad \text{while} \quad h = x_o - r$$

The stopping criterion is a problem of accuracy. If f_v is the accuracy point and $h = -\frac{f(r)}{f'(r)}$, the searching will stop when $abs(h) \leq f_v$.

Thus if,

$$I = n_p I_{sc} - n_p I_s \left(e^{q(Vn_s + IR_s/n_p)/AKT_c} - 1 \right) - \frac{Vn_p/n_s + IR_s}{R_p} \tag{7}$$

Then,

$$F(I) = I - n_p I_{sc} + n_p I_s \left(e^{q(Vn_s + IR_s/n_p)/AKT_c} - 1 \right) + \frac{Vn_p/n_s + IR_s}{R_p} \tag{8}$$

where A is the ideality factor, q is the charge, K is the Boltzmann constant and T_c is the PV cell temperature. The I-V and P-V performances under varying temperature and irradiance are shown in Refs. [40,41].

2.3. Converter model

In modelling a suitable dc-dc boost converter for the proposed BLM-HEMS, a voltage source (V_i) is utilized to represent a PV panel and a voltage controlled current source ($I_{pv}(V_i)$) to represent the equivalent PV short circuit current generated through the photoelectric effect as shown in Fig. 3. Applying Kirchhoff's laws to Fig. 3 yields the state representation for both "ON" and "OFF" states.

During the "OFF" state, i.e. $S_1 = 0$, $r_L I_L + L\frac{dI_L}{dt} + V_o = V_i + r_i(I_{pv} - I_L)$. Re-arranging yields,

$$\frac{dI_L}{dt} = \frac{1}{L}V_i - \frac{(r_L + r_L)}{L}I_L - \frac{1}{L}V_o - \frac{r_i}{L}I_{pv}(V_i) \tag{9}$$

Similarly, for current at the input side, $I_{pv}(V_i) - C_i\frac{dV_i}{dt} = I_L$. Re-arranging yields,

$$\frac{dV_i}{dt} = -\frac{1}{C_i}I_L + \frac{1}{C_i}I_{pv}(V_i) \tag{10}$$

Also, at the output side, current is computed $I_L = C_o\frac{dV_o}{dt} + \frac{V_o}{R_L}$. Re-arranging yields,

$$\frac{dV_o}{dt} = \frac{1}{C_o}I_L - \frac{1}{C_o R_L}V_o \tag{11}$$

The equivalent state space equation is shown in equation (12) while Fig. 4 presents the equivalent circuit during the "OFF" state.

$$\begin{bmatrix} \dot{V}_i \\ \dot{I}_L \\ \dot{V}_o \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{C_i} & 0 \\ \frac{1}{L} & -\frac{(r_i + r_L)}{L} & -\frac{1}{L} \\ 0 & \frac{1}{C_o} & -\frac{1}{C_o R_L} \end{bmatrix} \begin{bmatrix} V_i \\ I_L \\ V_o \end{bmatrix} + \begin{bmatrix} \frac{1}{C_i} \\ \frac{r_i}{L} \\ 0 \end{bmatrix} I_{pv}(V_i) \tag{12}$$

During the "ON" state, i.e. $S_1 = 1$, $V_i + (I_{pv}(V_i) - I_L)r_i = I_L r_L + L\frac{dI_L}{dt}$. Re-arranging yields,

$$\frac{dI_L}{dt} = \frac{1}{L}V_i - \frac{(r_i + r_L)}{L}I_L + \frac{r_i}{L}I_{pv}(V_i) \tag{13}$$

Similarly, $I_{pv}(V_i) - C_i\frac{dV_i}{dt} = I_L$. Re-arranging yields,

$$\frac{dV_i}{dt} = -\frac{1}{C_i}I_L + \frac{1}{C_i}I_{pv}(V_i) \tag{14}$$

At the output side, the capacitor is discharging and this yields $-C_o\frac{dV_o}{dt} = \frac{V_o}{R_L}$. Re-arranging yields,

$$\frac{dV_o}{dt} = -\frac{1}{C_o R_L}V_o \tag{15}$$

The equivalent state space equation for the "ON" state is shown in equation (16) while Fig. 5 presents the equivalent circuit during the "ON" state.

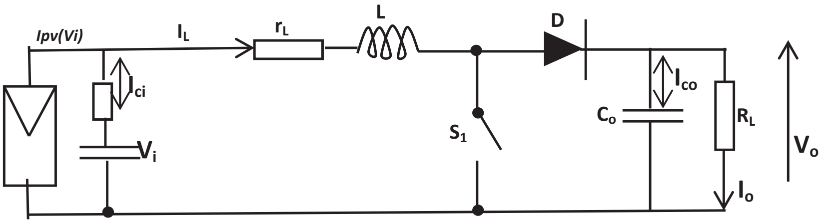

Fig. 3. PV/DC-DC boost-converter model.

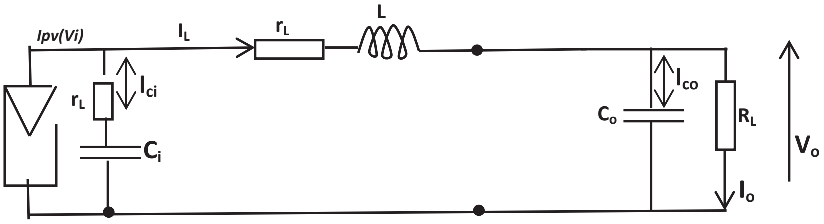

Fig. 4. PV/DC-DC Boost-Converter Model for “OFF” state operation.

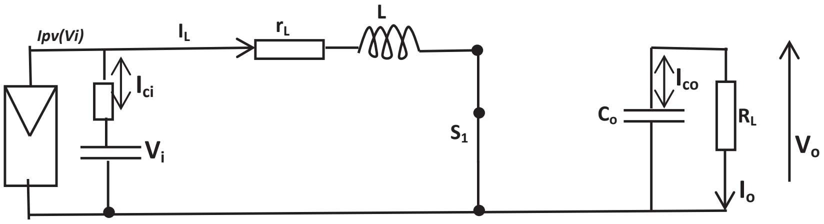

Fig. 5. The PV/DC-DC Boost-Converter Model during the “ON” state.

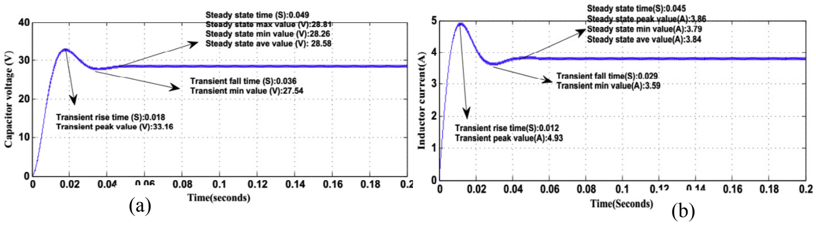

Fig. 6. Transient and steady state response for (a) Capacitor voltage and (b) Inductor current.

$$\begin{bmatrix} \dot{V}_i \\ \dot{I}_L \\ \dot{V}_o \end{bmatrix} = \begin{bmatrix} 0 & -\dfrac{1}{C_i} & 0 \\ \dfrac{1}{L} & -\dfrac{(r_i+r_L)}{L} & 0 \\ 0 & 0 & -\dfrac{1}{C_o R_L} \end{bmatrix} \begin{bmatrix} V_i \\ I_L \\ V_o \end{bmatrix} + \begin{bmatrix} \dfrac{1}{C_i} \\ \dfrac{r_i}{L} \\ 0 \end{bmatrix} I_{pv}(V_i) \qquad (16)$$

Equation (17) presents the comprehensive equation that represents both the “ON” and “OFF” states based on the value of a with $a = 0$ during the “ON” state and $a = 1$ during the “OFF” state. Fig. 6 (a and b) presents the transient and steady state response of the capacitor voltage and inductor current.

$$\begin{bmatrix} \dot{V}_i \\ \dot{I}_L \\ \dot{V}_o \end{bmatrix} = \begin{bmatrix} 0 & -\dfrac{1}{C_i} & 0 \\ \dfrac{1}{L} & -\dfrac{(r_i+r_L)}{L} & -\dfrac{a}{L} \\ 0 & \dfrac{a}{C_o} & -\dfrac{1}{C_o R_L} \end{bmatrix} \begin{bmatrix} V_i \\ I_L \\ V_o \end{bmatrix} + \begin{bmatrix} \dfrac{1}{C_i} \\ \dfrac{r_i}{L} \\ 0 \end{bmatrix} I_{pv}(V_i) \qquad (17)$$

Table 10 presents the associated parameters for the PV panel, converter and battery utilized in modelling where η_{PV} is PV efficiency, r_i is internal resistance of input capacitor of capacitance C_i, r_L is input side series resistance to inductor, R_L is load resistance, F_s is sampling frequency of the converter, k is duty cycle of converter, C_o is capacitance of output capacitor, L is inductance of input inductor, η_{batt} is battery efficiency, DOD is depth of discharge of battery, σ is the monthly self-discharge rate of battery, V_{mp} is the maximum power voltage for the PV panel, I_{mp} is the maximum power current for the PV panel and η_{inv} is inverter efficiency. Other associated costs include generator initial purchase cost ($491.80), installation cost ($81.97) and lifecycle (5000 h). Table 11 presents the detailed costs (initial purchase, installation etc.) and hourly operations for PV/battery, Utility and Generator. For further reading on converter design and modelling including the different topologies, refer to [42–44].

2.4. Maximum power point tracking

Generally, the output of photovoltaic generation systems (PGS) are influenced directly by varying solar irradiance and ambient temperature. Coupled with the problem of shading, it thus becomes necessary to operate PGS at maximum power [45]. Historically, mechanical systems were first developed to move solar panels in order to get maximum solar radiation while subsequent designs known as electrical MPPT utilized the operating voltage/current profile of solar panels to adjust converter switching frequency for maximum power tracking [46]. PV systems are designed to operate at maximum output power levels for any solar irradiance intensity and temperature with their load impedance determining their output power. To provide for operational control, a DC/DC converter is inserted between the PV panel and the batteries with the PV panel array forming the input to the DC/DC converter and the

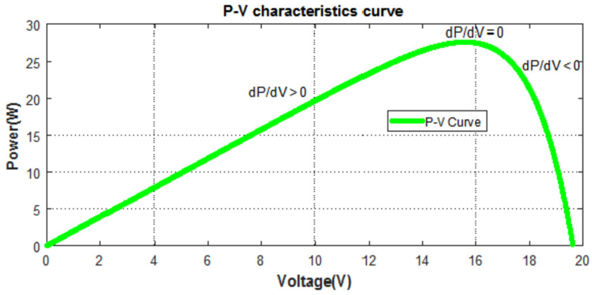

Fig. 7. $\frac{dP}{dV}$ monitoring across the P-V profile.

batteries and load forming its output. With the DC/DC converter acting as an impedance matching circuit, a computing system can modify the duty cycle (and implicitly the input impedance of the DC/DC converter) until the system reaches maximum power point (MPP) [46].

Various MPPT techniques such as fixed duty cycle, beta method, hill climbing/perturb and observe, incremental conductance, constant voltage and current, fuzzy logic controller etc. have been extensively discussed by Ref. [47]. A current perturbation algorithm (CPA) with a variable perturbation step and fractional short circuit current algorithm (FSCC) was proposed by Ref. [48] to determine an optimum operating current. Furthermore, [49] applied a radial basis function network-sliding mode (RBFNSM) and a general regression neural network (GRNN) for MPPT control. For wind application, there was a 5.7% improvement in performance over the PI control mechanism with power extraction efficiency of 84% and a transient time response of 0.3 s. Similarly, [49] achieved a 15% improvement over the perturb and observe method with a transient response time of 0.09 s for PV applications. Other applications of novel MPPT algorithms include [50] where a hybrid power control system (consisting of the Wilcoxon RBFN and the improved Elman neural network) for grid connected hybrid power generation system was proposed, [51] where a fuzzy-logic-based voltage-regulated solar MPPT system for hybrid power systems was proposed and [52] that developed a high performance neuro-fuzzy indirect wavelength-based adaptive MPPT control for PV systems.

In tracking maximum power point (MPP) for this work, a hopping algorithm is developed. The hopping algorithm evaluates maximum solar power based on a modified incremental conductance method, perturb and observe method and normal operation. The maximum value in real-time is chosen and used in adjusting the duty cycle of the converter. There have been extensive discussions on incremental conductance and perturb and observe methods in literature [53–59]. From Fig. 7, the monitoring of the behaviour of $\frac{dP}{dV}$ is a trigger for adjusting the converter duty cycle (in incremental conductance) while the successive difference between power $P_t - P_{t-1}$ is used in adjusting voltage in perturb and observe method. The slight modification added to the incremental conductance method is in the converter duty cycle variation. Rather than varying the sampling time for the "ON" state using a fixed step value, i.e. $t_{ON} = t_{ON} \pm \Delta$, "ON" state time is varied using a varying fraction of t_{ON} to produce $t_{ON} = t_{ON} \pm (frac \times t_{ON})$. The hopping algorithm is further described in Algorithm 1.

2.5. Battery management

The internal working structure of BLM-HEMS is shown in Fig. 8. The state of charge of the battery $SOC(t)$ at any time t is defined as the charge quantity in the battery at the time t and is defined/bounded as:

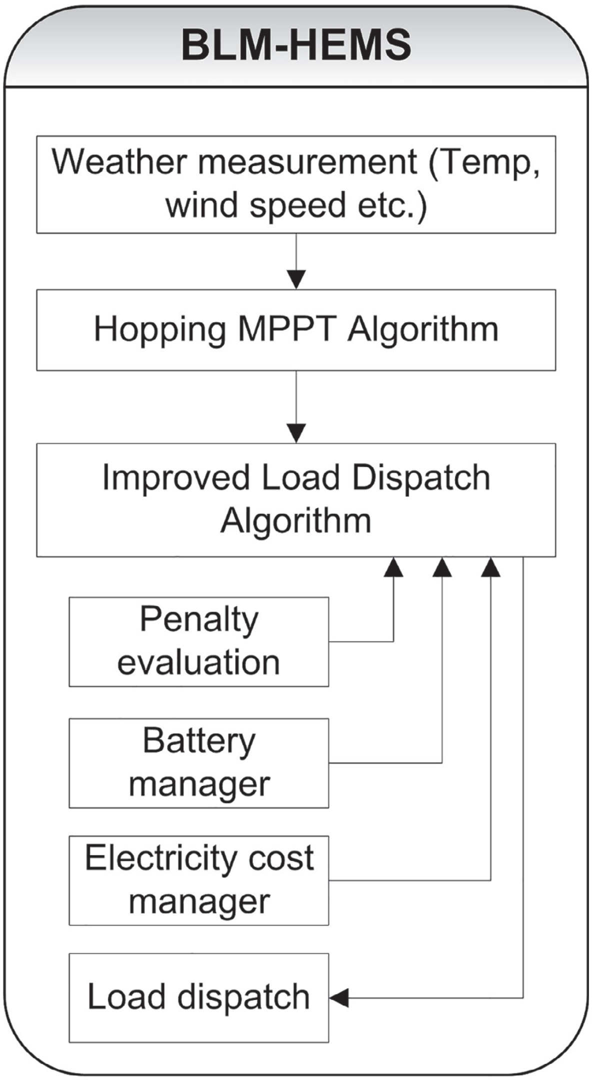

Fig. 8. BLM-HEMS internal working architecture.

$$SOC_{\min} \leq SOC(t) \leq SOC_{\max} \tag{18}$$

The minimum charge quantity $(SOC_{\min})$ is a function of the DOD, i.e. $SOC_{\min} = f(DOD)$ which implies that $SOC_{\min} = (1 - DOD) \times C_{batt}$, with $SOC(t) = SOC_{\max}$ at maximum charge C_{batt}, where C_{batt} is the capacity of the battery (100 Ah). Under operation of the PV panel, 3 possibilities could occur.

- ✓ Case 1: $D_i(t) < E_{PV}(t)$ which would result in battery charging.
- ✓ Case 2: $D_i(t) = E_{PV}(t)$ which would result in $SOC(t) = SOC(t) \times (1 - \sigma)$
- ✓ Case 3: $D_i(t) > E_{PV}(t)$ which could result in either battery charging or discharging.

Where $E_{PV}(t)$ is the PV panel power output at time t and $D_i(t)$ is the time t demand. The battery management function of the BLM-HEMS is to ensure that equation (19) is always maintained for the simulation period (1 day) where $SOC(t_{initial})$ is the battery state of charge at the beginning of simulation time and $SOC(t_{final})$ is the battery state of charge at end of simulation.

$$SOC(t_{initial}) = SOC\left(t_{final}\right) \tag{19}$$

2.5.1. Battery charge and discharge models

Battery charging occurs during Case 1 and in Case 3 when the eventual allocation/dispatch of load results in only a fraction of $E_{PV}(t)$ being utilized. During excess power generation from the PV panel as presented by Case 1, the excess power $Sup(t) = E_{PV}(t) - D_i(t)$ gets dumped into the battery as shown in equation (20). Charging in Case 3 as a result of $\alpha E_{PV}(t)$ being dispatched also follows equation (20) where $0 < \alpha < 1$.

$$SOC(t) = SOC(t-1) \times (1-\sigma) + (Sup(t) \times \eta_{batt}) \tag{20}$$

Given $def(t) = D_i(t) - E_{PV}(t)$ to be the deficit power needed from the battery for hour t due to insufficient PV power, then $\overline{def(t)} = \frac{def(t)}{\eta_{inv} \times \eta_{batt}}$ is defined and any of the following discharge types can occur.

✓ Type 1 $SOC_{\min} \leq \overline{def(t)} < SOC(t-1) \times (1-\sigma)$ in which case

$$SOC(t) = SOC(t-1) \times (1-\sigma) - \overline{def(t)} \tag{21}$$

✓ Type 2: $SOC(t-1) \times (1-\sigma) < \overline{def(t)}$ in which case

$$SOC(t) = SOC_{\min} \tag{22}$$

Further reading on battery systems and management especially for stand-alone PV systems is found in Ref. [60].

```
Algorithm 1: Hopping algorithm description
1. Start2. Input: $P(t), P(t-1), V(t), V(t-1), k, I(t), I(t-1), t_{ON}$
    3. Perform Perturb and observe4. Perform $P_{diff} = P(t) - P(t-1)$
        5. Adjust voltage accordingly - $V(t) = V(t-1) \pm \Delta$
        6. Locate $P^{\max}_{P\&O}$ (maximum power for perturb and observe method)
    7. Perform Incremental conductance8. Perform $P_{\Delta}(t) = \frac{dP(t)}{dV(t)}$ and
            $G_{\Delta}(t) = -\frac{I(t)}{V(t)}$
        9. Adjust $t_{ON}$ accordingly - $t_{ON} = t_{ON} \pm (frac \times t_{ON})$
        10. Locate $P^{\max}_{incr-cond}$ (maximum power for incremental
        conductance method)
    11. Perform normal operation with $k$
        12. $\frac{V_o}{V_i} = \frac{I_L}{I_o} = \frac{1}{1-k}$
        13. $t_{ON} = k \times T_p = \frac{k}{F_s}$
        14. $P^{\max}_{normal} = I_o \times V_o$
    15. Generate $\overline{P} = \{P^{\max}_{P\&O}, P^{\max}_{incr-cond}, P^{\max}_{normal}\}$
        16. $P(t) = \max(\overline{P})$
  17. Output: $P(t)$
18. End
```

Fig. 9 presents the simplified low chart depicting the general BLM-HEMS flow and operation.

3. Results and discussion

A typical 2-bedroom residential flat in a low-cost housing estate in Lagos (South-West, Nigeria) is considered. The choice of Lagos is due to the high prevalence of generators within the city [10]. The low-cost flat is assumed to house a family of 4, comprising of the father, mother and children. The combined annual income of the household is 1,200,000 Naira ($6557.38) which translates to a monthly income of 167,000 Naira ($546.45). The monthly income of the family puts them above the poverty line of 55,000 Naira ($180.33) per year [9]. Table 12 presents a typical audit of the major expected electrical appliances in the house with Table 13 providing a further breakdown to the classification of grouped loads in Table 12. From Table 12, assuming a 0.85 demand factor (df) which is closely similar to [31], the peak consumption of the house is estimated to be around 4000 Wh which is usually at weekends from 7pm to 9pm. The location of the low-cost house (Ikeja) means that Ikeja Electricity Distribution Company (IKEDC) is responsible for billing the case study house. The case study house has a single-phase 240 VAC pre-paid electric meter installed. Based on the prevailing tariff system prescribed by the electricity regulator – NERC (Nigerian Electricity Regulatory Commission) through the multi-year tariff order (MYTO) II, the per unit electricity rate is charged at 21.30 Naira ($0.07) per kilowatt-hour. No additional standing charges are billed the customer.

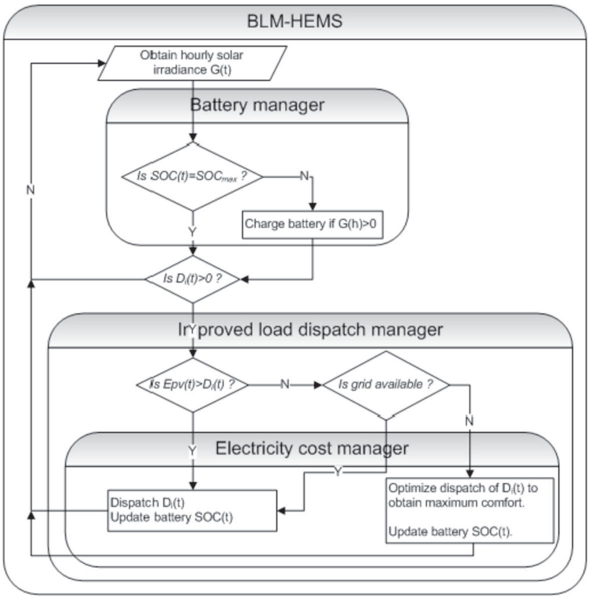

Fig. 9. The BLM-HEMS flow chart.

The tracking of maximum power using perturb and observe, incremental conductance, normal operation and hopping algorithm is shown in Fig. 10. As seen in Fig. 10, the hopping algorithm vacillates between the incorporated methods in determining the possible maximum power and adjusting the duty cycle of the converter (shown in Fig. 12). The overall efficiency in terms of maximum power tracking for a day is 70.90%, 67.59%, 66.36% and 72.20% for normal, perturb and observe, incremental conductance and hopping algorithms respectively. This implies that the hopping algorithm achieves an extra 7% and 9% efficiency in terms of MPPT over perturb and observe and incremental conductance methods respectively. These values compare favourably with the 15% improvement in terms of MPPT by Ref. [49].

The transient behaviour for the various MPPT methods is observed in Fig. 11 for a 4 s window with smaller resolution. Fig. 12

Table 13
Power rating of others 1 and others 2 sub-load points.

Class definition	Class constituent	Number	Description	Unit rating (W)	Total power (W)
Others 1	Satellite decoder	1	LP5 (1)	10	10
	Phone charger	2	LP5 (2)	10	20
	DVD player	1	LP5 (3)	25	25
Others 2	Laptop	1	LP6 (1)	65	65
	Bedside light	1	LP6 (2)	10	10

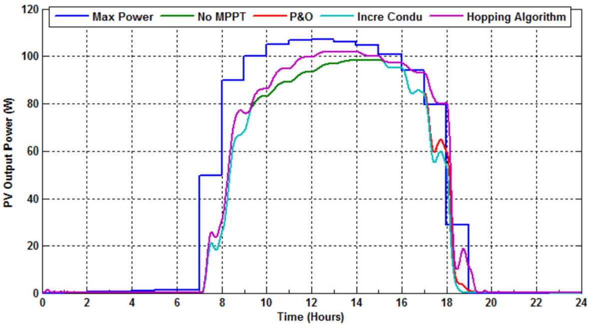

Fig. 10. The daily MPPT tracking of the various methods employed.

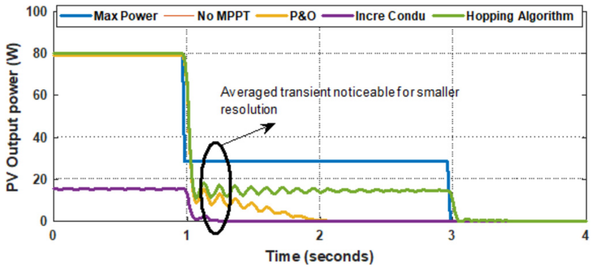

Fig. 11. Transient behaviour of the various methods for smaller resolution.

shows a snippet of the overall firing sequence of the converter (i.e. the state – ON/OFF of the converter during MPPT) for the various MPPT algorithms. As seen, a similar ON/OFF state sequence is noticed for the perturb and observe and incremental conductance methods which is at variance with the normal operation (No MPPT) of the converter (using fixed duty cycle).

A major impediment to the MPPT tracking by the perturb and observe methods and the incremental conductance method is the rapid change in solar irradiance level which necessitates for rapid adjustment of converter duty cycle and could lead to over or under compensation. However, during stable operations at high power output (>100 W), the perturb and observe and the incremental conductance methods outperform the normal operation with efficiency of up to 95%.

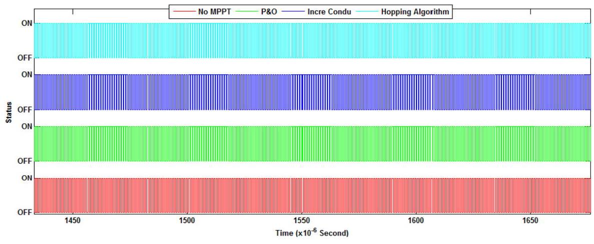

Fig. 12. Snippet of the firing sequence of the converter for the various MPPT algorithms.

The sizing of the PV/battery system was done for only one day with the battery initial charge set to 10% (being the lowest discharge capacity of the battery). The demerit of this set up thus means that demands from 8pm till 7am will hardly be dispatched by the PV/battery setup. Demands that will be mostly dispatched (depending on the available number of sunshine hours) are demands within the hours from 4pm till 8pm. The analysis of dispatch and comparison of associated costs and comfort will thus centre around dispatch occurring within the hours 4pm till 8pm. Considering the two major seasons in Nigeria (dry and wet seasons), the simulation was run with sunshine data to represent on average, the daily irradiance for both wet season (April to October) and dry season (November to March).

Table 14 presents the demand for the hours (4pm till 8pm) under consideration that are to be dispatched from PV/battery/utility configuration depending on PV/battery capacity and utility (grid) availability. A justification for the selected hours under consideration is found in Ref. [61] who opines that the selected hours under consideration form a sub-set of the typical hours of peak demand for low/middle income households. From Table 14, 340 Wh is demanded from 4pm – 5pm, 385 Wh is demanded for 5pm – 6pm, 409 Wh is demanded from 6pm – 7pm and 396 Wh is demanded from 7pm to 8pm. Total demand for the time spanning 4pm – 8pm is 1530 Wh. The N-1, N-2, N-3 and N-4 needs computation for 4pm till 8pm as well as the appliances selected for dispatch by the user and the eventual wattage of the appliances dispatched are shown in Table 15. It is seen from Table 15 that utility though available for hours 4pm – 7pm, is not utilized in dispatching any selected load from 4pm till 5pm.

However, from 5pm till 7pm when PV/battery capacity becomes insufficient, the utility supplies the shortfall of 4.70 Wh (5pm – 6pm) and 367.63 Wh (6pm – 7pm). Total PV power supplied from 4pm till 8pm is 310.68 Wh while battery supply within the same time span is 453.33 Wh with the utility supplying 372.33 Wh from 4pm till 8pm. Demand unmet within the time from 4pm till 8pm is 396 Wh and occurs particularly within 7pm – 8pm when PV/battery is insufficient and utility is unavailable. Table 16 presents a detailed description of Table 15 in terms of $H_{i,j}$, $U_{i,j}^{PV/battery}$, $C_{i,j}^{unmet}$ and savings (nominal) where the nominal savings represent the real savings in actual money terms based on a reduction in utility billing as a result of the dispatch of load from an alternative energy source. All computed values are for a typical day.

The computation of $U_{i,j}^{PV/battery}$ in Table 16 shows the direct relationship that exists between $U_{i,j}^{PV/battery}$ and $C_{i,j}^{unmet}$. For any dispatch of loads (appliances) to meet needs that incurs $C_{i,j}^{unmet}$, then a corresponding drop in $U_{i,j}^{PV/battery}$ is expected. The insufficiency of PV/battery capacity for time spanning 6pm – 8pm leads to a corresponding decrease in $U_{i,j}^{PV/battery}$ with $U_{i,j}^{PV/battery}$ going below $U_{baseline}$ from 6pm.

Table 14
Demand schedule for hours under consideration.

	LP1	LP2						LP3		LP4			LP5			LP6	
		LP2 (1)	LP2 (2)	LP2 (3)	LP2 (4)	LP2 (5)	LP2 (6)	LP3 (1)	LP3 (2)	LP4 (1)	LP4 (2)	LP4 (3)	LP5 (1)	LP5 (2)	LP5 (3)	LP6 (1)	LP6 (2)
Rating (W)	200	16	16	16	16	16	16	16	16	75	75	75	10	20	25	65	10
4pm – 5pm	V										V		V	V	V		V
5pm – 6pm	V									V		V	V		V		
6pm – 7pm						V	V	V	V	V	V	V	V	V	V	V	
7pm – 8pm	V	V	V	V	V												

V – Load demanded for hour under consideration (does not connote dispatch).

Table 15
Daily needs computation and dispatch schedule.

Needs	Time span under consideration			
	4pm – 5pm	5pm – 6pm	6pm – 7pm	7pm – 8pm
N-1	0/0 Wh	0/0 Wh	64/41.37 Wh	96/0 Wh
N-2	75/75 Wh	150/150 Wh	225/0 Wh	75/0 Wh
N-3	200/200 Wh	200/200 Wh	0/0 Wh	200/0 Wh
N-4	65/65 Wh	35/30.30 Wh	120/0 Wh	25/0 Wh
Notes	PV + battery only Utility available	PV + battery + utility Utility available	PV + battery + utility Utility available	No PV + battery Utility unavailable

64/41.37 Wh represents 64 Wh demanded and 41.37 Wh supplied by PV/battery. The deficit is met by the utility (grid) if available.

Table 16
Daily computation of $U_{i,j}^{PV/battery}$, $C_{i,j}^{unmet}$ and savings (nominal).

	Needs for 4pm – 5pm				Needs for 6pm – 7pm			
	N-1	N-2	N-3	N-4	N-1	N-2	N-3	N-4
$H_{i,j}$	0 Wh	75 Wh	200 Wh	65 Wh	64 Wh	225 Wh	0 Wh	120 Wh
$U_{i,j}^{PV/battery}$	–	5.31	5.94	5.78	5.24	4.98	–	4.98
$C_{i,j}^{unmet}$ (Naira)	–	0.00 ($0.00)	0.00 ($0.00)	0.00 ($0.00)	10.00 ($0.03)	15.00 ($0.05)	–	12.00 ($0.04)
$Savings$(Naira)	0.00 ($0.00)	1.6 ($0.01)	4.26 ($0.01)	1.38 ($0.00)	0.88 ($0.00)	0.00 ($0.00)	–	0.00 ($0.00)
	Needs for 5pm – 6pm				**Needs for 7pm – 8pm**			
	N-1	**N-2**	**N-3**	**N-4**	**N-1**	**N-2**	**N-3**	**N-4**
$H_{i,j}$	0 Wh	150 Wh	200 Wh	35 Wh	96 Wh	75 Wh	200 Wh	25 Wh
$U_{i,j}^{PV/battery}$	–	5.65	5.94	5.14	4.99	4.98	4.94	4.98
$C_{i,j}^{unmet}$ (Naira)	–	0.00 ($0.00)	0.00 ($0.00)	3.00 ($0.01)	30	5	5	3
$Savings$(Naira)	0.00 ($0.00)	3.20 ($0.01)	4.26 ($0.01)	0.65 ($0.00)	0.00 ($0.00)	0.00 ($0.01)	0.00 ($0.00)	0.00 ($0.00)

The battery state of charge during the simulation period is shown in Fig. 13. It is observed from Fig. 13 that the battery mainly charges from 8am till 4pm when it starts being discharged. Its maximum charge capacity in terms of power for the day is 780.64 W (65.1% of its maximum capacity) and this occurs at 4pm. $SOC(t_{initial})$ is 10% and $SOC(t_{final})$ is 10.8% which satisfies the law of energy conservation. The battery is solely charged from the PV panel with the grid (utility) only coming in (when available) to offset unmet demand. The operational behaviour of the PV/battery/utility system alongside demand and dispatch profile for the day is shown in Fig. 14. It is observed from Fig. 14 that total demand within the day (including the specific hours under consideration) is 4420 Wh of which 2161 Wh went unmet (due to utility unavailability and insufficient PV/battery capacity). Utility supply within the day is 1496.60 Wh, PV effective supply (excluding battery charging) is 308.96 Wh while battery supply is 453.44 Wh. Utility supply was unavailable for 11 h within the day of which 7 were during periods of demand.

In standardizing Tables 15 and 16, there is the need to compare the results obtained for utility with PV/battery and generator as alternatives in terms of associated costs, carbon footprint and return on investment (RoI). Table 17 presents the daily, monthly and yearly cost of dispatch for the effective demand (demand during utility availability) for PV/battery/utility, utility only and Utility/generator. It is seen from Table 17 that for a daily demand of 4420 Wh, the daily effective demand is 2269 Wh (with 7 h of grid available during the demand hours). While 48.12 Naira ($0.16) is spent daily dispatching 2269 Wh, 31.89 Naira ($0.10) is spent dispatching same demand for PV/battery/utility representing a 33.7% savings. Using the Utility/generator option results in a daily expenditure of 3198 Naira ($10.49) which translates to 1,167,390 Naira ($3828) in a year.

In terms of RoI, the initial cost of purchase and installation for the PV/battery is repaid within 25 years with 6000 Naira ($19.67) yearly savings of the PV/battery/utility option over Utility only option (for the adopted hourly electricity cost of 21.30/kWh). Any outstanding cost however is due to the battery replacement and yearly maintenance within the 25 years. Table 18 presents the equivalent carbon emissions for (PV, battery, utility and the generator) and is used in computing the carbon emissions for PV/battery/utility, Utility only and Utility/generator options (shown in Table 19). In addition to generating the lowest cost for electricity dispatch, the PV/battery/utility option also has the lowest daily carbon emissions (1.179kgCO_2) compared with 1.588kgCO_2 (Utility

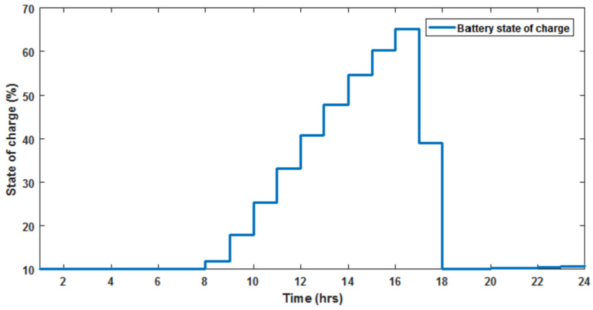

Fig. 13. Battery daily state of charge during dry season.

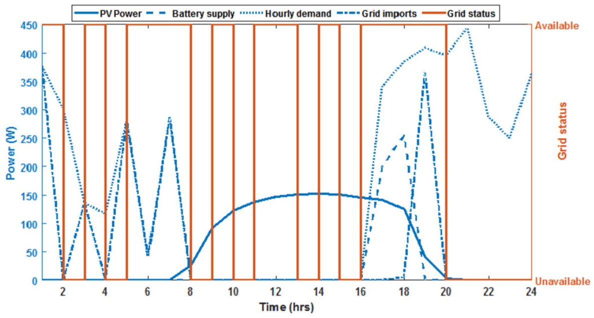

Fig. 14. Hourly demand/dispatch profile, utility status and PV/battery capacity.

only) and 28.384kgCO_2 (Utility/generator).

The comparison of evaluated $U_{i,j}^{utility}$, $U_{i,j}^{PV/battery/utility}$ and $U_{i,j}^{utility/generator}$ for the hours 4pm – 5pm, 5pm – 6pm, 6pm – 7pm and 7pm – 8pm is shown in Figs. 15–18 for N-1, N-2, N-3 and N-4 needs. The superiority of the PV/battery/utility configuration is shown in Figs. 15, 16 and 18 where it achieves average hourly comfort levels ($U_{avg}^{PV/battery/utility}$) of 5.68 (4pm – 5pm), 5.58 (5pm – 6pm) and 4.97 (7pm – 8pm) compared with 5.32, 5.32 and 4.24 respectively for Utility only option. Another observation is that the PV/battery/utility configuration shows a better integration and seamless operation than the Utility/generator configuration. This observation is better explained in Fig. 19 which presents the graduation of the hourly cost of dispatching electricity for Utility only, PV/battery/utility and Utility/generator. A common observation from Fig. 19 is the fact that $U_{i,j}^{utility}$ increases as the hourly electricity dispatch cost difference between Utility only and PV/battery/utility configuration increases. From 4pm to 5pm, the difference in hourly electricity dispatch cost between Utility only (7.24 Naira, $0.02) and PV/battery/utility (0.29 Naira, $0.00) which is 6.95 Naira ($0.02) results in $U_{avg}^{PV/battery/utility} = 5.68$ while for 5pm – 6pm the hourly electricity dispatch cost difference of 7.81 Naira ($0.03) results in $U_{avg}^{PV/battery/utility} = 5.58$. However, for 6pm – 7pm, the hourly electricity dispatch cost of 0.59 Naira ($0.00) results in $U_{avg}^{utility} = 5.59$.

Table 18
Carbon emissions for PV, battery, utility and generator.

Component	Emission rate
PV	72gCO_2e/kWh$^{+,@}$
Battery	50gCO_2/kWh^{++}
Utility	0.703kgCO_2/kWh*
Generator	3.827kgCO_2/hour$^{\#}$

+ - see Ref. [63]; ++ - see Ref. [64].
*- see Ref. [65]; # - Computed in this paper.
@ - has been taken to be CO_2/kWh.

The summary of the associated statistics for Utility only, PV/battery/utility and Utility/generator configurations for 4pm – 8pm is shown in Table 20. In expatiating on Figs. 15–18, Table 20 provides at a glance the $C_{i,j}^{mtd}$, U_{avg}^{mtd}, utility status (available or unavailable), PV/battery capacity (sufficient or insufficient) and demand for each hour between 4pm and 8pm. This is useful in evaluating quickly the performance of each configuration hourly and the best dispatch configuration in terms of selection.

3.1. *Sensitivity analysis*

From the results obtained, the PV/battery/utility option achieves a yearly savings of about 6000 Naira using utility electricity charge of 21.30/kWh. However, since electricity prices vary across Nigeria based on the distribution company serving a state, we run sensitivity analysis for 25.00/kWh, 30.00/kWh and 50.00/kWh with fixed solar production levels and 0% increment in electricity hourly cost by the utility to determine the effect of hourly electricity cost in influencing RoI. Table 21 presents the yearly electricity cost for Utility only and PV/battery/utility options including their yearly savings and payback period for varying hourly cost of electricity. It is observed from Table 21 that for 25.00/kWh, the yearly savings of 6 715 ($22.02) translates to a payback time of about 21 years. Similarly, for 30.00/kWh, the yearly savings of 7 395 ($24.24)

Table 19
Daily carbon emissions from the various sources.

Electricity source	Daily emission
Grid only	1.588 kgCO_2[a]
PV/battery/utility	PV – 0.104kgCO_2 Battery – 0.023kgCO_2 Utility - 1.052kgCO_2[b] 1.179kgCO_2
Utility/generator	Utility – 1.588kgCO_2[a] Generator – 26.789kgCO_2 28.384kgCO_2

[a] - Utility supply is 2259 Wh
[b] - Utility supply is 1496.60 Wh

Table 17
Daily, monthly and yearly effective demand cost for the different options.

	Daily	Monthly	Yearly
Effective demand (kWh)	2.27	69.02	828.19
Utility only cost (Naira)	48.12 ($0.16)	1470 ($4.82)	17640 ($57.84)
PV/battery/utility cost (Naira)	31.89 ($0.10)	976 ($3.20)	11716 ($38.41)
Utility/generator cost (Naira)	Utility (48.12 Naira, $0.16)	1470 ($4.82)	17640 ($57.84)
	Generator (3150 Naira, $10.33)	95813 ($314)	1149750 ($3770)
	3198.12 ($10.49)	97283 ($319)	1167390 ($3828)

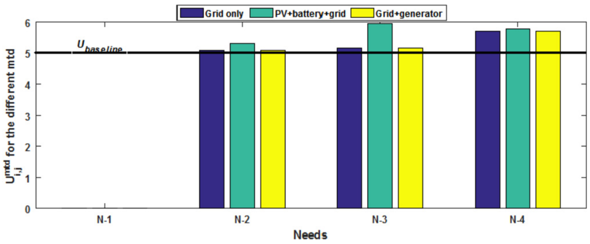

Fig. 15. $U^{mtd}_{i,j}$ chart for 4pm – 5pm.

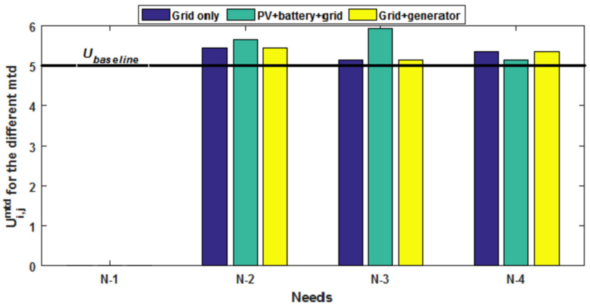

Fig. 16. $U^{mtd}_{i,j}$ chart for 5pm – 6pm.

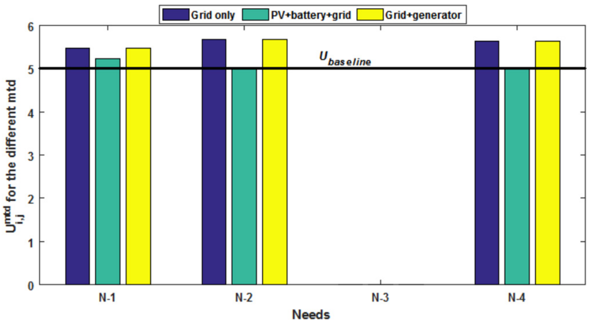

Fig. 17. $U^{mtd}_{i,j}$ chart for 6pm – 7pm.

results in a payback time of 16 years with 50.00/kWh resulting in yearly savings of 10 112 and an eventual payback time of about 8.4 years.

The implication of this sensitivity analysis is that across Nigeria, different states with varying hourly costs of electricity have varying potential payback periods. This thus implies that in encouraging the adoption of the PV/battery/utility option, there should be an incentive to the buyer which shows significant potential savings over a reasonable time. Furthermore, while this sensitivity analysis has only examined the effect of hourly electricity cost on payback period computation, advancements in solar PV efficiency imply that there could be further reduction in payback period thus making the adoption of PV/battery/Utility option quite attractive. The attractiveness of the PV/battery/Utility option notwithstanding, solar irradiance plays a crucial role as its stochasticity can increase the payback period invariably making the utility/generator or Utility only options better alternatives.

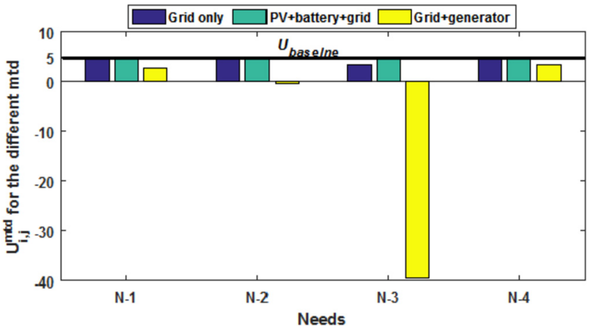

Fig. 18. $U^{mtd}_{i,j}$ chart for 7pm – 8pm.

In benchmarking the results obtained in this work, the savings obtained in Ref. [3] show that annual savings on electricity bills was about 38%. For this work, it is seen from Table 21 that annual savings vary from 34% (at 21.30/kWh), 52% (at 23.00/kWh), 56% (at 25.00/kWh) to 64% (ta 30.00/kWh) for the considered loads. Furthermore, in terms of peak demand reduction, Table 15 shows that BLM-HEMS achieves an average peak demand reduction of 52% for the time between 4pm and 8pm compared with 42% peak time electricity demand reduction in Ref. [3]. The cumulative effect of the peak demand reduction thus implies that the utility can take advantage of BLM-HEMS (as a demand response mechanism) for targeted areas to shave peak demand as also posited in Ref. [3] where it was argued that the savings is of more advantage to the utility. The benefits of the significant reduction in peak demand implies that the utility has improved utilization of its supply capacity and can optimally dispatch its generators at reduced operations cost. Furthermore, the utility can balance demand/supply with minimized reserve margins [62].

3.2. Policy discussions for improving the adoption of BLM-HEMS

Energy poverty in Nigeria is both a problem of access (primarily) and mobility (i.e. the ability of households to increase their electricity consumption either by increasing electrical appliances owned or extending the duration of usage of already owned electrical appliances). As noted in Ref. [4], there was limited usage of solar PV systems. This is not unusual owing to the huge costs involved in initial purchase and for subsequent upgrades. In order therefore to improve the ownership of more solar PV systems across households, government could implement an additional surcharge for fossil-based electricity generation. This cost which is billed the utility would invariably be transferred to the consumers through higher electricity costs. With higher electricity costs, there is more incentive for households to consider adopting a hybrid system.

However, while the government implements a fossil-based tax on the utility, it must ensure that policy is put in place to reduce the cost of purchase of solar PV systems. According to [1], the government could explore options such as tax exemption for imported solar PV products and financing options for their purchase. Also, considering the need for technical expertise in their set up, government should also encourage the training of skilled manpower necessary for the installation, maintenance and repair of these systems.

4. Conclusions

A biased load manager home energy management system (BLM-HEMS) has been proposed and modelled in dispatching specific loads for low income consumers, using low cost buildings in Lagos, South-West Nigeria. The users' electricity appliances have been classified accordingly with the BLM-HEMS which provides an interface for integrating the grid and alternative power system for

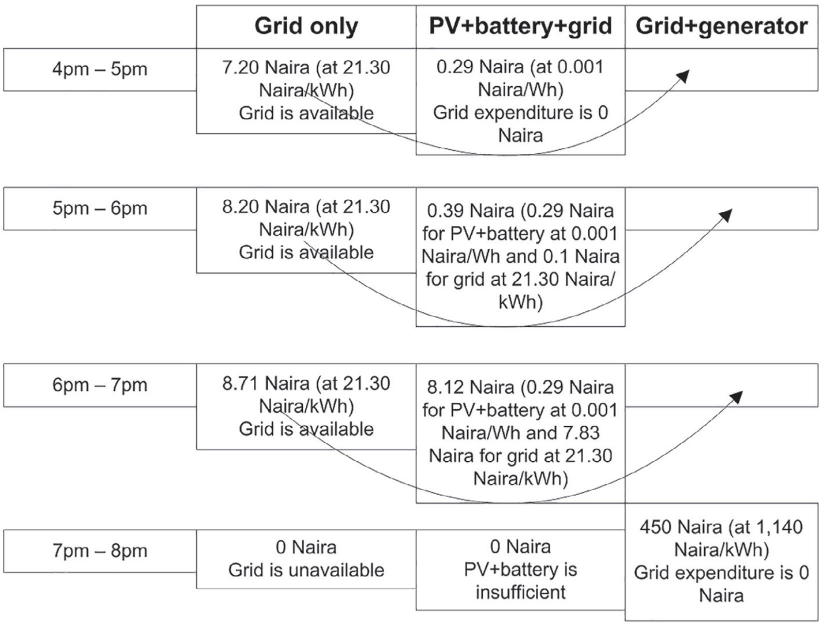

Fig. 19. Price fluctuation across the various *mtd*.

Table 20
Summary of associated statistics for Utility, PV/battery/utility and Utility/generator configurations.

Time	Demand	Utility only		PV/battery/utility		Utility/generator	
4pm – 5pm	340 Wh	$C_{i,j}^{utility}$	7.24 Naira	$C_{i,j}^{PV/battery/utility}$	0.29 Naira	$C_{i,j}^{utility/generator}$	7.24 Naira
		$U_{avg}^{utility}$	5.32	$U_{avg}^{PV/battery/utility}$	5.68	$U_{avg}^{utility/generator}$	5.32
		Status	Available	PV/battery	Sufficient	Utility	V
				Grid	Available	Generator	VX
5pm – 6pm	385 Wh	$C_{i,j}^{utility}$	8.20 Naira	$C_{i,j}^{PV/battery/utility}$	0.39 Naira	$C_{i,j}^{utility/generator}$	8.20 Naira
		$U_{avg}^{utility}$	5.32	$U_{avg}^{PV/battery/utility}$	5.58	$U_{avg}^{utility/generator}$	5.32
		Status	Available	PV/battery	Insufficient	Utility	V
				Grid	Available	Generator	VX
6pm – 7pm	409 Wh	$C_{i,j}^{utility}$	8.71 Naira	$C_{i,j}^{PV/battery/utility}$	8.12 Naira	$C_{i,j}^{utility/generator}$	8.71 Naira
		$U_{avg}^{utility}$	5.59	$U_{avg}^{PV/battery/utility}$	5.07	$U_{avg}^{utility/generator}$	5.59
		Status	Available	PV/battery	Insufficient	Utility	V
				Grid	Available	Generator	VX
7pm – 8pm	396 Wh	$C_{i,j}^{utility}$	8.43 Naira	$C_{i,j}^{PV/battery/utility}$	0.29 Naira***	$C_{i,j}^{utility/generator}$	450 Naira
		$U_{avg}^{utility}$	4.24	$U_{avg}^{PV/battery/utility}$	4.97	$U_{avg}^{utility/generator}$	−8.48
		Status	Not available	PV/battery	Insufficient	Utility	X
				Grid	Unavailable	Generator	VV

V – utilized in dispatching hourly needs; X – Source not available for dispatching needs.
VX – Source available but not utilized in dispatching needs.
VV – Source available and utilized in dispatching needs.
***- PV/battery normal hourly cost of electricity is assumed.

Table 21
Sensitivity analysis results for varying $E_{PC}(Naira/kWh)$.

E_{PC} $(Naira/kWh)$	Annual electricity cost (Naira)		Yearly savings (Naira)	Payback period (Years)	Annual electricity cost savings (%)
	Utility only	PV/battery/utility			
21.30	17 640 ($57.84)	11 716 ($38.41)	5924 ($19.42)	25	34
25.00	13 957 ($45.76)	6715 ($22.02)	7242 ($23.75)	21	52
30.00	16 749 ($54.91)	7395 ($24.24)	9354 ($30.67)	16	56
50.00	27 915 ($91.52)	10 112 ($33.16)	17 802 ($58.37)	8.4	64

load dispatch. Based on the maximum amount users are willing to spend, analysis has been conducted to investigate the best configuration (alternative power source) that would lead to an improvement in occupants' comfort level while reducing their electricity bill and carbon footprint.

Results obtained show that the PV/battery/utility configuration offers the best option due to its low yearly maintenance cost, reduced carbon emissions and improvement in consumer comfort compared to the Utility only and Utility/generator configurations. Results have also established that although the Utility/generator configuration is capable of meeting entirely the needs of the user daily, its high operations and maintenance cost coupled with its high carbon footprint decimate drastically any potential savings accrued from its dispatch of occupants' needs. Furthermore, the peculiarity of utility availability in Nigeria (frequent grid interruptions) makes the Utility only option a poor choice owing to the lack of an alternative to offset demand during grid interruptions.

The daily savings of the PV/battery/utility configuration over the Utility only configuration for hourly electricity cost of N21.30/kWh is about 34% with a 26% reduction in carbon emissions by the PV/battery/utility configuration over the Utility only configuration. The yearly savings of the PV/battery/utility configuration of about 6000 Naira ($19.67) translates to about 4% of the cost of initial PV/battery purchase and installation. This implies that the PV/battery/utility configuration can repay the initial purchase and installation costs within 25 years excluding yearly maintenance and battery replacements. In terms of daily usage, the proposed BLM-HEMS is not intended to be complicated as it is envisaged to be interoperable with existing solar PV systems. However, a discrimination of household load points is necessary for easy application of the load allocation component of the BLM-HEMS.

The sensitivity analysis carried out has shown that the adopted BLM-HEMS reacts favourably to higher hourly electricity cost from the utility with potential annual electricity savings of up to 64% and a payback period of 8.4 years. This value exceeds the reported savings in Ref. [3] which shows the viability of the proposed BLM-HEMS. Furthermore, the 4% improvement in comfort level for the house also implies that the systems multi-objectives are fully meant. The BLM-HEMS is thus capable of mitigating poverty in households since it guarantees savings for households which can be utilized for other activities or for extending the utilization time of already owned electrical appliances. The BLM-HEMS thus improves the application of solar PV systems beyond basic household needs as presented in Ref. [4], by ensuring that yearly savings from the PV/battery/utility option can be utilized in upgrading households SHS for increased solar PV participation in household electricity generation. This implies that such households can engage in other economic activities beyond basic household needs due to improvement in electricity access. This study can be useful for better understanding of on-grid/off-grid home energy systems which are instrumental for future energy planning and incentive analysis in developing countries, including Nigeria.

Future research would be to investigate the effect of load ownership and duration of use on the comfort level and productivity of households. This is necessary to help provide low/middle income households an improved guide to owning electrical appliances that will lead to improvement in their quality of life and overall productivity.

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CHAPTER 7

PAPER 6 - IEEM

Brief summary

This chapter presents the paper entitled ***Policy discussion for sustainable integrated electricity expansion in South Africa***. This chapter harmonizes DSM and the proposed ConCEMS in presenting an integrated electrification and expansion model (IEEM) for South Africa. The proposed IEEM provides a sustainable pathway for generation and transmission capacity expansion across South Africa and provides the utility and the electricity regulator NERSA (National Energy Regulator of South Africa) an avenue to observe the impact of pricing tariff increase and emissions penalty on consumer expenditure. Also, the proposed IEEM offers the utility a platform to evaluate the impact of various DSM initiatives on network performance. The findings from this chapter provide further policy discussions especially on poverty mitigation.

Paper status: Accepted in Energy Policy (ISI)

Policy discussion for sustainable integrated electricity expansion in South Africa

Monyei, C. G.[1,2,4], Jenkins, K.[3], Viriri, S.[1] and Adewumi, A. O.[1]

[1]School of Mathematics, Statistics and Computer Science, University of KwaZulu-Natal,
Westville Campus, Private Bag X54001, Durban 4000, South Africa
[2]Gidia Oaks Centre for Energy Research, Lagos, Nigeria
[3]School of Environment and Technology, University of Brighton, Cockcroft Building,
Moulsecoomb, Brighton BN2 4GJ, United Kingdom
[4]Corresponding author

Abstract

Emerging reports have shown that despite Eskom's continued investment in increasing electricity supply capacity to grid connected and off-grid households, there has been a steady decline in electricity consumption (kWh/month/individual) and household income (ZAR/month). This paper presents an integrated electricity expansion model (IEEM) for South Africa that seeks to incorporate demand side management (DSM) in providing a roadmap for improving and increasing energy (electricity) access that is sustainable, viable, ethically compliant and cost effective. In modelling IEEM, a modified genetic algorithm (MGA) would be utilized in simulating the dispatch of DSM loads (residential houses only) across the country. This paper advances traditional grid expansion planning by presenting smart policy discussions on the usefulness of IEEM in reducing associated network losses, enhancing utilization of local energy sources and minimizing expansion and plant operations costs. This paper also discusses the impact of the IEEM on the quality of life (QoL) of households and quality of service (QoS) of the utility. Electricity consumption data have been adopted from the existing literature and appropriately modified.

Keywords - integrated electricity expansion model, energy poverty, sustainability, smart policy, demand side management

Highlights

✓ Presents an integrated electricity expansion model (IEEM) for South Africa.

✓ Outlines the potential of IEEM to integrate DSM to minimize grid expansion.

✓ Presents techno-economic policy discussions on potential network loss reduction.

✓ Extends further policy discussions on poverty mitigation and REPs utilisation.

Nomenclature

DLC	Direct Load Control
DP1, DP2, DP3	Dynamic pricing tariff options
FBAE	Free Basic Alternative Energy
FBE	Free basic Electricity
k,z	Indices of buses
MGA	Modified Genetic Algorithm
QoL	Quality of Life
QoS	Quality of Service
REPs	Renewable Energy Projects
SHS	Solar Home System(s)
T	24 hours duration or 96 time slots
t	time slot of 15 minutes interval
TOU	Time of Use pricing tariff option

1 Introduction

According to the Transmission Development Plan (TDP) (Eskom 2015b), Eskom is expected to step up the construction of additional electricity supply capacity from 2017. The accelerated efforts by Eskom are sequel to the energy crisis that has plagued South Africa since 2008; originally leading to massive blackouts, load shedding and huge economic losses (Kohler 2014; Shezi 2015). While about 3,516 MW is expected to be lost from the grid due to deteriorating and decommissioning of ageing power plants between 2021-2024, about 19,000 MW is expected to be added to the grid capacity through new builds and capacity expansion between 2017-2024 (Eskom 2015b). Table 1 (Eskom 2015b) presents the planned decommissioning between 2021-2024 while Tables 2 (Eskom 2015b) and 3 (Eskom 2015b) present the planned supply capacity increment between 2017-2024. Within, Table 2 shows the Medupi and Kusile coal-fired and Ingula pumped storage power stations as key developments to meet peak demand. The power plants in Table 2 all feed into the national grid.

Further, additional costs are expected to arise given the need to increase the transmission network capacity and the requirement to build additional transmission and distribution stations in order to wheel power to homes and industry sites. It is expected that the bulk of the costs for expansion will be borne by the electricity consumers in form of increased electricity bills while further support will come from loans from the government and commercial creditors (BusinessReport 2018). The population growth predictions shown in Table 4 (Eskom 2015b) present a growing trend in electricity demand forecasts. An assumed consequence of the increasing population, increasing energy needs and increasing industrialization is the need for Eskom to continue to boost generation capacity to always match projected demand. Yet this idea is at variance with a global trend, where demand side management (DSM) initiatives are being implemented in order to reduce the need for new builds and efficiently utilize existing technologies to meet current demand. This is due, largely, to the huge costs involved in building power stations and the long timespan between construction the synchronization of power plant outputs (Ofgem 2015).

Figure 1 presents the conventional electricity expansion plan currently being exploited by Eskom. During the process of executing electricity expansion, Eskom models electricity demand increases considering diverse factors (Gross Domestic Product (GDP), inflation, previous electricity demand growth, government policies etc.) to come up with various growth patterns considering multiple variants (shown in Table 4).

1.1 Prevailing problems associated with South Africa's electricity expansion plan

The demerits of the conventional electricity expansion plan of South Africa are as follows:

- There is the possibility of a supply glut (surplus) due to over-compensation of supply capacity. Such an instance was witnessed in the 1990's and led to the mothballing of the Komati, Camden and Grootvlei power stations (Monyei and Adewumi 2017).
- There is the possibility of a supply deficit owing to either demand exceeding projections or policy inconsistencies that mitigate against the development of new builds to shore up supply capacity. Such an instance was witnessed in 2008, when supply could not meet peak demand leading to massive load shedding and blackouts (Kohler 2014; Shezi 2015).
- Low utilization of renewable energy resources. Despite considerable increase in renewable energy projects (REPs), the lack of control over end user load dispatch (flexible DSM loads) by Eskom prevents them from fully utilizing the potentials of REPs due to their stochasticity. System operation and planning is thus done using base load stations (coal and nuclear) whose capacities and performances can be evaluated exactly.
- The loss of loads and blackouts remain a possibility. In instances of peak demand, the inability of Eskom to quickly dispatch end user loads without financial penalties means the possibility of load shedding becomes high.
- Electricity billing could be excessive. According to Eskom (2017b), between 2008 and 2013, electricity price cumulatively rose by about 114% which was at variance with declining electricity prices prior to 2008/09. The sharp increase in electricity price (which was to enable Eskom raise future revenue to cover for new builds) was met with increasing public resistance (Eskom 2017b). Eskom has thus consistently argued for further increases in electricity prices to enable it to bridge its revenue shortfall (R35 billion in 2014/15).

1.2 Major contributions of this research

The aim of this paper is to study and show the impact of an electricity expansion model (that integrates all aspects of the electricity grid) on peak demand reduction, expansion costs reduction, capacity utilization maximization, maximization of earnings (for the supply side), minimization of electricity costs (consumption/utilization side) and network loss reduction. This is consequent on the fact that in addressing the issues associated with the conventional system of electricity expansion planning in South Africa, there is the need for an electricity expansion plan that is capable of:

- Isolating consumers from extreme price fluctuation due to the utility's billing system that attempts to recoup investments on new builds.

- Utilizing REPs effectively.Rather than expending huge sums building large-scale storage facilities for wind and solar projects, end user loads could be dispatched during times of wind/solar availability. While we acknowledge the role of battery energy storage in stabilizing the electric grid and enabling the integration of REPs (Hu et al. 2017), we however draw caution from DiOrio et al. (2015) who offer that *it is necessary to evaluate the utility rate structure, and determine whether the addition of battery storage can be leveraged to reduce costs enough to justify the upfront capital expenditure and replacement costs.* This is important in ensuring that consumers do not become unnecessarily over-burdened with huge electricity bills.

- Efficiently utilizing installed supply capacity. With adequate knowledge of demand schedules and operational control of a fraction of end users loads, the utility is able to optimally dispatch generation sources and allocate end user loads such that dispatched supply capacity is efficiently utilized. This is necessary to prevent energy wastage, reduce emissions and operations losses.

- Minimizing network losses[1]. With advanced knowledge of demand growth profiles across the provinces, it becomes possible to evaluate the associated costs (economic, losses) and benefits of situating a generation source closer to a demand hub[2] or extending the transmission network from the generation hub [3] to the demand hub. While it might be economical to locate power plants close to primary fuel sources, there is the possibility of incurring high economic costs and he network losses through evacuating power from the generation site to load centres. Balancing the location of generation sources to minimize economic costs and network losses becomes important.

- Minimizing expansion. The ability to predict demand growth and evaluate operational DSM (by which we mean flexible loads whose operation hours can be influenced externally) capacity provides the utility company with an avenue to explore varied energy supply mix options, including REPs. This may minimize the utility's expansion of supply capacity, inherently improving efficiency and reducing expansion costs.

Figure 2 presents the proposed integrated electricity expansion model (IEEM). In differing from Figure 1, Figure 2 operationalizes DSM. By this, we mean that it makes DSM load hours of operation flexible. In Figure 1, DSM initiatives being adopted by Eskom consist of energy efficiency demand side management (EEDSM). In 2008, Eskom began a campaign to exchange incandescent bulbs in homes for more energy efficient compact fluorescent lamps (CFLs) with about 65 million of such energy efficient CFLs installed in South African homes to date. The result has been considerable energy savings and reduced electricity bills, job creation and a culture of greater energy efficiency among South Africans. It is estimated that about 11.8 TWh of DSM programs are

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[1] According to Eskom (2015a), total technical energy losses for the 2014/15 financial year was estimated at 8.79%. While transmission losses (estimated at 2.53%) are mainly associated with power evacuation and increase with distance, distribution losses (estimated at 6.78%) are influenced by factors such as network design, network topology, load distribution and network operations.

[2] We define a demand hub to be a cluster of provinces with cumulative demand exceeding 15% of the total demand for South Africa.

[3] By generation hub we mean a cluster of power plants with generation capacity exceeding 30% of total generation capacity of South Africa. An example of such is the Mpumalanga Power Pool (MPP).

currently in place in South Africa with expected cumulative savings of 466 MW by 2017/2018 from the additional Residential Mass Rollout lighting LED program which commenced 2015/2016 (Eskom 2017a). However, despite the projected savings expected from such measures, their impact is passive due to the fact that the utility has no influence over the utilization time of EEDSM initiatives like CFLs distribution in South Africa. Figure 2 advances Figure 1 by incorporating price based DSM with specific loads either being controlled directly by the utility (direct load control, DLC) or by the home owners (within a flexible window).

2 The integrated electricity expansion model (IEEM) and related works

As shown in Figure 2, in predicting demand growth, the growth of flexible customers[4] is also predicted across the provinces. This is necessary as it helps in determining the minimum expansion needed (rather than the conventional expansion model shown in Figure 1 that aims for maximum expansion units).

A review of related literature for South Africa shows that only Monyei and Adewumi (2017) have been able to quantitatively illustrate growing energy poverty in South Africa as well as providing initial evidences of the benefits of operationalizing DSM for an isolated case. Other related works on the electricity sector in South Africa have centred around associated statistics and policy, for example Blommestein and Daim (2013)who carried out the evaluation of consumers decision making processes around energy efficient devices using a hierarchical decision model (HDM) to determine if there was a sync between consumers technology focus and current efficiency initiatives; Amusa et al. (2009) who applied bounds testing approach to co integration with an autoregressive distributed lag framework to examine South Africa's electricity demand during the period 1960-2007 and Inglesi (2010) who forecast (using the Eagle-Granger methodology for co-integration and error correction models) the electricity demand of South Africa up to 2030. Similarly, DSM studies have been carried out by Clark (2000), who investigate the factors inhibiting municipalities from investing in DSM initiatives; Lombard et al. (1999) where a program for thermal efficiency in the South African residential sector was proposed and Rankin and Rousseau (2008) where the authors described how an improved inline water heating concept was capable of achieving peak load reduction without availability compromise within the specified operating time. Furthermore, other researchers have extended studies to pricing and its effect on electricity demand. For example, the effect of pricing policy on aggregate electricity demand and the magnitude of demand change/response to a variation in pricing policy between 1960-2007 for South Africa was studied in Amusa et al. (2009), while Inglesi-Lotz (2011) applied the Kalman filter in estimating the price elasticity of electricity in South Africa between 1980-2005.

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[4] We define flexible customers for this paper to be households with grid access and who have agreed to participate in DSM initiatives by either leaving the dispatch of selected loads to the utility within a flexible window or strict flexible window. By flexible window, we mean 24-hours window and by strictly flexible window, we mean a 2-hour window. Selected loads for this paper are cloth washers, cloth dryers and dishwashers. The incentive for participation is a reduction in electricity bills for the participating loads.

2.1 Motivation for IEEM

The 1990's mothballing of power production plants (see Monyei and Adewumi 2017) as well as the subsequent supply deficit in 2008 that precipitated the blackouts and load shedding that characterized the electricity network of South Africa between 2008-2015, necessitates a more proactive model that is sustainable and flexible. Furthermore, growing/expanding grid access has not directly translated to increasing electricity consumption (kWh/capita). Monyei and Adewumi (2017) illustrate this by investigating declining electricity per capita, as do STATSSA (2017), who illustrated an increase in South African poverty rates (estimated to be about 55.5%). It can thus be inferred that increasing poverty will directly result in decreasing disposable income and increasing energy poverty (since households would spend more of their disposable income purchasing lesser electricity units due to increasing electricity tariffs). In addition, Monyei and Adewumi (2017) offer that the estimated addition to the grid capacity between 2017-2024 is over 500% in energy terms. This thus implies that Eskom stands at a higher risk of incurring further revenue shortfall due to increasing operational losses (owing to underutilization of installed capacity, increasing operations and maintenance costs and reduced revenue owing to decreased electricity units purchases). IEEM is thus important in obviating the need for maximum demand sizing in grid expansion by introducing flexible customers and efficiently utilizing REPs. Further, this paper advances the discuss in Monyei and Adewumi (2017) beyond an isolated case by computing DSM potentials and evaluating its impact (in terms of cost and expansion) for South Africa and making policy recommendations.

3 The IEEM description and application

In attempting to model DSM for South Africa and provide policy recommendations as regards electricity expansion, network losses, REPs utilization and electricity tariffs, we first describe South Africa's main electricity company and the electricity network model employed in this paper.

3.1 A brief description on Eskom

The major electricity provider in South Africa is Eskom, which generates over 95% of the total electricity consumed in South Africa and about 45% of electricity produced in Africa. In addition to electricity generation, Eskom owns the majority of the transmission network in South Africa with an average yearly production of about 200 000 GWh. Eskom generates and sells electricity to municipalities (42.7%), industries (22.3%), mines (14.4%), commercial and agricultural based companies (7%), rail companies (1.4%) and exports about 5.6% of its electricity. Their major production sources for electricity include coal (83%), nuclear (5%) and imports (4%). Imports are from the Southern African Power Pool (SAPP) which is an inter-connected regional transmission network of the Southern African Development Community (SADC) (Monyei and Adewumi 2017).

3.2 Description of model electricity network for South Africa

Figure 3 presents a network model for the South Africa grid. It consists of ten buses (BUS 1 - BUS 10), nine load points (LP1 - LP9), five major power generation points (PP1 - PP5) and fifteen transmission lines (Line 1 - Line 15). For the model shown in Figure 3, all the transmission lines are assumed to be 400-kV transmission lines[5]. For the purpose of this paper, the generation sources considered are coal and nuclear, which form the base load stations for South Africa. Table 5 presents the relationship between Buses 1 - 9 and the respective province electricity statistics.

3.3 Problem description

The aim of this paper is to study and show the impact of IEEM on peak demand reduction, expansion costs reduction, capacity utilization maximization, maximization of earnings (for the supply side), minimization of electricity costs (consumption/utilization side) and network loss reduction. The mathematical description of the preceding problems are as follows:

3.3.1 Peak demand minimization

Given P^t (MW), BL^t (MW) and DSM^t (MW),

$$BL^t + DSM^t = P^t \tag{1}$$

The objective function P^t_{IEEM} is defined as

$$P^t_{IEEM} = min(P^t) \tag{2}$$

Where P^t (MW) is the total power demand, BL^t (MW) is the total base load demand and DSM^t (MW) is the DSM demand for South Africa for slot t. A slot is defined as a 15-minutes interval.

3.3.2 Expansion costs minimization

Given C^{exp} (ZAR/MW) to be the cost of adding an additional MW to the national grid, then the objective function C^{exp}_{IEEM} is defined as

$$C^{exp}_{IEEM} = min(C^{exp}) \tag{3}$$

3.3.3 Capacity utilization maximization

Given $Util^t$ (%) to be the average utilization of power plants across South Africa, the objective function $Util^t_{IEEM}$ is defined as

$$Util^t_{IEEM} = max(Util^t) \tag{4}$$

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[5] Major transmission network of South Africa consists of 765-kV, 533-kV, 400-kV, 275-kV, 220-kV and 132-KV lines.

3.3.4 Revenue maximization - supply side

Given $Supp^T$ (ZAR/day) to be the total daily revenue earned by the supplier from electricity sold, the objective function $Supp^T_{IEEM}$ is defined as

$$Supp^T_{IEEM} = max(Supp^T) \tag{5}$$

where $Supp^T = \sum_{t=1}^{t=96}(Supp^t)$

3.3.5 Electricity cost minimization - consumer side

Given H^{exp} (ZAR/day) to be the daily electricity cost for a house participating in DSM, the objective function H^{exp}_{IEEM} is defined as

$$H^{exp}_{IEEM} = min(H^{exp}) \tag{6}$$

3.3.6 Network loss minimization - transmission only

Given $Loss^T$ (MW) to be the daily transmission losses for the electricity network, the objective function $Loss^T_{IEEM}$ is defined as

$$Loss^T_{IEEM} = min(Loss) \tag{7}$$

where $Loss^T = \sum_{t=1}^{t=96}(Loss^t)$

3.3.7 Operations cost minimization

Given OP^T (ZAR/day) to be the daily operations cost in generating and distributing electricity by the utility, the objective function OP^T_{IEEM} is defined as

$$OP^T_{IEEM} = min(OP^T) \tag{8}$$

Subject to

$$OP^T = F^T + E^T + Mt^T \tag{9}$$

where F^T (ZAR/day) is the daily fuel cost (coal cost, water cost etc.) for running power generation plants, E^T (ZAR/day) is the daily emissions cost based on power sent out and Mt^T (ZAR/day) is the daily cost of maintenance for the power generation plants.

3.4 Solving the network model

The Gauss-Seidel model has been chosen for attempting to solve the resulting load flow problem from Figure 3. Its choice is basically due to familiarity and ease of programming and speed since Newton-Raphson takes longer because of the need to recalculate the Jacobian (Gilbert et al. 1998). Applying Kirchoff's current law given the bus admittance matrix yields equation 10.

$$I = Y_{bus}V \tag{10}$$

The k^{th} nodal current of N nodes (BUSES) is obtained to be $I_k = \sum_{z=1}^{N}(Y_{kz}V_z)$ which can be resolved to give (11).

$$I_k = Y_{kk}V_k + \sum_{z=1}^{N}(Y_{kz}V_z) \tag{11}$$

Re-arranging (11) to obtain V_k is shown in (12).

$$V_k = \frac{I_k}{V_{kk}} - \frac{1}{Y_{kk}}\sum_{z=1}^{N}(Y_{kz}V_z) \tag{12}$$

if $S_k = P_k - jQ_k$ then (13) is obtained.

$$V_k^{t'+1} = \frac{1}{Y_{kk}}[\frac{P_k - jQ_k}{(V_k^{t'})^*} - \sum_{z=1}^{N}(Y_{kz}V_z^{t'})] \tag{13}$$

Where I_k is current, V_k/V_z is voltage and Y_{kk}/Y_{kz} is bus admittance matrix. The modelling of the Gauss-Seidel operation is constrained to ensure that convergence is only possible within allowed bus voltage limits. Similarly, S_k, P_k and Q_k are the apparent, real and reactive power (all in per unit) at bus k.

3.5 Assumptions for network

The network model shown in Figure 3 is assumed, within realistic approximations, to present valid values for the South African electricity network. The following have been assumed in simplifying the electricity network for South Africa:

- Only base load generation stations (coal and nuclear) have been used in the simulation.
- All base load generation stations within a province have been merged to form a pool (PP1-PP5).
- The load within a province have been merged to also form a pool (LP1-LP9) .
- Random lengths have been assigned to the transmission lines to enable the computation of line losses due to variation in situating generation plants. For this paper, the length of the transmission line is immaterial since we are solely interested in the variation (percentage increase/decrease) of network transmission losses due to variations in the location of power generation plants.
- The transmission lines are all assumed to have infinite ampacity limits.
- Power imports have been included in PP1 (from Botswana) and PP3 (from Mozambique).

4 Scenario modelling

Three scenarios (Scenarios 1, 2 and 3) are modelled and discussed with respect to Section 3.3.1 to Section 3.3.7. For each Scenario being modelled, three cases are considered. The adoption of varying locations for power station placement is to explore the effect of power plant location on parameters such as network loss, utilization, reactive power compensation, voltage profile etc. The scenario modelling thus assists in determining the optimal location for locating power plants that will achieve an optimal system configuration at the minimum cost. Furthermore, the variation in the DSM profiles is to evaluate the extent to which flexibility in DLC affects peak demand, supply capacity utilization and other associated costs.

- Case 1: Here, households participating in DSM determine when participating DSM loads are to be dispatched within a time-frame[6]. For this case, the time-frame is 05:00-08:00 and 17:00-22:00. It is also assumed that the dispatch of DSM loads (DSM-potential for each province is shown in Table 5) under this case follows the natural and unconstrained usage pattern of participating households.
- Case 2: Under this case, the participating DSM loads (DSM-potential shown in Table 7) are dispatched by the utility across the day. The time-frame is from 00:00 - 00:00 (next day). The incentive for participation is the reduction of electricity bills for the participating households. This case also offers the utility the most flexibility in optimizing the dispatch of generation plants to reduce its operation costs and improve capacity utilization. The DSM loads are under direct load control (DLC) by the utility.
- Case 3: Under this case, the utility dispatches participating households DSM loads within the time-frame 05:00-08:00 and 17:00-22:00 with the possibility of exceeding 08:00. DSM loads (DSM-potential shown in Table 5) are under DLC in this case. In differing from Case 1, Case 3 incorporates DLC for the dispatch of the DSM loads. Similarly, Case 3 differs from Case 2 by adopting a more constrained time-frame (similar to Case 1). Case 3 also offers households reduction in electricity bills and reduced operation costs for the utility.

Figure 4 depicts the dispatch time profile for participating DSM loads. It is seen from Figure 4 that the time-frame is denoted by w_i where w_i is 2-hours for Cases 1 and 3[7] and 24-hours for Case 2. Also, $t_{i,j}^{start}$ is the earliest start time for DSM load j in house i and is 05:00 for Cases 1 and 3 and 00:00 for Case 2. $t_{i,j}^{'}$ is the latest time a participating DSM load can be dispatched based on its hours of operation ($t_{i,j}^{duration}$), $t_{i,j}^{dispatch}$ is the time of actual dispatch of the DSM load j, $t_{i,j}^{stop}$ is the latest stop time for a dispatched DSM load j while $t_{i,j}^{final}$ is the actual stop time for a dispatched DSM load j. Table 6 presents the description of the participating DSM loads including their duration of dispatch and power rating while Figure 5 presents the daily base load profile for all provinces. The justification for the choice of the participating DSM loads is explicitly discussed in Monyei and Adewumi (2017). In modelling the different Cases (1, 2 and 3), the incorporated MGA (Monyei and Adewumi 2017) aims at minimizing the peak demand (MW) for the DSM loads (irrespective of the base loads). Figure 6 presents the cumulative DSM profile for all Cases and provinces and is utilized for all Scenarios.

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[6] A time-frame for this paper is the period within which DSM loads are to be dispatched i.e. from $t_{i,j}^{start}$ to $t_{i,j}^{stop}$.

[7] This would not always hold for Case 3 due to the possibility of $t_{i,j}^{stop}$ exceeding the 2-hours limit for some households.

4.1 Scenario 1

In Scenario 1, we model the electricity network shown in Figure 3 with DSM and base load considerations as shown in Figures 6 and 5 respectively and the normal placement of base load power generation plants as shown in Table 7. This scenario provides a baseline for comparison purposes with all other scenarios. Table 8 provides further explanation to Table 7. BUS 2 is assumed to be the slack bus for this case while other generating plants are dispatched at 70% capacity utilization.

4.2 Scenario 2

In Scenario 2, we model the same electricity network as used in Scenario 1 (i.e. Figure 3) utilizing same DSM and base load profiles (shown in Figures 6 and 5 respectively) but with power plant distribution as shown in Table 7 (as modified). The placement of the additional power plants for this scenario is by inspection (randomly) and does not follow any scientific method. Similar to Scenario 1, BUS 2 is taken to be slack bus while other generation power stations are dispatched at 70% capacity utilization.

4.3 Scenario 3

Scenario 3 is similar to Scenario 2 but with an additional power plant as described in Table 7. The additional plant added to the indicated bus is assumed to be a base load power generation plant (typically coal or nuclear). However, the plant could also be a combination of other sources - natural gas, REPs etc. BUS 2 is taken to be the slack bus with other generation power plants dispatched at 70% capacity utilization.

4.4 Price modelling

Four varying pricing models are utilized in order to show the robustness of IEEM and aid policy discussions. The time of use (TOU) and 3 dynamic pricing schemes (DP1, DP2 and DP3) as shown in Figure 7, are adopted in evaluating electricity cost for the DSM loads only in all Cases. Irrespective of the scenario modelling (1, 2 or 3) adopted, the cost of the DSM loads for all cases remains the same for the scenarios. The Eskom TOU pricing scheme adopted is for a household whose monthly electricity consumption is an average of $600kWh$. The cost for off-peak periods is about $ZAR1.25/kWh$ and is exclusive of the peak period prices. For the purpose of this research, 20% has been added to the spot price during off-peak periods to generate the peak period (6am-8am and 6pm-9pm) TOU price. Weekdays and weekend peak periods have been assumed to be similar. Similarly, for the dynamic pricing schemes adopted, the computation of the dynamic price DP^t (where DP could be DP1, DP2 or DP3) follows the time of use (TOU) pricing being used by Eskom. Given FP^t as the TOU pricing electricity spot price, then $\frac{1}{96}\sum_{t=1}^{t=96}(DP^t) = \overline{FP^t}$ (Monyei and Adewumi 2017).

5 Results and discussion

Table 9 presents the associated statistics for the DSM loads only. It is observed from Table 9 that irrespective of the scenario, Case 2 has the lowest build size of 173.48 MW while Case 1 has the highest build size of 495.01 MW. The selection of the maximum build size is based on the highest power demand (based on DSM load allocation by MGA) across the day. Also presented in Table 9 is the cost of electricity (DSM loads only) across the cases. Using TOU cost as the baseline cost, it is seen that Cases 1 and 3 offer competitive prices in terms of cost reduction for the participating households (utilizing DP1 and DP2). For example, in Case 1, DP1 offers a 25.41% cumulative reduction in combined DSM load electricity cost while DP2 offers a 13.41% cumulative electricity cost reduction for all participating households. Similarly, for Case 3, DP1 offers 18% cumulative reduction in electricity cost with DP2 offering cumulative electricity cost reduction of 8.67%. The cumulative reduction in electricity costs (for Case 1 using DP1) translates to 3.26 kWh daily savings per household (based on 1.25 ZAR/kWh). This could either be used in extending electricity usage or other activities that could improve the quality of life (QoL) of households.

Based on Eskom (2017b) and Eskom (2015b), the average cost of building supply capacity for 2016/17 is estimated at ZAR 9.39 million/MW. The implication of this is that excluding operations and other associated costs, the build cost for Case 3 (363.84 MW) can be recovered (from DSM loads only) in about 194 days using DP1 and about 174 days using DP2. While Case 2 offers a very competitive value in terms of expansion cost reduction, its offer of competitive pricing for participating households is almost negligible. Table 10 presents the daily cumulative losses across the network (Figure 3) for all cases and scenarios. Across all cases, it is observed that losses reduced by 2.5% between Scenario 1 and Scenario 2 for Cases 1 and 3 (2.65% for Case 2) and 0.35% between Scenario 2 and Scenario 3 for all cases.

It is observed that the placement of arbitrary generation plants in BUS 8 (Scenario 2) and BUSES 3 and 8 (Scenario 3) results in a reduction in transmission losses (shown in Table 10). The implication of this is that less pressure (in terms of extra demand) is put on the Mpumalanga Power Pool (MPP). This frees up capacity at MPP for maintenance and also reduces capacity expansion at MPP due to utilization of the local generation power stations (or local REPs).

Figure 8 presents the effect of the additional power plants (Scenarios 2 and 3) on the ampacity of the transmission lines. It is observed from Figure 8 that there is a significant drop in current flowing through lines 1, 8, 10, 13, 14 and 15 with significant increase in line current observed in lines 2, 3, 4, 5, 6 and 12. Current through lines 9 and 11 remained averagely unaffected across the scenarios and cases. The utility of this result is in determining transmission lines that need to be upgraded or supported to enable evacuation of power from one bus to another.

The variation in BUS voltage across the scenarios is shown in Figure 9. It is observed from Figure 9 that bus voltage profile is averagely unaffected for most buses with significant drop in bus voltage observed for BUSES 3, 7 and 9. Also, while no bus voltage exceeds the upper bus limit of 1.113 per unit, BUSES 2, 3, 6, 7 and 8 fall below the lower limit 1.007 per unit for all scenarios and cases (base voltage is 1.06 per unit).

The utilization of capacity build for participating DSM loads is further shown in Table 9 to be 33.34% for Case 1, 95.14% for Case 2 and 45.36% for Case 3 (irrespective of scenario). The high utilization observed for Case 2 as a result of DLC compromises on electricity bill reduction for participating households. Under Case 2, DP1, DP2 and DP3 tariffs translate to about ZAR 10.62 (8.50 kWh/month), ZAR 8.75 (7.00 kWh/month) and ZAR 12.74 (10.19 kWh/month) monthly electricity bill reduction/energy savings for participating households. In offering higher utilization of capacity build and guaranteeing maximum revenue accrual to the utility (based on the similarity in earnings irrespective of the tariff method adopted), Case 2 compromises on significant electricity bill reduction for participating households. Cases 1 and 3, which both compromise on utilization of capacity build and maximum returns for the utility (for DP1 and DP2), guarantee participating households significant monthly electricity bill reduction of 16.3% and 8.6% (for Case 1) and 11.3% and 5.4% for (Case 3). IEEM thus provides an interactive platform that enables Eskom investigate the impact of DSM and varying load control options (Cases 1, 2 and 3) on its capacity expansion and revenue accrual.

6 Policy discussions

In discussing further the results obtained, policy discussions on IEEM would focus on its network loss reduction capabilities, expansion cost minimization potentials, electricity cost reduction potentials, poverty mitigation, technical and economic evaluation potentials for electricity network expansion. Here, we discuss each in turn.

6.1 Policy discussion on network loss reduction

According to Eskom (2017b), transmission loss is about 7.5% of total power produced which results from the long distance between the major power pool (BUS 2) and load points LP3, LP4, LP8 and LP9. Results obtained show that the majority of losses occur on lines 1, 3, 11 and 15. This is as a result of the unavailability of local base power stations or alternative power sources at BUSES 3, 4, 8 and 9. However, the introduction of fictitious power stations at BUSES 3 and 8 lead to significant current drop in lines 1, 14 and 15. Since losses are directly related to current flow, this means that reducing the current flowing through a transmission line would lead to a corresponding decrease in the losses through the respective line. IEEM this offers Eskom a model to assess the cost of citing power stations at local points of consumption (construction, fuel, maintenance, water etc.) and savings/benefits (loss reduction, enhanced grid security and utilization of local REPs). Furthermore, a reduction in network losses translates to longer operational life of the transmission line, reduced costs for transmission network expansion and network security.

6.2 Policy discussion on expansion costs reduction

The transmission development plan (TDP) (Eskom 2015b) outlines the intent to expand supply capacity by over 500% in energy demands in response to anticipated demand growth between 2017-2024 (Monyei and Adewumi 2017). With a moderate estimated cost of ZAR 9.39 million/MW, Eskom would need to hike electricity prices excessively to recoup their investments. IEEM provides an alternative. By incorporating DSM at 10%

participation of electrified households in South Africa, IEEM reduces capacity expansion from 495.01 MW to 173.48 MW (Case 1 to Case 2) and 495.01 MW to 363.84 MW (Case 1 to Case 3). This translates to savings of over ZAR 3 billion for Case 1 to Case 2 and over ZAR 1.2 billion for Case 1 to Case 3. This thus implies that more savings could be achieved with the incorporation of further households and loads (heating, cooling, lighting, industrial etc.).

6.3 Policy discussion on electricity cost reduction

IEEM offers Eskom the opportunity of incentivizing households through the adoption of pricing tariffs that reduce the electricity bill of participating households DSM loads. For example in Table 9, under Case 1, DP1 offers about ZAR 122/month/household savings which is about a 16% reduction in a typical household's monthly electricity bill (households consuming 600 kWh/month and under). In energy costs, this translates to about 98 kWh/month/household (at ZAR 1.25/kWh).

6.4 Policy discussion on poverty mitigation

According to STATSSA (2017) and Monyei et al. (2018b), over 50% of South Africa's households are poor. It can be inferred that the declining electricity consumption in households (Monyei and Adewumi 2017) despite increasing investments in electricity capacity expansion has been exacerbated by the increasing cost of electricity. Households are thus forced to purchase less electricity units due to higher tariffs leading to energy poverty. IEEM provides policy makers an avenue to improve households QoL and precipitate economic growth through the adoption of flexible pricing tariffs (DP1, DP2 and DP3) and operational DSM. From Table 9, under Case 1, households are able to reduce monthly electricity bill by up to 16% which translates to energy savings of about 98 kWh/month/household. The savings can be used to either extend operation time of electrical appliances that can contribute to households QoL (lighting, entertainment, heating, cooking) or engage in other activities that are also capable of improving households QoL.

6.5 Policy discussion on capacity utilization

The impact of varying load control strategies - constrained user defined (Case 1), DLC (Case 2) and constrained DLC (Case 3) has been presented in Table 9. IEEM enables Eskom investigate the potential impact varying control strategies in terms of load dispatch could have on plant utilization, revenue accrual and electricity bill reduction. As observed from Table 9, DLC (Case 2) offers Eskom more operational control of the electricity network (generation, transmission and end-use dispatch time). Also, despite Cases 1 and 3 offering reduced capacity utilization compared to Case 2, Eskom is able to dispatch base loads during the periods of low utilization by reducing generation capacity for base loads during the periods of low utilization.

6.6 Policy discussion on rural electrification expansion

The Free Basic Electrification (FBE) (GNESD 2017) and Free Basic Alternative Energy (FBAE) (DME 2007) policies aim at providing energy to poor and vulnerable households. While Solar Home Systems (SHS) are distributed to poor off-grid rural homes (or 50 kWh/month free to grid connected poor homes) under the FBE, the FBAE provides other poor off-grid homes without SHS limited quantities of alternative energy fuels at no cost to meet their basic energy needs (Monyei et al. 2018a). With the incorporation of DSM, IEEM provides Eskom with enormous savings which can be invested in strengthening off-grid SHS and microgrids. Considering the problem of weather variations which is capable of disrupting SHS output for off-grid poor homes, with additional resources recouped from reduced expenditure on capacity expansion, Eskom can finance hybrid generation schemes at the community level to improve electricity supply to the rural off-grid homes thus reducing rural peripheralisation[8](Monyei et al. 2018a).

6.7 Policy discussion on operations cost minimization

Notwithstanding fuel, maintenance and operations costs, emissions cost also contributes to the overall expenditure of Eskom. According to News24 (2013), a proposed carbon tax of $ZAR120/tCO_2$ energy equivalent by National Energy Regulator of South Africa (NERSA) was expected to add about R11 billion to Eskom's expenses from 2015. With over 80% of Eskom's generating capacity sourced from coal power plants, this implies that the additional costs would be transferred to consumers through tariff hikes (Gosling 2011). Through the incorporation of DSM into the IEEM proposed and modelled in this paper, Eskom is provided with flexible loads which can be dispatched by REPs during hours of their (REPs) availability. Considering the net zero carbon charges on electricity production from REPs, Eskom not only reduces emissions and its associated costs but also fuel costs.

6.8 Policy discussion on Quality of Service

Through IEEM, Figure 9 provides Eskom with technical statistics associated with voltage regulation. This is important in helping Eskom determine the additional costs associated with improving power quality (reactive power compensation, voltage regulation, frequency regulation). Furthermore, the peaking power plants like the hydro electric power (HEP) stations and combined cycle gas turbines (CCGT) can be effectively dispatched to maintain network operating frequency. The maintenance of operational frequency and balanced voltage improve Eskom's Quality of Service (QoS) since end users do not have to employ local improvement schemes to improve the quality of power supplied.

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[8] By rural peripheralisation, we extend its meaning beyond Sovacool et al. (2017) to mean discrimination in the quality of electricity households can access based on their proximity to the grid.

6.9 Policy discussion on network security

According to eePublishers (2014), South Africa's electricity grid is expected to be N-1 compliant by 2022. This means that the loss of any major transmission line or generating station is capable of precipitating grid collapse. Furthermore, in the event of a major network fault, the unavailability of flexible customers/loads implies that deliberately disconnecting consumers leads to economic losses and impacts negatively on their QoL. IEEM, through the incorporation of DSM, provides Eskom with leeway (operational freedom) in balancing the grid without economic repercussions. Furthermore, IEEM provides Eskom with an advanced simulation tool that can be used in simulating extremities on the grid to evaluate the extent of grid security and response during faults.

6.10 Policy discussion on pricing

Eskom's pricing is mostly influenced by its projected capital expenditure on maintenance, new builds, overhead, operations, insurance and other associated running costs. According to Eskom (2017b), there was a revenue shortfall of about R35 billion for 2014/15 due to low tariff. However, while Eskom aims at maximizing revenue accrual through higher tariffs, the resulting increase in tariff is capable of precipitating poverty. Households are thus forced to spend a higher percentage of their income on reduced electricity units, leading to energy poverty. This, in turn, can lead to reduced electricity consumption (as established in Monyei and Adewumi 2017) and lower utilization of supply capacity, inherently leading to higher operations cost and increased operational losses. According to Zhang (2012), investment in energy efficiency (especially for households and industries) can be improved upon by mandatory targets and electricity prices. Appropriate pricing regimes are thus needed that are capable of billing households based on their income level and rate/level of participation in DSM activities and also encouraging energy efficiency investments. IEEM thus offers a platform for the exploration of the effect of various pricing schemes on revenue accrual (for the utility) and peak demand reduction.

7 Conclusion

This paper has presented IEEM and studied its impact on both Eskom and consumers. This paper has shown that IEEM advances traditional generation expansion planning (GEP) beyond conventional demand growth expansion and generation capacity estimation. IEEM through the incorporation of DSM, provides Eskom with varied options in terms of expansion planning (expansion capacity, possible revenue accrual and associated network losses) which helps in better informing decisions on the type of generation capacity to build and location. Considering the dispersed REPs across South Africa, IEEM has provided a platform that enables Eskom utilize their capacity in dispatching flexible loads. Furthermore, IEEM has also shown its capability in mitigating poverty through electricity bill reduction for participating households. With up to 16% reduction in electricity bill for a typical household, more units could either be purchased by households to extend usage of electrical appliances or for other activities that are capable of improving their QoL.

In mitigating rural peripheralisation, IEEM provides enormous savings for Eskom through reduction in expansion costs (due to the incorporation of DSM) which can be used in financing and strengthening the FBE and FBAE. Considering the huge disparity in the quality of energy access between grid connected poor home and off-grid poor homes, extra revenue saved from minimized capacity expansion can be used in improving off-grid electrification projects. Such improvement in electricity access for rural and off-grid communities is capable of stimulating economic growth. This is in line with Azimoh et al. (2017), who offer that while electrification cannot solve the entirety of the developmental problems plaguing rural households, households cannot access development assistance opportunities without having access to electricity.

Considering previous cases of power plants mothballing (due to excess supply capacity) and subsequent load shedding due to demand exceeding supply capacity, IEEM helps in preventing this by ensuring that despite reduced reserve margins, the availability of flexible customers/loads provides it (the utility) with allowance to always balance the grid and optimally utilize available supply capacity to dispatch demand. With increased operational control over electricity generation, transmission and utilization time, Eskom is able to ensure grid security and stability. This becomes necessary as the participation of REPs in the grid increases. Due to the stochasticity in the availability of REPs, the presence of flexible loads aids Eskom in maximizing REPs output whenever available without negatively impacting on the QoL of households.

With deliberate action plans being undertaken by countries to reduce carbon emissions, IEEM provides Eskom with a platform for evaluating resulting expansion options based on pre-determined emissions cap. Based on estimated number of households participating in DSM operations and capped emissions, IEEM provides Eskom with possible expansion options which help in formulating decisions/policy on billing strategy to be adopted. This is important to Eskom, especially when applying for tariff increase approval from NERSA. IEEM thus offers an interactive platform for expansion planning beyond traditional generation expansion models by aiding NERSA in appropriately billing Eskom for emissions without adversely affecting consumers (who often bear such penalties).

IEEM can also be useful to the regulator (NERSA) as it enables them to view the impact of its policies (carbon tax, tariff increase approval) on Eskom (revenue accrual, operations cost) and consumers (electricity cost, QoL, poverty). This thus helps NERSA in formulating streamlined regulatory frameworks (SRFs)[9] that are capable of stimulating economic growth and mitigating poverty.

8 Policy implementation and its challenges

A key benefit of the proposed IEEM is its interoperability. IEEM is capable of syncing effortlessly with existing structures since its needed inputs (participating DSM households, emissions cap, network model, generation plants, tariffs etc.) are 'plug-ins'. However, the absence of an advanced metering infrastructure (AMI) for South Africa and the low penetration of smart meters mean that Eskom would not be able to directly communicate

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[9] By streamlined regulatory frameworks (SRF) we mean policy bounded regulations that are optimized to ensure that its enforcement on Eskom does not lead to adverse effects on electricity end users. For example, SRFs could include limits for electricity tariff and carbon tax increase within a range of years based on prevailing GDP growth projections and other economic implications. SRFs could also include the possibility of carbon tax relief based on prevailing economic trends.

(in real/near-real time) with participating DSM loads. Furthermore, the municipalities make profit from sale of electricity to households [who make up over 40% of municipalities customers (Eskom 2017b)]. The problem of price harmonization becomes a problem since sale of electricity is a major source of income to the municipalities. Lastly, security concerns do exist in households to smart meters owing to fears of intrusion and subtle monitoring of consumption pattern which the utility could use in developing billing strategies that would penalize them higher than the TOU pricing scheme (Sovacool et al. 2017).

9 IEEM limitation and future research

While IEEM has explored the impact of residential DSM on capacity expansion, there is the need to incorporate industrial and commercial consumers to evaluate the effect of flexible industrial loads (heating, ventilation and cooling, HVAC) and flexible industrial processes on capacity expansion, network losses, revenue accrual and electricity costs reduction. Furthermore, IEEM has not considered the role of social institutional processes in facilitating a smart and just electricity expansion. Future work would seek to integrate socio-technical transition processes in improving IEEM.

10 Acknowledgements

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Table 1: 2021-2024 Planned Power Plant Decommissioning (Eskom 2015b)

	Camden		Hendrina		Arnot	
Year	Unit	MW	Unit	MW	Unit	MW
2021	6	-160	4	-190		
2022	7	-170	3	-190		
	8	-180	5	-180		
2023	5	-180	2	-190	3	-380
	4	-185			2	-380
2024	3	-185	1	-190	1	-376
	2	-190				
	1	-190				

Table 2: 2017-2020 Planned Power Plant Capacity Increment (Eskom 2015b)

	Medupi		Kusile		Ingula		New coal			O & C CGT		
Year	Unit	MW	Unit	MW	Unit	MW	Unit	Name	MW	Unit	Name	MW
2017	3	738	2	738	4	333						
	4	738										
2018	5	738	3	738								
			3	738								
2019	6	738	5	738			1	Coal IPP1	200	3	Dedisa	237
							2	Coal IPP1	200			
2020			6	738			1	Coal IPP3	200	4	Dedisa	237
							2	Coal IPP3	200			

IPP - Independent Power Producer

Table 3: 2021-2024 Planned Power Plant Capacity Increment (Eskom 2015b)

	Nuclear			Newcoal			O & C CGT			Hydro import		
Year	Unit	Name	MW	Unit	Name	MW	Unit	Name	MW	Unit	Name	MW
2021							5	Dedisa	237			
2022				1	Coal IPP2	250	6	Dedisa	269	1	Maputo	570
				2	Coal IPP2	250	7	Dedisa	269	2	Maputo	570
				1	Coal IPP4	250	8	Dedisa	269			
				2	Coal IPP4	250		Dedisa				
2023	1	Thyspunt	1600	3	Coal IPP2	250				3	Maputo	570
				3	Coal IPP4	250				4	Maputo	570
				4	Coal IPP4	250						
2024	2	Thyspunt	1600	4	Coal IPP2	250				5	Maputo	283

IPP - Independent Power Producer

Table 4: Electricity demand forecast by Eskom (Eskom 2015b)

	Year								
Scenario	2017	2018	2019	2020	2021	2022	2023	2024	2025
2010 IRP High Demand (MW)	51090	53276	55573	57649	59885	61932	63955	65870	68458
2010 IRP Low Demand (MW)	44710	45815	46952	47848	48828	49596	50299	50872	51903
2015 TDP Demand (MW) - Constrained	38885	40036	40904	41921	43990	46629	49427	52193	53600
2015 TDP Demand (MW) - Unconstrained	47720	48271	49328	50398	51528	52501	53403	54296	55310

Table 5: BUS-Province description

BUS	Province	X 1000			GWh
		HWEC*	DSM-Households	DREC	DSM-Potential
BUS 1	Limpopo	1424	142.2	13.63	0.41
BUS 2	Mpumalanga	1063	106.3	34.33	0.31
BUS 3	KwaZulu-Natal	2244	224.4	41.68	0.65
BUS 4	Eastern Cape	1422	142.2	8.86	0.41
BUS 5	Gauteng	3901	390.1	57.58	1.12
BUS 6	Free State	806	80.6	10.32	0.23
BUS 7	Western Cape	1600	160	22.7	0.46
BUS 8	Northern Cape	296	29.6	5.16	0.09
BUS 9	North West	1021	102.1	29.18	0.29

* - modified from Monyei and Adewumi (2017)
BUS 10 acts as a conduit for conducting power from BUS 6 to BUSES 4, 7 and 8.
HWEC - Number of households per province with electrical connection (i.e. connected to the electricity grid).
DSM-Households are households per province participating in the DSM.
DREC - daily residential electricity consumption per province in GWh.
DSM-Potential is the daily provincial computed DSM potential (in GWh) based on DSM-Households.

Table 6: DSM load description

Loads	Power (W)	Slots	Energy (Wh)
Dish washer	1200	5	1500
Cloth washer	500	3	375
Cloth dryer	1000	4	1000
Total	2700	12	2875

Table 7: Scenarios 1, 2 and 3 power plant distribution.

Bus	Province	Generation plant number
BUS 1	Limpopo	24,9
BUS 2	Mpumalanga	1,2,3,4,6,8,10,11,12,13,14,26
BUS 3	KwaZulu-Natal	27**
BUS 4	Eastern Cape	NBPP
BUS 5	Gauteng	NBPP
BUS 6	Free State	7
BUS 7	Western Cape	5*
BUS 8	Northern Cape	28***
BUS 9	North West	NBPP

NBPP - No base load power plant
* - Nuclear power plant
** - Considered only in Scenario 3
*** - Considered only in Scenarios 2 and 3
Every other numbered power plant is coal fired

Table 8: Considered power plant description.

Generation plant number	Name	Type	Capacity (MW)
1	Arnot	Coal	2352
2	Duvha	Coal	3600
3	Hendrina	Coal	2000
4	Kendal	Coal	4116
5	Koeberg	Nuclear	1940
6	Kriel	Coal	3000
7	Lethabo	Coal	3708
8	Majuba	Coal	4110
9	Matimba	Coal	3990
10	Matla	Coal	3600
11	Tutuka	Coal	3654
12	$Camden^{*}$	Coal	1510
13	$Grootvlei^{*}$	Coal	1200
14	$Komati^{*}$	Coal	940
24	$Medupi^{**}$	Coal	4788
26	$Kusile^{**}$	Coal	4800
27	$SB1^{**}$	Coal	1429
28	$SB2^{**}$	Coal	1429

* - return to service power plants

** - new builds

SB1/SB2 - simulated builds 1 and 2 are the fictitious power plants randomly used during Scenarios 2 and 3 simulation.

Table 9: Daily DSM load associated statistics for all cases.

	Maximum build (MW)	Capacity utilization (%)	DSM cost (x10000000)			
			TOU cost (ZAR)	DP1 cost (ZAR)	DP2 cost (ZAR)	DP3 cost (ZAR)
Case 1	495.01	33.34	2.2093	1.648	1.9131	2.3183
Case 2	173.48	95.14	2.0669	2.0181	2.0267	2.0084
Case 3	363.84	45.36	2.1616	1.7726	1.9742	2.2515

Table 10: Daily cumulative losses (MW) for all scenarios and cases.

	Scenario 1	Scenario 2	Scenario 3
Case 1	86512	84321	84029
Case 2	86438	84150	83858
Case 3	86498	84305	84014

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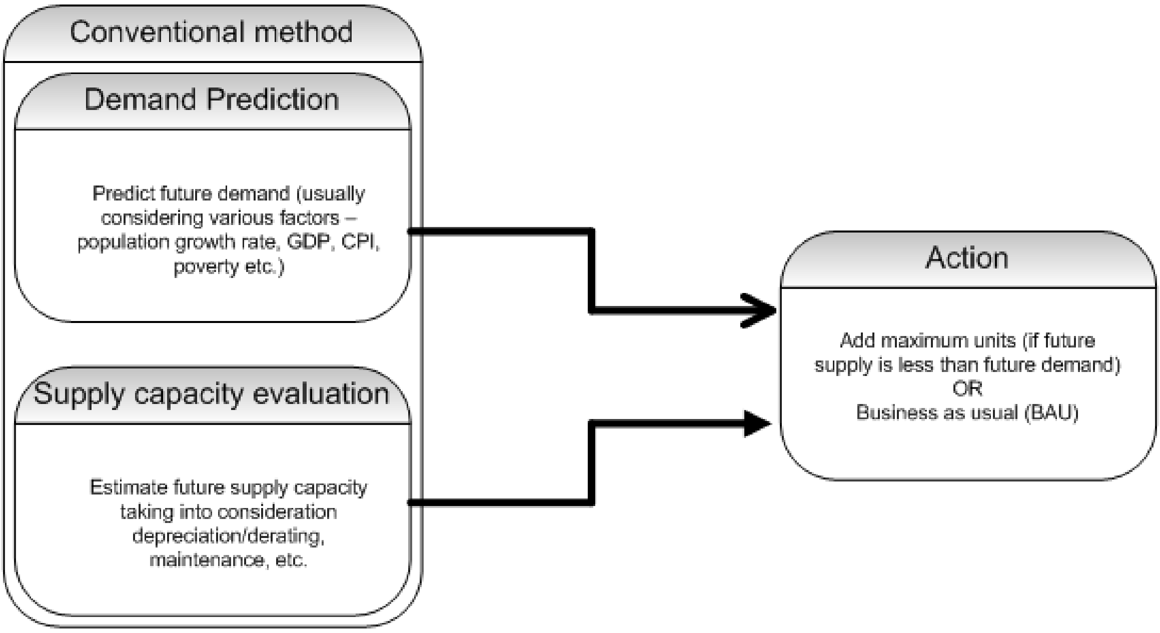


Figure 1: Eskom’s conventional electricity expansion model (authors own compilation).

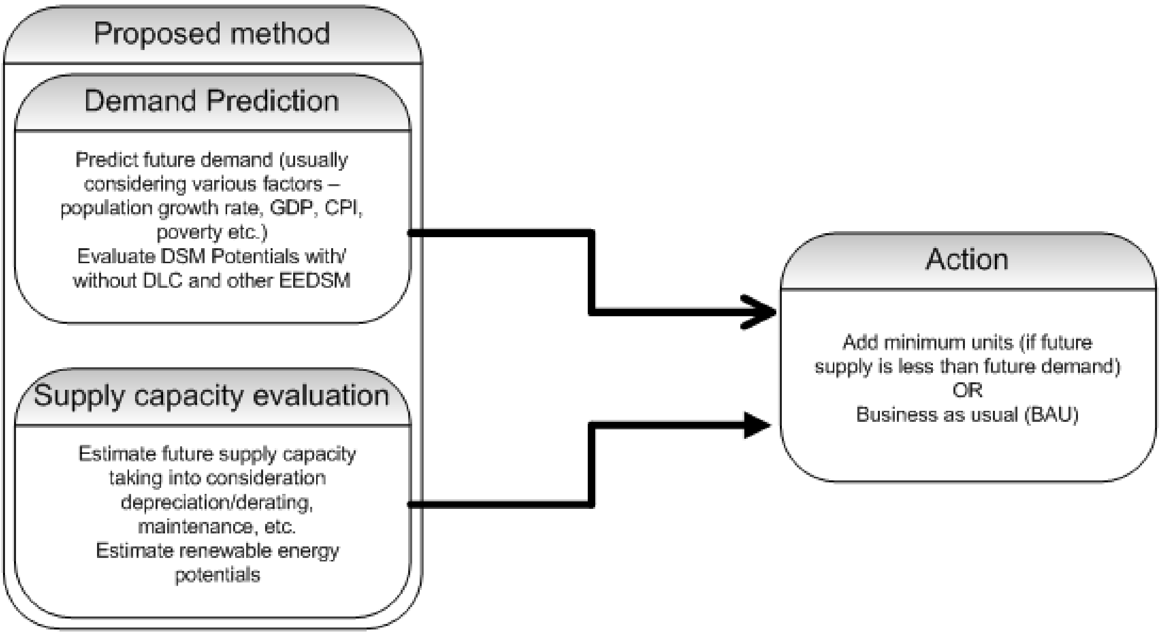


Figure 2: Integrated electricity expansion model (IEEM) (authors own compilation).

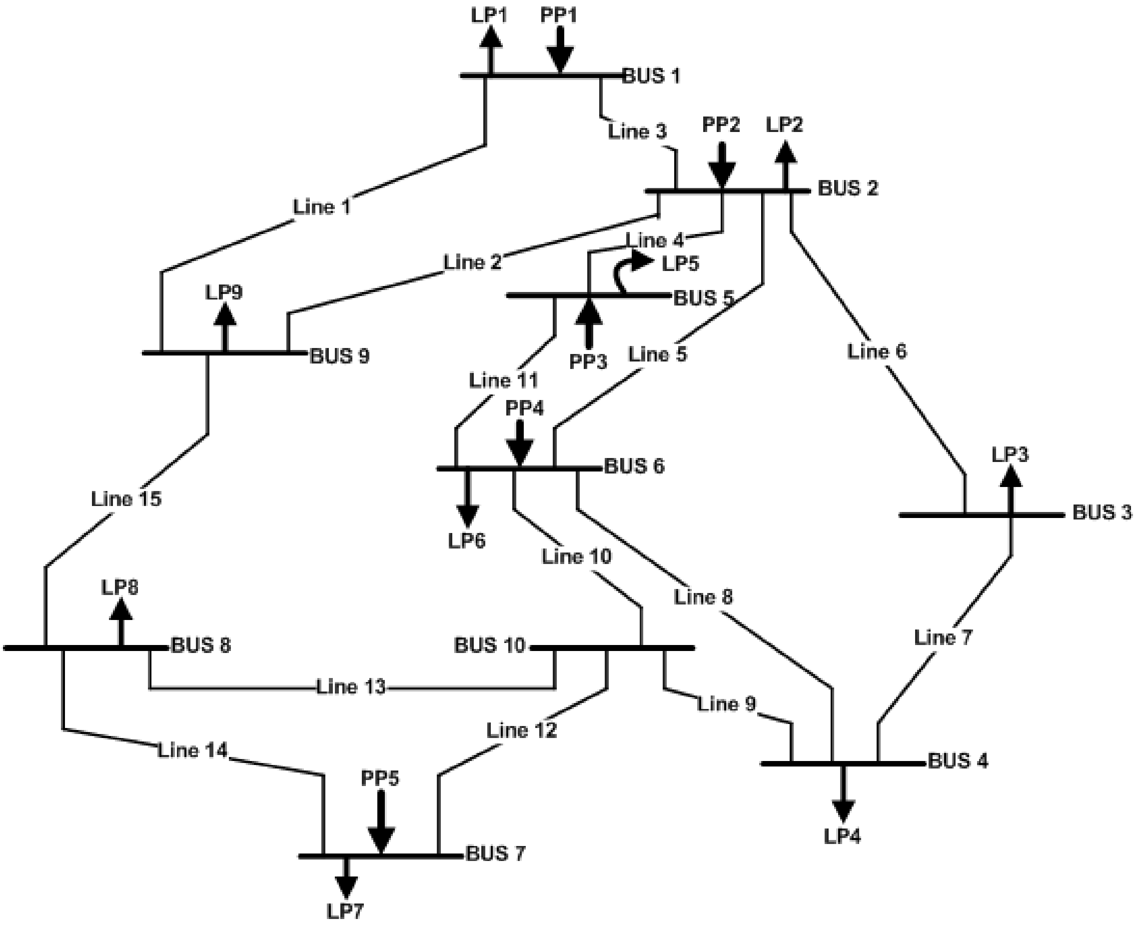


Figure 3: Model electricity network for South Africa (authors own compilation).

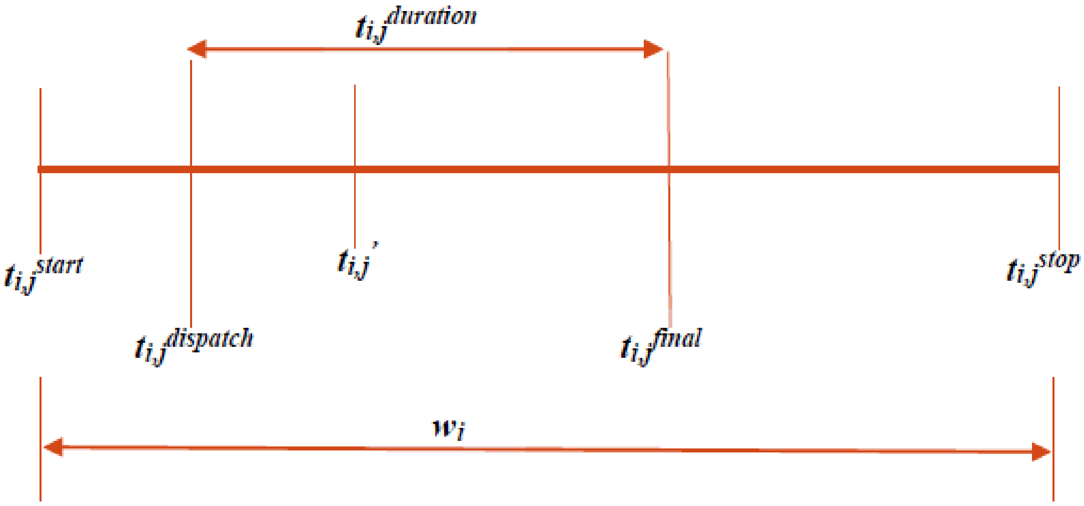
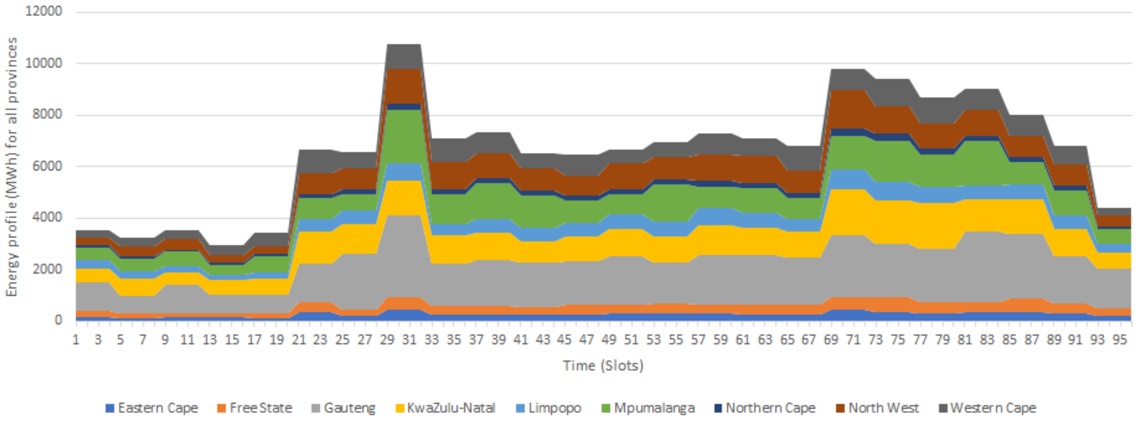
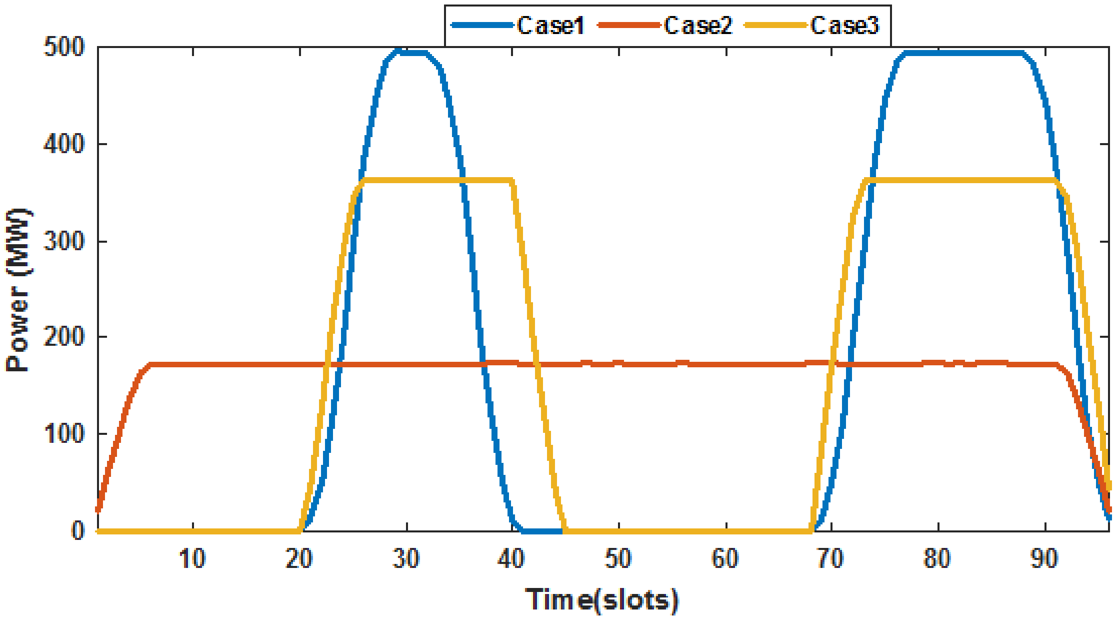


Figure 4: Dispatch time profile for DSM loads (authors own compilation).



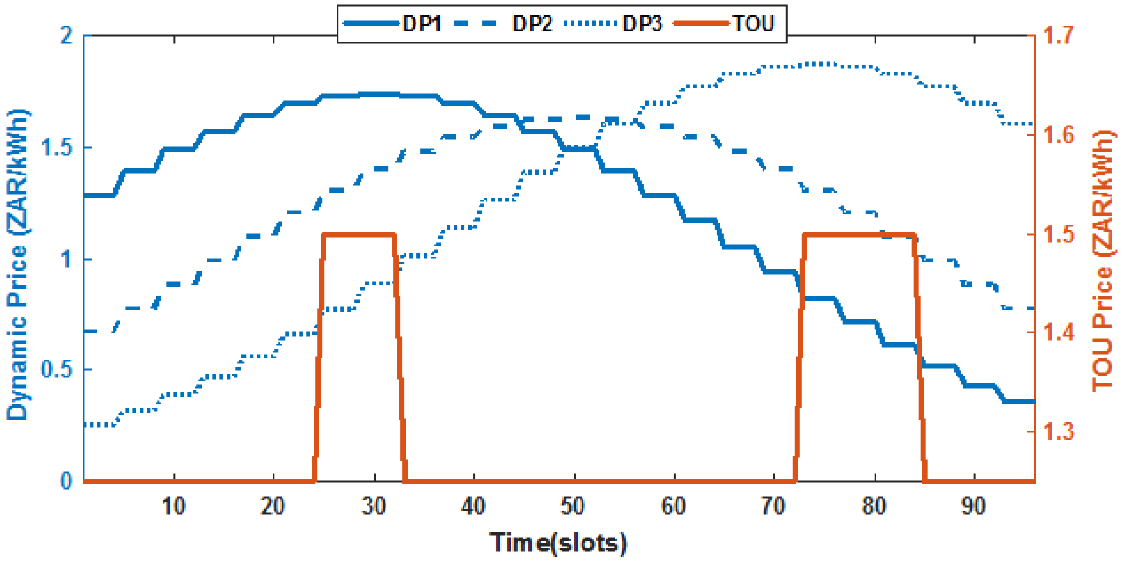
A slot is a 15 minutes interval. The start time is taken to be 00:00 (midnight/slot 1).

Figure 5: Base load dispatch profile for all provinces (authors own compilation).



A slot is a 15 minutes interval. The start time is taken to be 00:00 (midnight/slot 1).

Figure 6: Cumulative DSM load profile for all Cases (authors own compilation).



A slot is a 15 minutes interval. The start time is taken to be 00:00 (midnight/slot 1).

Figure 7: Pricing schemes adopted.

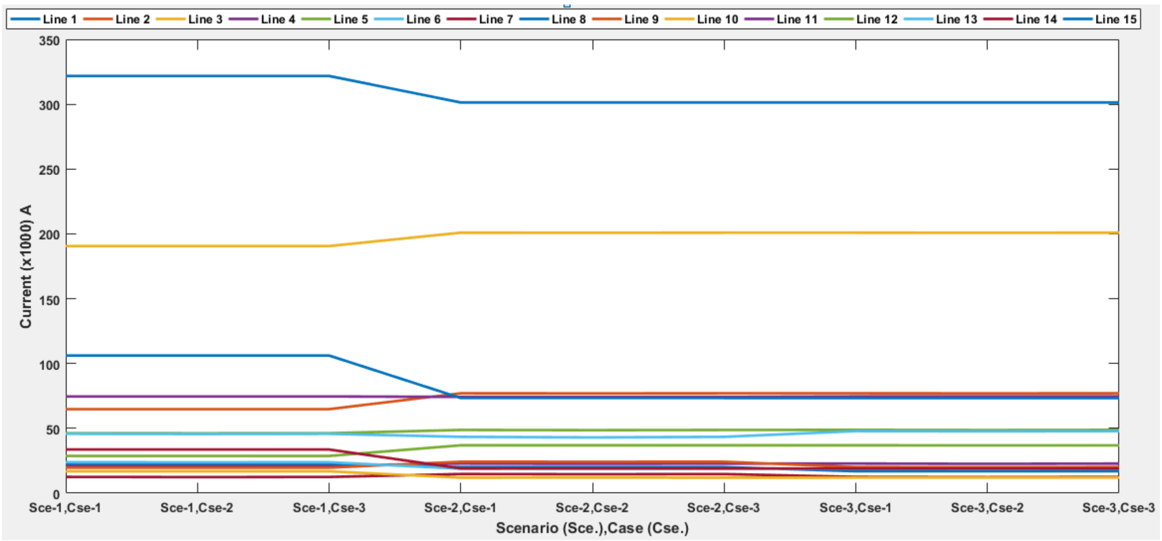


Figure 8: Daily current evacuated per line (in kA).

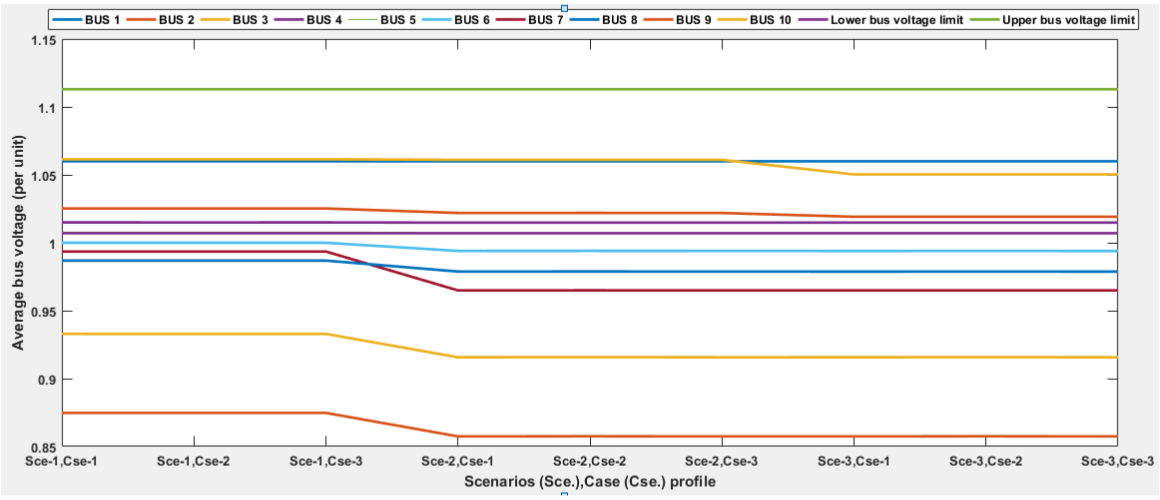


Figure 9: Daily average bus voltage (in per unit) profile.

CHAPTER 8

PAPER 7 - HYBRID GENERATION SCHEME MODELLING

Brief summary

This chapter presents the paper entitled ***Energy (in)justice in off-grid rural electrification policy: South Africa in focus***. This chapter addresses exhaustively the problem of failed off-grid electrification projects in South Africa (and by extension SSA) by proposing a hybrid generation scheme that localizes smart grid concepts (DSM, DR), utilises smart load distribution boards and incorporates MGA in optimally scheduling the dispatch of connected loads. A major result from this chapter is the fact that the proposed hybrid generation scheme which incorporates diesel generator as backup is capable of reducing carbon emissions by over 70% under certain conditions. In further evaluating the potential of the proposed hybrid generation scheme to guarantee equivalent quality and quantity of electricity as obtainable from grid electricity and also mitigate energy poverty, principles from the energy justice framework are exhaustively used in critically evaluating the hybrid generation scheme.

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Energy (in)justice in off-grid rural electrification policy: South Africa in focus

C.G. Monyei[a,b,*], A.O. Adewumi[a,b], K.E.H. Jenkins[c]

[a] *Applied Artificial Intelligence Research Unit, School of Mathematics, Statistics and Computer Science, University of KwaZulu-Natal, Westville Campus, Private Bag X54001, Durban 4000, South Africa*
[b] *School of Mathematics, Statistics and Computer Science, University of KwaZulu-Natal, Westville Campus, Private Bag X54001, Durban 4000, South Africa*
[c] *School of Environment and Technology, Cockcroft Building, University of Brighton, BN2 4GJ, United Kingdom*

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ABSTRACT

Generally speaking, increasing rural marginalisation in sub-Saharan Africa has sat alongside a rise in energy poor homes in rural off-grid communities. Even measures meant to improve electricity access have exacerbated the energy access gap between grid connected and off-grid homes. For example, the South African Non-Grid Electrification Policy Guidelines for electrifying off-grid, rural poor homes promote the adoption of Solar Home Systems (SHS), which are expected to produce 7.5 kWh/month on average. However, for poor homes within grid coverage, the Free Basic Electricity (FBE) programme allocates 50 kWh/month. This paper investigates the resulting disparity in terms of electricity cost (ZAR/kWh), including associated costs for heating, cooking and other needs. It does so through the energy justice framework, highlighting the mismatch in policy formulation (procedural injustice), resource distribution (distributive injustice) and spatial distribution (injustice in the recognition of population groups' special needs). Through a combination of mathematics and social science perspectives, it then moves beyond a critique of the current SHS system to proposes a new one: a hybrid generation approach with a flexible pricing scheme and centralized system of operation that is both ethically compliant *and* capable of improving electricity access to off-grid communities with standards comparable to grid access.

1. Introduction

As of 2014, sub-Sahara Africa (SSA) had 62.8% of its population living in rural areas, of which only 35.3% had access to electricity. In comparison, urban areas had a 71.6% electrification rate [1]. In striving to bridge the widening energy access gap between rural and urban areas, countries in SSA have adopted varied measures. Notable among these has been the use of Solar Home System (SHS),[1] designed with the aim to increase the availability of energy to all. Yet, despite the widespread penetration of SHS in rural communities and the regional variations therein, there has been no noticeable or systematic reduction in rural peripheralisation[2] and poverty alleviation to date. We make this perhaps controversial statement based on the exhaustive findings on the failure of 29 trans-regional renewable energy projects in SSA by Ikejemba et al. [3], the findings on the failure of SHS projects and in particular the Lucingweni project by Azimoh et al. [4] and the position of [5]. Each of these has inadvertently created instances of rural peripheralisation. For South Africa in particular, Azimoh et al. [4] state that "*despite substantial government spending on SHS, assessment of the socio-economic impact of the South African SHS program revealed that the energy needs of the households are seldom met due to the low power capacity of the system.*" Indeed, according to [1], 727 million people in SSA continue to rely on traditional biomass and charcoal as their primary cooking fuel.

Urmee and Md [5] further corroborate this situation as they explain that end-users expectations of SHS and the performance of these SHS did not match, especially in terms of load capacity and hours of utilisation. Most end-users had expected grid quality electricity level from SHS and did not have their expectations fulfilled. This implies, in effect, that the increasingly widespread use of SHS has not improved

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* Corresponding author at: Applied Artificial Intelligence Research Unit, School of Mathematics, Statistics and Computer Science, University of KwaZulu-Natal, Westville Campus, Private Bag X54001, Durban 4000, South Africa.

E-mail addresses: chiejinamonyei@gmail.com (C.G. Monyei), adewumia@ukzn.ac.za (A.O. Adewumi), k.e.jenkins@brighton.ac.uk (K.E.H. Jenkins).

[1] Which are made up of 1–50 Wp photovoltaic panel, 1 charge controller, wiring and small outlets for small appliances, 1–105 Ah battery and 4 energy efficient compact fluorescent lamps.

[2] By rural peripheralisation we extend its meaning beyond [2] to mean discrimination in quality and quantity of electricity access to households of the same income bracket due to their proximity to the national grid

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2214-6296/

electricity access per capita (kWh) (which is about 511.90 kWh compared to 3064.50 kWh for the world (average)) [1]. Thus, the huge costs of installation of these SHS and their limited usage options creates a gap in terms of energy access between grid connected and off-grid households, leading to rural peripheralisation (a somewhat similar example to the case of the smart meter roll out in the UK, perhaps [2]). Further, this low rate of electricity access (which some may argue is a product of ineffective policy, see [4]), increases the exposure of off-grid rural households to diseases such as childhood pneumonia, chronic obstructive pulmonary disease (COPD), and lung cancer caused by the smoke emanating from alternative energy sources like firewood [1].

This paper comes to this challenge from two perspectives. Firstly, it seeks to outline that this peripheralisation and maldistribution of electricity access is an issue of energy justice. Secondly, in order to move past what would otherwise just be a critique of off-grid electrification policies, it makes a practically oriented contribution to addressing these failings through mathematics and modelling. Specifically, we address this gap by examining the efficacy of the current SHS system and based on its failings, proposing an alternative hybrid generation system that meets the demands of the energy justice framework. As an impact-oriented output, we provide, in effect, an alternative means of electrifying off-grid communities that incorporates energy justice values and in terms of its modelled impact, is ethically compliant.

This work is as timely as it is necessary for (at least) two reasons. Firstly, despite the claim that energy justice scholarship appears across many disciplines [6], few mathematics and modelling techniques have been applied. Indeed, this paper is arguably the first of its kind (although we do acknowledge the work of [7] which also uses modelling techniques, albeit in a very different way). In this regard, we provide an important applied contribution. Secondly, and practically, according to [8], about 60% of additional electricity generation needed to provide universal access to energy is expected to be generated through off-grid systems. For this reason, we require sustainable generation schemes that are both ethically compliant *and* capable of improving electricity access to off-grid communities with standards comparable to grid access. This paper illustrates one potential means of achieving this. This has implications across SSA countries, developing countries in Asia, and indeed, many regions of the world.

This paper proceeds as follows. We begin with an overview of the energy justice concept followed by the South African case. Then, using modelling techniques, we investigate the potential SHS output power across seven provinces in South Africa using weather data from nine South African weather stations. We illustrate that a lack of consideration for the spatial distribution of the population and the stochasticity of weather conditions negates the benefits of SHS schemes with energy justice knock-ons in terms of procedure (procedural justice) and resource distribution (distributive justice). Our paper also shows that the current electrification plans for off-grid rural poor homes do not guarantee adequate energy access. To remedy this failing, we then present a concerted approach to a viable and sustainable generation platform that hybridizes SHS and diesel-generators. A flexible pricing scheme (for pricing electricity) along with a smart load distribution board [9] (that incorporates an artificial intelligence tool (MGA) by [10] for dispatching electricity needs) are also presented. As energy justice scholars seek to take their work beyond academic scholarship to practical application (including through engagement with innovative business models [11], for instance), this is one exciting example of how just electrification processes may be achieved.

2. Energy justice – 5 guiding principles

The concept of energy justice is becoming a much-researched topic that seeks to establish a nexus between energy generation and delivery and justice (equity/fairness) [6,12]. Islar et al. [13], p. 671 define it as “respecting universal human rights and ensuring that every person has a right to the level of energy required to attain a minimum of well-being”. Sovacool and Dworkin [12] posit that energy justice is capable of assisting the energy decision process and choices of consumers and energy planners by presenting itself as a useful decision-making tool. With this potential in mind, we utilize the energy justice approach to (1) critique the Non Grid Electrification Policy Guidelines, which we argue impedes the development of the off-grid poor rural households, and (2) to argue for our proposed hybrid generation scheme, which can improve off-grid poor rural households quality of life (QoL) and overall welfare whilst achieving energy justice.

Several energy justice frameworks have emerged. The first is the tripartite distributional justice, procedural justice and justice as recognition approach – terms that we have mentioned in passing and continue to apply throughout this piece (see [14,6]). The second elaborates on energy justice as an analytical tool that helps in understanding how values can be built into energy systems [12] and provides the building blocks for a series of core principles later elaborated by Sovacool et al. [15]. Within this paper, we focus on five of the eight principles originally presented[3]:

- The availability principle [Principle 1];
- The affordability principle [Principle 2];
- The due process principle [Principle 3];
- The intra-generational equity principle [Principle 4];
- The sustainability principle [Principle 5].

We also consider an explicitly spatial dimension brought to the fore by Bouzarovski and Simcock [16] as they conceptualize energy poverty as a form of injustice.

We do not take these approaches to be exclusionary. That is to say, we do not believe that one is better than the other and that they cannot be used in tandem. In our approach, the tripartite energy justice framework offers a means of evaluating energy (in)justices of a spatial nature and principles 1–5 offer a series of goals we should seek to achieve. For this reason, we use these 5 principles alongside the spatial dimension to reflect on the simulation results obtained through our model we present in the proceeding paragraphs.

Before going further, however, and in order to navigate the gap between descriptive and prescriptive claims, the need arises for the formulation of a realistic utopia. For the purposes of this paper, we define a realistic utopia to be an ideal setting in which households are able to meet their monthly billing obligations. With reference to the four major standards of justice theory, Table 1 illustrates the conditions this leaves. This is, in effect, our own normative goal.

3. Electrification in South Africa: an introduction

With attention to the United Nations (UN) Sustainable Development Goals (SDGs) 7 and 11 [17], and in mitigating the effects of the planned decommissioning of ageing power plants [18], Eskom, a South African electricity public utility, has recently stepped up its construction of additional electricity supply capacity (see [19]). The accelerated efforts by Eskom coincide with the energy crisis that has plagued South Africa since 2008, leading to massive blackouts, load shedding and huge economic losses [20,21]. This rapid electrification programme has seen electrification rate move rapidly from less than 33% (in 1990) to 58% (1996) and 90% (2016) and has succeeded largely due to various government policies and interventions [22].

Yet in terms of the socio-economic background of the population, evidence suggests that electrification rates remain deeply uneven between differing ethnic groups, as evidenced by the following tables. Table 2 shows the provincial distribution of South Africa's population

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[3] Where a full list would include availability, affordability, due process, transparency and accountability, sustainability, equity and responsibility [15]

Table 1
Conditions of our proposed realistic utopia.

Theory	Meaning	Applied approach
Egalitarianism	Favours equality among living entities. Advocates the removal of inequalities among people	Constrained by the ownership of electrical appliances
Libertarianism	Emphasizes freedom, liberty, voluntary association, and respect of property rights	Bounded by the maximum hourly allocation allotted to each household
Utilitarianism	The proper course of action is the one that maximises the overall happiness In other words, actions are right if they are useful or for the benefit of the majority	Is as measured from the Duration-Comfort plot
Sufficientarianism	Rather than making sure we are equal and all as well of as possible, the aim is to make sure that each of us has enough	Limited by electrical appliance ownership and hourly demand factor

Table 2
Provincial population by population group for 2015 (X1000) [23].

	Population group			
Province	Black African	Coloured	Indian/Asian	White
Western Cape	1967	3217	39	1022
Eastern Cape	5944	488	23	237
Northern Cape	638	455	2	87
Free State	2419	75	6	263
KwaZulu-Natal	9499	113	779	297
North West	3406	60	34	203
Gaunteng	10308	408	429	2123
Mpumalanga	3955	12	14	256
Limpopo	5509	33	38	74

Table 3
Provincial number of households by population group for 2015 (X1000) [23].

	Population group			
Province	Black African	Coloured	Indian/Asian	White
Western Cape	894	1462	18	465
Eastern Cape	2702	222	10	108
Northern Cape	290	207	1	40
Free State	1100	34	3	120
KwaZulu-Natal	4318	51	354	135
North West	1548	27	15	92
Gaunteng	4685	185	195	965
Mpumalanga	1798	5	6	116
Limpopo	2504	15	17	34

Average household size of 2.2 is used [24].

Table 4
Provincial households connected to the mains by population group for 2015 (X1000) [23].

	Population group			
Province	Black African	Coloured	Indian/Asian	White
Western Cape	507	648	11	434
Eastern Cape	1213	117	5	88
Northern Cape	161	99	1	35
Free State	690	25	4	87
KwaZulu-Natal	1889	27	217	111
North West	913	22	7	79
Gaunteng	3004	110	112	675
Mpumalanga	982	4	3	74
Limpopo	1388	5	7	23

by population group for 2015 (an estimated 54,432,000 people in total) [23]. Table 3 then shows the household population distribution across the provinces (calculated using a national average household size of 2.2 [24]). The number of households connected to the mains across the provinces by population group for 2015 is shown in Table 4. A critical evaluation of Table 4 shows that on average across the provinces, household electrification rates for Black African, Coloured households, Indian/Asian population group varies significantly with 54.14% of Black African households electrified compared to 47.87% for Coloured households, 59.29% for Indian/Asian households and 77.40% for White households. This shows a trend for the greater electrification in majority white provinces. Beyond distributional injustice, this is an issue of justice as recognition – the unequal marginalization of a particular group or groups.

According to DME [25], the majority of the un-electrified households are in deep rural areas necessitating, in their argument, government responsibility for ensuring the electrification of all its citizens, and especially the rural poor in order to improve living conditions. With a similar goal in mind, and to achieve universal access to electricity by 2019, the free basic electricity (FBE) policy was introduced in 2004 to completely subsidize 50 kWh of electricity monthly for the very poor households connected to the grid [26]. This is in line with the 1998 White Paper on energy policy, where emphasis was placed on households access to adequate energy services for cooking, heating, lighting and communication [27]. In addition, the Non Grid Electrification Policy Guidelines identify non-grid SHS as a suitable temporary alternative to grid electricity for rural, poor and off-grid homes. In order to extend this electricity access, energy service companies (ESCO), concessionaires and service providers act on behalf of the Department of Energy (DOE) to roll out SHS delivery [25].

According to [25], the SHS should produce about 250Wh daily and power a black and white television (for 4 hours), lighting (4 hours), portable radio (10 hours) and phone charging points daily. The implication of this is that on average each off-grid rural poor home gets 7.5 kWh monthly from the SHS. Yet a critical evaluation of the fall-out of this policy reveals the following potential problems:

1. The over-simplification of the policy implementation has failed to consider the varying weather disparity (solar irradiance and temperature) across South Africa, which would affect the output power of the SHS.
2. The failure of the policy to compensate for varying weather conditions across South Africa's provinces creates injustice in resource distribution (distributive injustice) and policy conceptualization.
3. The huge disparity between the FBE allocation of 50 kWh monthly and the estimated 7.5 kWh monthly for on-grid and off-grid poor homes inadvertently contributes to widening energy access gap and increasing energy (electricity) poverty across households. This goes against energy justice in terms of recognition principles since majority of the off-grid poor homes are Black Africans.
4. The full subsidy in form of FBE for on-grid poor homes and 80% subsidy for off-grid poor homes implies that off-grid poor homes on average pay exorbitantly high and varying prices for electricity. This is due to the stochastic property of solar irradiance, which means that solar PV output is never fixed (despite monthly payments being fixed).
5. The stochastic nature of solar irradiance means that homes may not be able to meet even their basic energy-based needs due to non-availability of power, which potentially affects their quality of life (QoL) and socio-economic life.
6. Considering the limited usage options (in terms of electrical

Table 5
Weather stations and their description [28].

S/N	Code	Province	City	Latitude	Longitude	Elevation (m)
1	UNV-H	Limpopo	Vuwani	−23.13	30.42	628
2	UPR-H	Gauteng	Pretoria	−25.75	28.23	1410
3	KZW-H[a]	KwaZulu-Natal	Durban	−29.82	30.94	200
4	STA-H[a]	KwaZulu-Natal	Umlazi	−29.97	30.91	95
5	UFS-H	Free State	Bloemfontein	−29.11	26.19	1491
6	GRT-H	Eastern Cape	Graaff-Reinet	−32.49	24.59	660
7	SUT-H	Northern Cape	Sutherland	−32.22	20.35	1450
8	RVD-H	Northern Cape	Alexander Bay	−28.56	16.76	141
9	VAN-H	Western Cape	Vanrhynsdorp	−31.62	18.74	130

[a] 01/01/2017 data for station in KwaDlangezwa used.

appliances) of the SHS compared to the wide usage option of the FBE, off-grid rural poor homes are further impoverished by having to purchase fuels (firewood and paraffin, for examples) from the SHS providers at commercial prices (as acknowledged by the policy) to meet their cooking and heating needs [25].

Based on these points, we start with the assertion that the current SHS system may not fulfil its intended purpose, and that the outcome has serious energy justice knock-ons. Thus, the remainder of this paper first explores the potential output of the SHS scheme and second, introduces a hybrid generation system that may reduce or remedy the above policy flaws. We close with an analysis of the justice benefits of this new model according the 5 principles introduced above.

4. Methodology: a brief on simulation data

Our first aim was to establish the expected output of the SHS rollout. In evaluating the power output of a typical SHS rollout across South Africa, we used data from nine (9) weather stations set-up by the Southern African Universities Radiometric Network (SAURAN) [28]. SAURAN is an initiative of the Centre for Renewable and Sustainable Energy Studies (CRSES) at Stellenbosch University and the Group for Solar Energy Thermo-dynamics (GSET) at the University of KwaZulu-Natal and aims to make high-resolution, ground-based solar radiometric data available from stations located across the Southern African region, including South Africa, Namibia, Botswana and Reunion Island [29,28].

These nine (9) weather stations were located across seven provinces. We gathered data for one particular day – the 01/01/2016 – from 00:00 h to 23:00 h. The hourly data utilized are the Direct Normal Irradiance (DNI) and temperature. Table 5 presents the weather stations, their location (city/province), latitude/longitude/elevation and code (alternate identification form). The weather stations chosen were those that had valid hourly data for the arbitrarily chosen day for simulation. The retention of weather stations within the same province is to show that weather variation is spatial even within a province.

Table 6
PV panel specifications and parameter definition.

Power	50 Wp[a]
n_{PV}	16%
Life cycle	25 years
V_{mp}	12 V
I_{mp}	4.1 A
n_s	40
n_p	1

[a] From [25]. Other values are assumed.

4.1. SHS output power modelling

Table 6 presents the basic properties of the simulated solar panel. A utilization factor (fill factor) of 70% of the real-time maximum power is assumed. By utilization factor (fill factor) we mean the fraction of the real-time maximum power that can be harnessed based on converter settings. The solar panel is also assumed to be fixed while the converter settings are also fixed (i.e. no maximum power point tracking – MPPT). Fig. 1 presents the typical Power–Voltage (*P*–*V*) characteristic of a solar panel and the concept of maximum power point tracking using the incremental conductance method [30] while Fig. 2 presents the typical representation of the SHS integration with each rural poor off-grid house. The profile of the typical daily utilizable power from the solar panel across the various weather stations is shown in Fig. 3. The mathematical modelling of the SHS and the battery charging/discharging description is shown in Appendix I. For this paper, we assume that all solar power is initially directed into the battery before utilization. Table 7 presents the basic properties of the battery adopted in the simulation exercise.

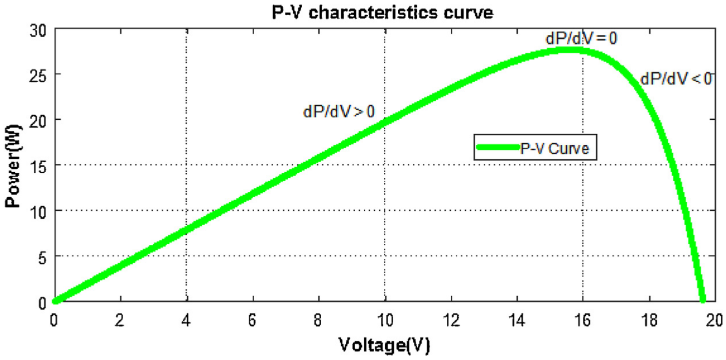

Fig. 1. Solar panel typical *P*–*V* plot.

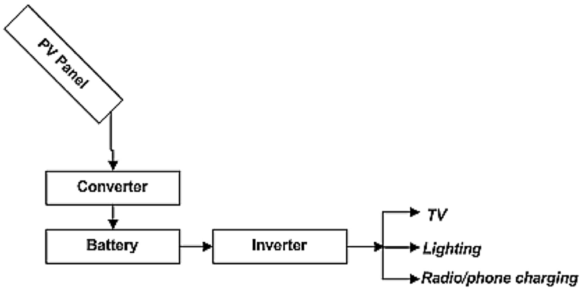

Fig. 2. Singe house typical SHS integration.

According to [31], p. 28, the prevailing climatic condition of a geographic location plays an important role in determining the energy consumption pattern of households. Fig. 4 depicts the radar plot of the daily utilizable power from the SHS across the provinces in South Africa. A critical observation of Fig. 4 shows 3 classes of off-grid poor rural households that are – Class 1, Class 2 and Class 3:

- Class 1: This refers to the off-grid houses whose SHS daily output power is below the proposed 250 Wh/day. From the simulation carried out, Off-grid houses in Limpopo, Gauteng, KwaZulu-Natal and Free State fall under this class. Hence, $\text{SHS}_i^j \leq 250$ Wh/day.
- Class 2: This refers to the off-grid houses in provinces whose SHS daily output was equivalent to or exceeded the proposed 250 Wh/day by about 50 Wh. Off-grid houses in western Cape fall under this class. Hence, 250 Wh/day $< \text{SHS}_i^j \leq 300$ Wh/day.
- Class 3: This class consist of off-grid houses that have their SHS daily output exceeding 300 Wh/day. Off-grid houses in Eastern Cape and Northern Cape fall under this class. Hence, 300 Wh/day $< \text{SHS}_i^j$.

Where SHS_i^j is the SHS daily output power for house i in province j.

4.2. Justification for class discrimination

The classification of the houses into various classes (based on the SHS daily output as modelled) is for the following reasons:

- To show that output power from the SHS varies across and within the provinces. For example, for the same day of modelling, SHS output from $KZW - H$ is about 32 Wh/day while it is 5.13 Wh/day for $STA - H$ with both locations in the same province (KwaZulu-Natal).
- To show that many off-grid houses may not be able to get up to the proposed 250 Wh/day due to spatial variations. For instance only 33% of the weather stations used for this research meet the 250 Wh/day requirement.
- To highlight the contribution of the battery and inverter system in further depleting the SHS output power. It is seen from Tables 7 and 8 the battery and inverter specifications. In charging the battery, energy (up to 10%) is lost due to battery efficiency while the discharging of the battery for home use contributes further loss. Also, the battery continuously self discharges (albeit quite slowly) when left unused. These factors thus necessitate class distinction to highlight off-grid locations whose daily SHS power output can compensate for these losses.

Table 7
Battery specifications and parameter definition.

Voltage	12 V
Rating	105 Ah[a]
η_{batt}	0.9
DOD	90%
σ	< 3% per month
Life	3 years

[a] From [25]. Other values are assumed.

Table 9 presents the typical electrical appliances ownership and usage description for an off-grid rural household utilizing the SHS. At 80% subsidy per month, this translates to about ZAR 12/month base cost ($\text{cost}_{\text{base}}^{\text{low}}$) paid by each household as running and maintenance costs. If $mSHS_{base}$ is the monthly base SHS power supply, then $c_{\text{base}}^{\text{low/high}}$ computation is shown in Eq. (1). $\text{QoL}_{\text{base}}^{\text{low}}$ is fixed at 5 (with 80% subsidy considered). However, if subsidy is not considered, $\text{QoL}_{\text{base}}^{\text{high}}$ is fixed at 0. Table 10 presents the evaluation of $c_{\text{base}}^{\text{low}}$ for $\text{QoL}_{\text{base}}^{\text{low}} = 5$ and $c_{\text{base}}^{\text{high}}$ for $\text{QoL}_{\text{base}}^{\text{high}} = 0$. For all cases, $mSHS_{base} = 7.5$ kWh. Thus, in the computation of $c_{\text{base}}^{i,j}$ and $\text{QoL}_{\text{base}}^{i,j}$, SHS_i^j is always standardized to $mSHS_{base}$. Eq. (2) presents the computation of $\text{QoL}_{\text{base}}^{i,j}$ while Table 11 presents the results (computation of $\text{QoL}_{\text{base}}^{i,j}$ and $c_{\text{base}}^{i,j}$) for all weather stations considered. Fig. 5 presents the Duration-Comfort plot which shows the

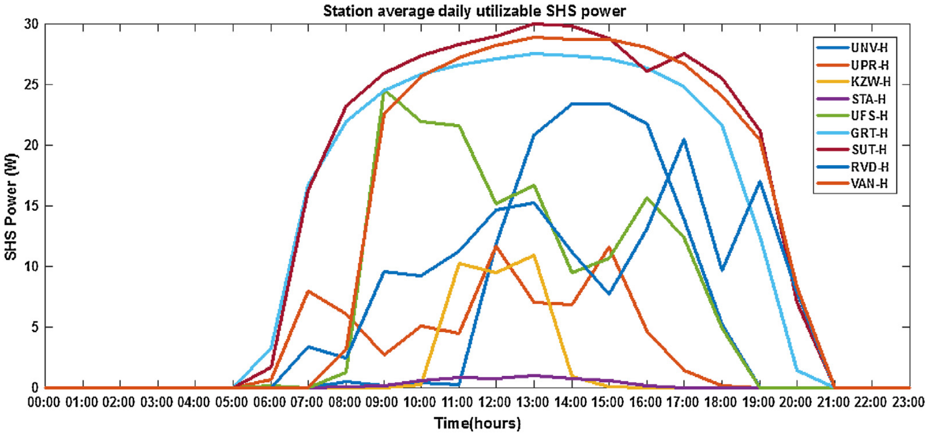

Fig. 3. Daily utilizable power profile across the weather stations.

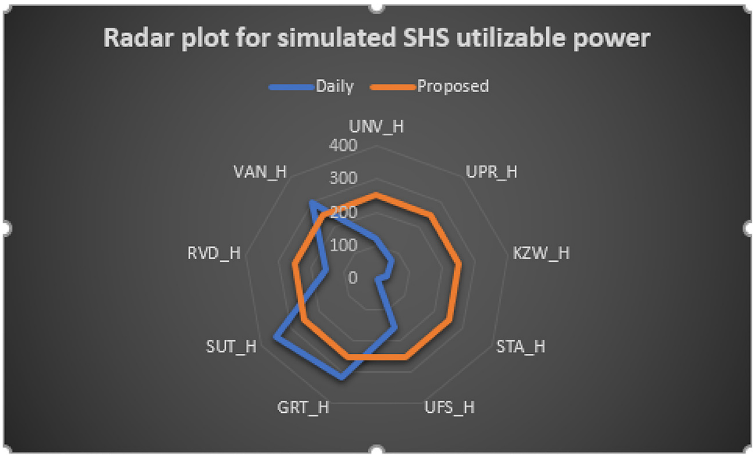

Fig. 4. Radar plot of daily utilizable SHS power across the weather stations.

Table 8
Inverter specifications and parameter definition.

Voltage	12 V
Rating	500 W
n_{inv}	0.9

Values are assumed.

Table 10
QoL, $c_{b}ase$ and duration values.

	$\text{QoL}_{\text{base}}^{\text{low/high}}$	$c_{\text{base}}^{\text{low/high}}$	$mSHS_{base}$	Duration (days)
Low	5	1.6	7.5	30
High	0	8	7.5	30

Table 11
$\text{QoL}_{\text{base}}^{i,j}$, $c_{\text{base}}^{i,j}$ and duration evaluation for weather stations considered.

Station	$\text{QoL}_{\text{base}}^{i,j}$	$c_{\text{base}}^{i,j}$	$mSHS_{base}$	Duration (days)
UNV-H	3.69	3.28	7.5	61.52
UPR-H	1.82	5.67	7.5	106.32
KZW-H	−3.52	12.51	7.5	234.54
STA-H	−54.66	77.97	7.5	1461.93
UFS-H	4.23	2.58	7.5	48.44
GRT-H	5.26	1.27	7.5	23.84
SUT-H	5.35	1.15	7.5	21.56
RVD-H	4.21	2.61	7.5	49.02
VAN-H	5.21	1.33	7.5	24.93

trade-off in comfort based on the duration (in days) it takes a household to receive 7.5 kWh.

$$c_{\text{base}}^{\text{low/high}} = \frac{\text{cost}_{\text{base}}^{\text{low/high}}}{\text{mSHS}_{\text{base}}} \quad (\text{ZAR/kWh}) \tag{1}$$

$$\text{QoL}_{\text{base}}^{i,j} = \frac{\text{QoL}_{\text{base}}^{\text{low}}}{c_{\text{base}}^{\text{low}} - c_{\text{base}}^{\text{high}}}\left(c_{\text{base}}^{i,j} - c_{\text{base}}^{\text{high}}\right) \tag{2}$$

We ask at this stage, what constitutes basic electricity need? While the Non Grid Electrification Policy Guidelines for electrifying off-grid rural poor households is premised on supplying 250 Wh/day, the analysis performed in this paper has shown that such target might not be feasible owing to geographic influence and the stochasticity of solar irradiance. Furthermore, the proposed SHS for off-grid rural poor homes impedes migration of households from lower energy levels to higher energy levels (through the acquisition of electrical appliances or extended usage of already owned electrical appliances). The Non Grid Electrification Policy Guidelines thus fail in guaranteeing energy security and availability for households. It is for this reason that the next section introduces the proposed hybrid generating system.

5. The proposed hybrid generation system

We now present our hybrid system for off-grid houses (Fig. 6), which we argue, has the potential to provide more energy just outcomes to the current SHS system. The proposed hybrid generation system is a

Table 9
Electrical appliances and duration profile.

Need	Device	Number	Wattage (W)	Duration (h)	Total consumption (W)
Lighting	CFL	4	6	–	21
Entertainment	TV	1	53	4	212
Others	Phone charging	1	10	–	5
	Radio	1	2	–	10

CFL: compact fluorescent lamp.

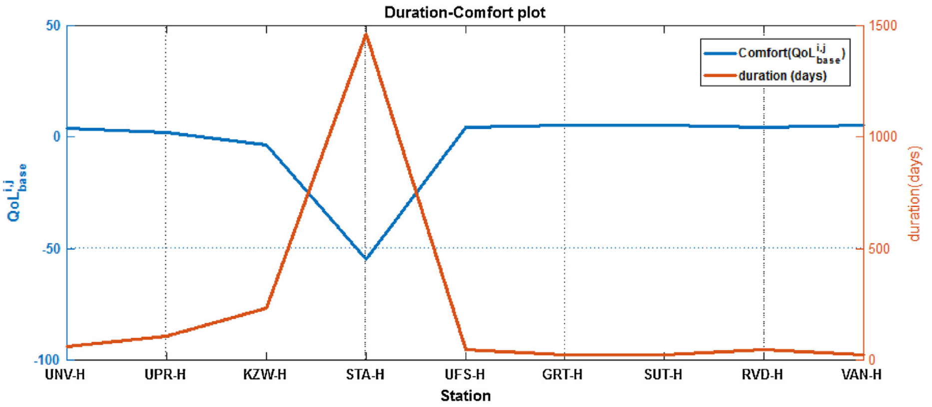

Fig. 5. Duration-Comfort plot for weather stations.

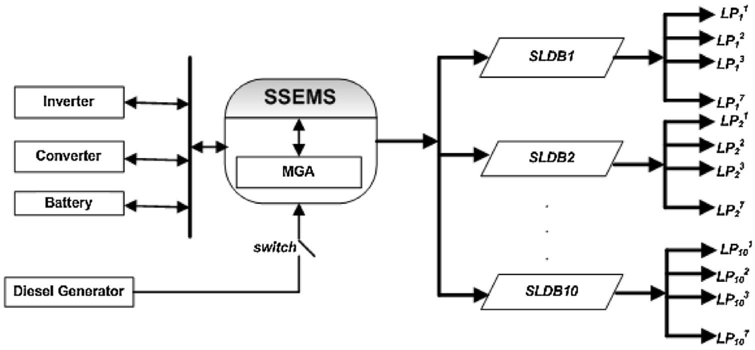

Fig. 6. Proposed hybrid generation scheme. Where *SLDBa* is the smart load distribution board for house a; LP_a^b is the load point *b* for house *a* (where *b* could be a lighting point, television point, cooking point etc., see [9]); SSEMS is the supply side energy management system and MGA is the modified genetic algorithm [10].

fixed site[4] generation scheme consisting of the solar PV modules, inverter system, converter system, battery and a diesel generator. It has a supply side energy management system (SSEMS) that performs MGA operations (for optimally scheduling LP5–LP7) and a smart load distribution board (SLDB) for each connected household. The following assumptions guide its operation:

- All the connected houses are assumed to be clustered together. This is to reduce losses owing to electricity distribution and the associated costs in extending supply to distant houses. A justification for this found in [32] who state that "Several regions show a highly focal population distribution, with 90% of the population concentrated in less than 10% of the land surface, such as in South Africa."
- The pricing scheme adopted is flexible and easily adaptable.

The proposed hybrid generation scheme consists of *u* number of 50 Wp PV panels (where *u* is the number of connected off-grid houses), and 1 5–kVA diesel generator. The operation of the diesel generator is at specific times, 5–8 am and 5–10 pm for weekdays and 5–8 am, 11 am – 2 pm and 5–10 pm for weekends. Each connected house has a smart load distribution board which has pre-set load points that are controlled from the generation point. High energy demand points (cookers, pressing iron, electric kettles, etc.) are connected to a fixed outlet point from the smart load distribution board which are only activated when the diesel generator is operational. This is to prevent the high energy demand loads from draining the battery supply. For the other times, the connected houses draw energy from the battery bank to meet such less energy demand needs as lighting, phone charging, etc. Tables 12 and 13 present the dispatch of LP5–LP7 using MGA (see Appendix II) while Table 14 presents the monthly energy consumption of each considered house. The billing method adopted and the evaluation of the Q-point are presented in Appendix III, while Tables 15 and 16 present the monthly electricity allocation and monthly electricity bill per house for *Q*-point = 4. Fig. 7 presents the Duration-Comfort plot for the proposed hybrid generation scheme for $n = 0$ while Fig. 8 presents the progression of C_n and G_n (government monthly counterpart funding in form of subsidy for year *n*) for *Q*-point = 4.

5.1. Sensitivity analysis of the proposed hybrid generation scheme

In evaluating the economic and environmental impact of the proposed hybrid generation scheme in comparison to the SHS option (currently obtainable), we examine for the current community the extent to which the proposed hybrid generation scheme impacts on the energy burden[5] and carbon emissions of the community under consideration. As seen from Appendix IV, for the proposed hybrid generation scheme, if all houses belong to class 2, energy burden is evaluated to be about 13.92% with the proposed hybrid generation scheme reducing cumulative carbon emissions by 73%. Similarly, all houses

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[4] By fixed site we mean a centralized base of operations where electricity is generated before distribution to the connected houses.

[5] By energy burden we mean the fraction of a household's income spent on meeting its energy needs [33].

Table 12
5–8 am and 11 am to 2 pm typical dispatch profile.

		05:00–05:10	05:10–05:20	05:20–05:30	05:30–05:40	05:40–05:50	05:50–06:00	06:00–06:10	06:10–06:20	06:20–06:30
House 1	Cooker	0	0	0	0	0	0	0	0	0
	Electric kettle	0	0	0	0	0	0	0	0	0
	Pressing iron	0	700	700	700	0	0	0	0	0
House 3	Cooker	0	0	0	0	0	0	0	0	0
	Electric kettle	0	0	0	0	0	0	0	0	0
	Pressing iron	0	0	0	0	0	0	0	0	0
House 4	Cooker	0	0	0	0	0	0	750	750	750
	Electric kettle	0	0	0	0	0	1000	0	0	0
	Pressing iron	0	700	700	700	0	0	0	0	0
House 5	Cooker	0	0	0	0	0	0	0	0	0
	Electric kettle	0	0	0	0	1000	0	0	0	0
	Pressing iron	0	0	0	0	0	0	0	0	0
House 7	Cooker	0	750	750	750	750	750	750	0	0
	Electric kettle	0	0	0	0	0	0	0	0	0
	Pressing iron	0	0	0	0	0	0	0	0	0
House 8	Cooker	0	0	0	0	0	0	0	0	0
	Electric kettle	1000	0	0	0	0	0	0	0	0
	Pressing iron	0	0	0	0	0	0	0	0	0
House 10	Cooker	0	0	0	0	0	0	0	0	0
	Electric kettle	0	0	0	0	0	0	0	0	0
	Pressing iron	0	0	0	0	0	0	0	0	0
Total (W)		1000	2150	2150	2150	1750	1750	1500	750	750
		06:30–06:40	06:40–06:50	06:50–07:00	07:00–07:10	07:10–07:20	07:20–07:30	07:30–07:40	07:40–07:50	07:50:08:00
House 1	Cooker	0	0	0	0	0	0	0	0	0
	Electric kettle	0	0	0	0	0	0	0	0	0
	Pressing iron	0	0	0	0	0	0	0	0	0
House 3	Cooker	750	750	750	750	750	750	0	0	0
	Electric kettle	0	0	0	0	0	0	0	0	0
	Pressing iron	0	0	0	0	0	0	0	0	0
House 4	Cooker	750	750	750	0	0	0	0	0	0
	Electric kettle	0	0	0	0	0	0	0	0	0
	Pressing iron	0	0	0	0	0	0	0	0	0
House 5	Cooker	0	0	0	0	0	0	0	0	0
	Electric kettle	0	0	0	0	0	0	0	0	0
	Pressing iron	0	0	0	0	0	0	0	0	0
House 7	Cooker	0	0	0	0	0	0	0	0	0
	Electric kettle	0	0	0	0	0	0	0	0	1000
	Pressing iron	0	0	0	0	0	0	0	0	0
House 8	Cooker	0	0	0	750	750	750	750	750	750
	Electric kettle	0	0	0	0	0	0	0	0	0
	Pressing iron	0	0	0	0	0	0	0	0	0
House 10	Cooker	0	0	0	0	0	0	0	0	0
	Electric kettle	0	0	0	0	0	0	1000	0	0
	Pressing iron	0	0	0	0	0	0	0	0	0
Total (W)		1500	1500	1500	1500	1500	1500	1750	750	1750

"0" signifies no dispatch for that time slot.

belonging in class 6 results in an energy burden of 13.46% and a reduction in cumulative carbon emissions by over 40%. With regards to the risks of particulate pollution from diesel generation or negative health impacts, these can be mitigated, to some extent, by situating the generators outside the houses (on the settlement periphery) and not within homes (as is the case with cookstoves and firewood). While we acknowledge that our proposed system might not be an ideal one given its dependence on a fossil resource, we also acknowledge that 100% renewable is currently not feasible owing to the associated costs of sizing and the historical failures of such projects, as investigated by Azimoh et al. [4] and Ikejemba et al. [3]. We note too, that the idea of incorporating diesel generators as a back up is not a new one (see [4]).

6. Results and discussion with respect to the energy justice framework

For the purpose of this paper, the following principles from [15] energy justice framework are used to extending discussions on our simulation results.

- The availability principle [Principle 1];
- The affordability principle [Principle 2];
- The due process principle [Principle 3];
- The intra-generational equity principle [Principle 4];
- The sustainability principle [Principle 5].

Table 13
5pm-10pm typical dispatch profile.

		17:00–17:10	17:10–17:20	17:20–17:30	17:30–17:40	17:40–17:50	17:50–18:00	18:00–18:10	18:10–18:20	18:20–18:30	18:30–18:40	18:40–18:50	18:50–19:00	19:00–19:10	19:10–19:20	19:20–19:30
House 1	Cooker	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Electric kettle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pressing iron	0	700	700	700	0	0	0	0	0	0	0	0	0	0	0
House 3	Cooker	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Electric kettle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pressing iron	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
House 4	Cooker	0	0	0	0	0	0	0	0	0	0	0	0	0	750	750
	Electric kettle	0	0	0	0	0	0	0	0	0	0	1000	1000	0	0	0
	Pressing iron	0	0	700	700	700	0	0	0	0	0	0	0	0	0	0
House 5	Cooker	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Electric kettle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pressing iron	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
House 7	Cooker	0	0	0	0	0	0	0	0	0	0	0	0	750	750	750
	Electric kettle	1000	1000	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pressing iron	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
House 8	Cooker	0	0	0	0	0	750	750	750	750	750	750	750	750	750	750
	Electric kettle	0	0	0	0	0	0	1000	1000	0	0	0	0	0	0	0
	Pressing iron	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
House 10	Cooker	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Electric kettle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pressing iron	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total (W)	1000	1700	1400	1400	700	750	1750	1750	750	750	1750	1750	1500	2250	2250

		19:30–19:40	19:40–19:50	19:50–20:00	20:00–20:10	20:10–20:20	20:20–20:30	20:30–20:40	20:40–20:50	20:50–21:00	21:00–21:10	21:10–21:20	21:20–21:30	21:30–21:40	21:40–21:50	21:50–22:00
House 1	Cooker	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Electric kettle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pressing iron	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
House 3	Cooker	0	0	750	750	750	750	750	750	750	750	750	750	750	750	0
	Electric kettle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pressing iron	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
House 4	Cooker	750	750	750	750	750	750	750	750	750	750	0	0	0	0	0
	Electric kettle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pressing iron	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
House 5	Cooker	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Electric kettle	0	0	0	0	0	0	0	0	0	0	1000	1000	0	0	0
	Pressing iron	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
House 7	Cooker	750	750	750	750	750	750	750	750	750	0	0	0	0	0	0
	Electric kettle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pressing iron	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
House 8	Cooker	750	750	0	0	0	0	0	0	0	0	0	0	0	0	0
	Electric kettle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pressing iron	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
House 10	Cooker	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Electric kettle	0	0	0	0	0	0	0	0	0	0	0	0	0	1000	1000
	Pressing iron	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total (W)		2500	2250	2250	2250	2250	2250	2250	2250	2250	1500	1750	1750	750	1750	1000

Table 14
Monthly house electricity consumption divided into source and week period.

	Monthly house energy consumption				Total monthly (kWh)
House	PV/ battery (kWh)	Generator (kWh)	Weekdays (kWh)	Weekends (kWh)	
1	22.09	41.66	44.47	19.29	63.76
2	22.09	18.8	29.07	11.82	40.89
3	22.09	84.05	70.32	35.82	106.14
4	23.64	129.03	102.72	49.95	152.67
5	22.09	38.8	43.74	17.15	60.89
6	22.09	18.8	29.07	11.82	40.89
7	23.64	106.16	87.32	42.48	129.8
8	23.64	106.16	87.32	42.48	129.8
9	22.09	18.8	29.07	11.82	40.89
10	22.09	38.8	43.74	17.15	60.89

6.1. *Principle 1 discussion: availability*

The analysis of simulation results based on Principle 1 would transverse sufficiency of supply, security of supply, reliability of supply source, investment guarantee for sustainability and supply resilience. We thus seek to provide answers to the following questions:

- What constitutes sufficient energy of high quality [for the off-grid poor rural households]?
- Is there a disparity (energy-wise) between grid connected poor homes and off-grid poor homes?

Fig. 4 shows the utilizable power from the SHS units across the provinces on a typical day. The implication of this is that in the seven provinces being considered, only GRT-H (Eastern Cape), SUT-H (Northern Cape) and VAN-H (Western Cape) are capable of meeting or exceeding the assumed 250 Wh daily production rates. The utilizable power produced in the other provinces is therefore *insufficient* in meeting the demands set out in Table 13. Furthermore, the stochastic nature of solar irradiance does not guarantee security and reliability of supply due to its unpredictable nature and variability in availability.

Considering the fact that under the Non Grid Electrification Policy Guidelines, the SHS are installed per household, monthly household collection rates are based on households' willingness to pay. This does not guarantee sustainable investment rates due to the risks involved in *recouping* investments. The huge costs involved in upgrading to the SHS systems also means that households cannot increase electricity consumption beyond the capacity of the installed SHS. Furthermore, the inability of the Non Grid Electrification Policy Guidelines to account for system depreciation irrespective of maintenance decimates household's energy consumption capacity yearly, which has the potential of making households poorer energy wise in the long run.

According to [34], 45 kWh/month/household is currently the minimum for any electrification project that aims to receive funds from the *Conta de Desenvolvimento Energetico – CDE*. The 45 kWh/month per household is evaluated and based on the assumption that this is the minimum energy required for lighting, communication and refrigeration. This value is similar to the 50–100 kWh/year/person for basic energy needs in [35], p. 718 (if average household size for off-grid rural households is estimated at 4 persons/household). We thus evaluate the daily household basic energy need to be around 1.5 kWh/day (for 45 kWh/month/household). While DME [25] justifies the low capacity of the proposed SHS for off-grid poor homes by highlighting low energy consumption from previous electrification projects, it fails to create allowances for energy growth in off-grid poor rural homes owing to the mutual influence between demand and supply that exists when communities are electrified due to the purchase of new appliances [34].

The FBE offered to grid connected poor homes (rural or urban) is 50 kWh/month, which resonates well with propositions in [34,35]. Yet none of the weather stations across the provinces considered achieves 25% of the FBE offer for grid-connected homes, creating or indeed compounding a disparity between grid connected and off-grid poor. This is due to the fact that the use of alternative energy sources such as firewood and paraffin for lighting, cooking and heating purposes would be proportionately *more* significant for the off-grid poor rural homes than the grid connected poor homes. In essence, for a number of reasons, the SHS does not fulfil the availability principle.

In contrast, by significantly improving the conventional system, the proposed hybrid generation system guarantees sufficient supply for lighting, entertainment and communication needs at the basic level with scheduled and regular intervention for more energy intensive needs (cooking, heating, ironing). The incorporation of an alternative energy source also guarantees the security and reliability of the supply, which makes it resilient to variations and fluctuations in solar irradiance. Investment wise, the proposed hybrid generation system coupled with its billing method guarantees its sustainability, making it attractive for investments. As seen from Tables 14 ($n = 0$) and 15 ($n = 0$ to $n = 9$), without additional system upgrades, the proposed hybrid generation scheme guarantees a minimum of 40.89 kWh/month/household at $n = 0$ and 37.02 kWh/month/household at $n = 9$ which creates some balance between grid connected and off-grid poor homes.

6.2. *Principle 2 discussion: affordability*

In examining the simulation results under Principle 2, price stability and sustainable pricing capable of mitigating energy poverty would provide guidance for our discussions. Considering the multidimensional issues – pricing, energy poverty, energy vulnerability and QoL, we seek to provide answers to the following questions:

Table 15
Standardized monthly allocation per house for Q-point = 4.

House	House monthly standardized allocation (kWh/month) incorporating depreciation across the years									
	$n = 0$	$n = 1$	$n = 2$	$n = 3$	$n = 4$	$n = 5$	$n = 6$	$n = 7$	$n = 8$	$n = 9$
1	63.76	63.06	62.36	61.68	61.00	60.33	59.67	59.01	58.36	57.72
2	40.89	40.44	40.00	39.56	39.12	38.69	38.26	37.84	37.43	37.02
3	106.14	104.97	103.82	102.68	101.55	100.43	99.32	98.23	97.15	96.08
4	152.67	150.99	149.33	147.69	146.06	144.46	142.87	141.30	139.74	138.20
5	60.89	60.22	59.56	58.90	58.25	57.61	56.98	56.35	55.73	55.12
6	40.89	40.44	40.00	39.56	39.12	38.69	38.26	37.84	37.43	37.02
7	129.8	128.37	126.96	125.56	124.18	122.82	121.47	120.13	118.81	117.50
8	129.8	128.37	126.96	125.56	124.18	122.82	121.47	120.13	118.81	117.50
9	40.89	40.44	40.00	39.56	39.12	38.69	38.26	37.84	37.43	37.02
10	60.89	60.22	59.56	58.90	58.25	57.61	56.98	56.35	55.73	55.12
Total (kWh/month)	826.62	817.53	808.53	799.64	790.84	782.15	773.54	765.03	756.62	748.29

Table 16
Monthly electricity bill for each house using Q-point = 4.

House	House monthly standardized payment (ZAR/month) for Q-point = 4 years									
	$n = 0$	$n = 1$	$n = 2$	$n = 3$	$n = 4$	$n = 5$	$n = 6$	$n = 7$	$n = 8$	$n = 9$
1	119.07	129.79	141.47	154.20	168.08	183.20	199.69	217.66	237.25	258.61
2	75.27	82.04	89.43	97.48	106.25	115.81	126.24	137.60	149.98	163.48
3	158.8	173.09	188.67	205.65	224.16	244.33	266.32	290.29	316.42	344.90
4	269.28	293.52	319.93	348.73	380.11	414.32	451.61	492.25	536.56	584.85
5	116.28	126.75	138.15	150.59	164.14	178.91	195.01	212.56	231.70	252.55
6	75.27	82.04	89.43	97.48	106.25	115.81	126.24	137.60	149.98	163.48
7	214.74	234.07	255.13	278.09	303.12	330.40	360.14	392.55	427.88	466.39
8	214.74	234.07	255.13	278.09	303.12	330.40	360.14	392.55	427.88	466.39
9	75.27	82.04	89.43	97.48	106.25	115.81	126.24	137.60	149.98	163.48
10	116.38	126.85	138.27	150.72	164.28	179.07	195.18	212.75	231.89	252.76
Total (ZAR/month)	1435.10	1564.26	1705.04	1858.50	2025.76	2208.08	2406.81	2623.42	2859.53	3116.88

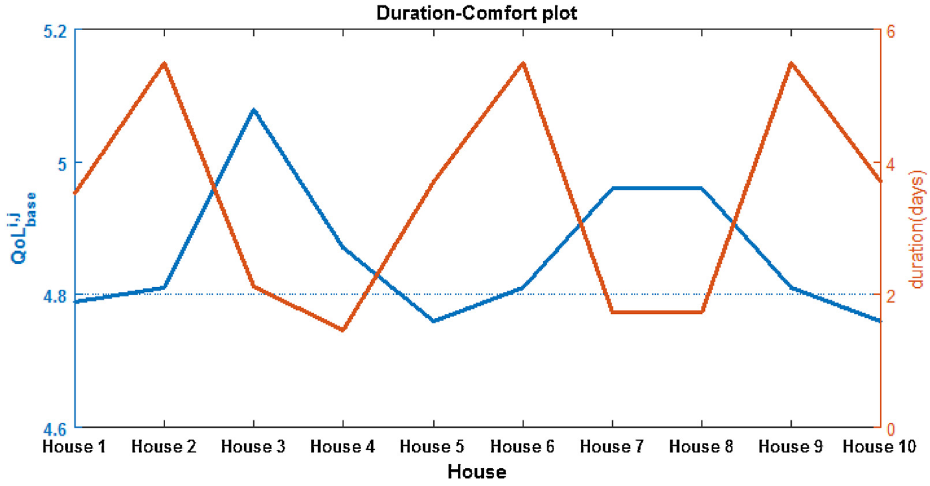

Fig. 7. Duration-Comfort plot for all houses for $n = 0$.

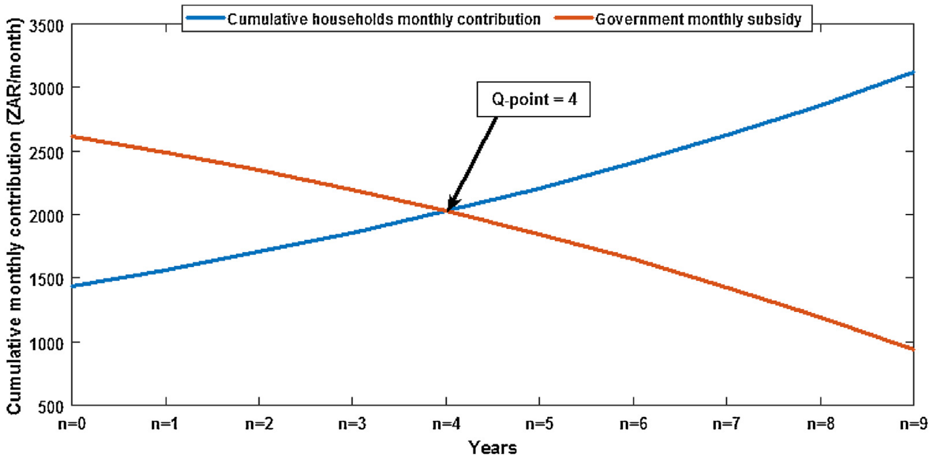

Fig. 8. C_n and G_n progression plot.

- Does electricity cost (based on unit cost) constitute energy poverty for homes?
- Is the SHS electricity bill justified based on variable supply?

According to [36], the poverty headcount in South Africa was 55.5% of the population in 2015. This was based on the upper-bound poverty line (UBPL) of ZAR 992/month. For the purpose of this paper, we define energy poverty (in terms of expenditure on energy) to be spending more than 12% of a household's income on energy bills monthly. Considering the fact that the monthly cost of electricity for off-grid poor rural homes is about ZAR 12/month, this implies that on face value, only about 1.2% of a households income is spent on electricity needs from the SHS. However, STATSSA [36], p. 110 shows that annual expenditure of rural households on housing, water, electricity, gas and other fuels was 25% and 23.6% in 2011 and 2015 respectively. Further, Table 11 (column 3) shows that the "per unit" cost of electricity from the SHS for the provinces under consideration varied from ZAR 1.15/kWh to ZAR 77.97/kWh.

Considering the fact that many of the SHS's may not be operational and reliable (see [4]), off-grid poor rural households may be forced to source find alternative sources for most/all of their energy needs (e.g. lighting, cooking and heating) including paraffin and firewood. This thus increases the expenditure of households. According to [31], about 47% of non-electrified households in South Africa experience energy poverty (using 10% household monthly income on energy as threshold).

The Duration-Comfort plot for the weather stations shown in Fig. 5 presents a valid basis for further analysis. Using the expected 7.5 kWh/month – which is the proposed monthly supply for households from the SHS under the Non Grid Electrification Policy, there is a wide disparity between the comfort derived by households from the SHS and the duration it takes to receive 7.5 kWh. Electricity cost and monthly billing are thus not justified for the SHS under the Non Grid Electrification Policy. Moreover, the total dependence of most houses with the SHS on alternative fuel sources exposes them to the volatility of price fluctuations, which has the potential of further impoverishing these vulnerable groups.

Considering the fact that energy fuels and services are meaningless if households cannot afford to access and utilize them [12], the proposed hybrid generation scheme adopts a sustainable and flexible billing system that is both progressive and adaptable. The yearly increment insures households from seasonal variations in prices of diesel while the guarantee of constant electricity for lighting and associated needs reduces households expenditure on alternative fuels. For example, Table 16 shows that the monthly expenditure of ZAR 214.74 guarantees households constant electricity for lighting, entertainment and communication and the daily scheduled supply for cooking and water heating purposes. Furthermore, the flexibility in utilizing lower-power rated electrical devices on higher-power rated points (LP7/LP6 or LP7/LP5 or LP4/LP6) reduces the inequity between House 4 and Houses 7 and 8 and also improves comfort as shown in the Duration-Comfort plot of Fig. 7. In mitigating energy poverty, a monthly expenditure of ZAR 214.74 (21.6% of a monthly income of ZAR 992) drastically reduces off-grid poor rural households need for extra fuel, with implications for their QoL.

Where there are difficulties in establishing this system, government subsidy can play an active role in the proposed hybrid scheme through waivers or electricity price discounts for very poor homes (paid as a subsidy directly to the proposed hybrid scheme operator). However, this might not be feasible in the conventional system since the alternative to upgrading the SHS is subsidizing alternative fuel sources.

6.3. Principle 3 discussion: due process

In extending discussions on the simulation results obtained with respect to Principle 3, the level of community/stakeholders involvement and conflict resolutions through judicial and administrative remedies would form the core of our discuss. The questions to be answered include:

- How involved are the host communities in the execution of the SHS projects?
- Does the involvement of host communities portend sustainability of project?

According to [37], a major contribution to the failure of the Lucingweni mini-grid project in South Africa was insufficient community engagement. The conventional system of SHS deployment creates no room for much community engagement since the SHS is tied to each house. Failure is thus guaranteed *ab initio* since any feedback from communities does not necessarily affect the technical and installation road maps. Furthermore, the issues of conflicts need not necessarily arise since households' SHS are independent of each other. Issues relating to maintenance and repairs are thus handled on a case-by-case basis.

Despite this, the proposed hybrid generation scheme still provides a better alternative as it improves on the failure of the Lucingweni project and the conventional SHS scheme for off-grid rural electrification by creating a model that allows for the active incorporation of the community. Since the success/failure of the proposed hybrid generation scheme is tied to the responsiveness of households in the community, the proposed hybrid generation scheme advocates for the creation of a community-led management responsible for computing electricity bills, allocating subsidies to households, penalizing households for failure to meet monthly obligations, determination usage savings accrued from excess solar irradiance and the like. The participation of the community through this community-led management may create a sense of 'shared ownership' since the project is deemed to be owned by all. The early engagement with the community regarding site selection and an environmental impact assessment (EIA) report is also necessary. In moderating resolutions, the ESCO along with the municipality act as unbiased members of the community-led management and provide technical and financial background to enable the community appreciate the long term goals of the proposed hybrid generation scheme. This line of argument is supported by the work of [38] who state in the context of community participation and community based management in African case studies that "community participation was shown to be effective when the local population is involved not as co-operating users but as natural resource managers or owner managers."

6.4. Principle 4 discussion: intra-generational equity

Principle 4, according to [12], argues for the right of people to access energy services fairly. In explaining further the simulation results from the perspective of Principle 4, we seek to address the issue of distributive justice by answering the following questions:

- What constitutes fairness in electrification exercises?
- To what extent should equity be applied in providing access (considering varying poverty levels)?

According to [13], sufficientarianism holds that for a distribution to be deemed fair, all must receive sufficient amount of goods to meet their basic needs while egalitarianism deems a fair distribution as one in which all persons have equal share of goods. Navigating the conflicts arising thus necessitates the formulation of realistic targets with fair input from sufficientarianism and egalitarianism concepts. In trying to establish a baseline for the definition of basic needs, we are confronted with the 7.5 kWh/month (for the off-grid poor rural households under the Non grid Electrification Policy) [25], 50 kWh/month (free basic electricity for grid connected poor homes) [26], 45 kWh/month [34] and 50–100 kWh/person/year [35]. A critical analysis of the Non grid Electrification Policy from Table 9 shows that the guarantee of 250 Wh/day for off-grid poor rural households only avails residents of 4 hours electricity supply for television and lighting (assuming one CFL being operational for 4 h) with very limited energy for phone and radio charging. A demerit of such a system is the fact that night time activities cannot be extended sufficiently to enable women perform home chores and allow school kids reading time. This negates the libertarian elements of freedom and choice as home users do not have choice in deciding to use available electricity or not since it is not initially sufficient. Furthermore, in terms of utilitarianism and welfare, the SHS system promoted by the Non Grid Electrification Policy contributes negatively to the QoL of households by providing no value for their investments to the SHS scheme due to varying and unpredictable weather conditions. Furthermore, the roll-out of a uniform rating of SHS across the provinces does not imply egalitarianism since our “realistic utopia” is constrained by an external condition – weather variation. In general, fairness is thus not derived from the Non grid Electrification Policy Guidelines.

A problem thus arises from the Non grid Electrification Policy in that an illusion of electrification is created for poor households in areas with poor solar irradiance thus depriving these off-grid poor rural households access to subsidized alternative fuel sources through the Free Basic Alternative Energy (FBAE) policy.[6]

The proposed hybrid generation system provides a minimum of 40.89 kWh/month per household (assuming no depreciation) as seen in Table 15. This at the basic level is capable of guaranteeing 24-hours of lighting (for 4 CFLs simultaneously) and radio use, 1-hour of phone charging and 13 h of television use for the basic household having LP1 (1 unit), LP2 (1 unit), LP3 (4 units) and LP4 (1 unit) on a weekday with extended usage (11.8% increase) on weekends. This satisfies sufficientarianism (since the basic provision meets the basic needs of lighting and entertainment sufficiently), egalitarianism (since based on our constrained utopia, basic electricity allocation is proportional to ownership of electrical appliances), libertarianism (since households have a choice over duration of use of devices though combination options under our constrained utopia is pre-defined) and utilitarianism (owing to the significant improvement in household welfare and QoL as evidenced from the Duration-Comfort plot in Fig. 7). In ensuring that households have a sufficient level of electricity supply guaranteed across a day that can dispatch singly any of the load points (LP1–LP4), the proposed hybrid generation scheme is fair. Furthermore, the adoption of the proposed billing system for the hybrid generation scheme and the community-led management creates room for government interface and intervention (through subsidy for very poor households) to guarantee the minimum level of electricity supply (40.89 kWh/month assuming 0% depreciation). Thus, the determination of equity in electricity access for poor households does not arise since government's intervention guarantees them basic access.

6.5. Principle 5 discussion: sustainability

In providing insights to our simulated results from sustainability perspective, we examine the frugality in the use of resources and the interaction of the generation scheme with the environment. We thus seek to provide answers to the following questions:

- Does the supply scheme inherently guarantee optimal usage of resources?
- How flexible is the supply scheme in adopting reparation measures that provide an option for system improvement in terms of sustainability?

According to [40], the Clean Development Mechanism (CDM) under the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC) permits industrialized countries having greenhouse gas reduction commitments to ‘off-shore’ investments in emissions reducing projects to developing countries as an alternative to costly reduction strategies in their countries. This thus underscores the need for sustainability and viability of emission reducing projects executed by developed nations in developing countries. According to [41], South Africa has received support from Danish Cooperation Programme (DANIDA), German Technical Co-operation Organization (GTZ), United Nations Development Programme (UNDP) and World Bank. The SHS installed in off-grid poor rural homes through the Non Grid Electrification Policy cannot be said to be sustainable especially when weather variations are incorporated. DOE [41] further posits that about 96,000 SHS have been installed at an estimated cost in excess of ZAR 350 million with the SHS delivering quite limited services with lighting as the only quality service (over candles and paraffin lamps) [41], p. 7. We can thus infer based on the limited services offered by the SHS (which is further decimated when weather variations are incorporated) that resources have not be optimally utilized. A justification for this stems from [41] where the redesigning of the entire off-grid electrification programme is being proposed to improve the quality of service (QoS) being offered through the establishment of a non-grid electrification authority. Furthermore, considering the isolated (per household) nature of the SHS installation, the conventional off-grid electrification scheme is not flexible enough to adopt reparation measures that would improve its QoS since that would come at a huge cost. While it may be argued that the SHS scheme does offer Certified Emission Reduction (CERs), this on the contrary cannot be substantiated considering the fact that in areas with poor solar irradiance, the SHS are of almost no importance since it depletes households income (through the once-off connection fee and monthly payments which do not obviate the need for households to still purchase alternative fuel sources to meet cooking, lighting and heating needs) and impacts negatively on households QoL (as shown in Fig. 5).

The proposed hybrid generation scheme on the contrary through its flexible billing and centralized operations system coupled with the incorporation of an artificial intelligence tool (MGA) for optimization of load dispatch, ensures that resources are optimally utilized. This is evidently reflected in the sizing of the diesel generator and load dispatch (LP5–LP7) shown in Tables 12 and 13 for the various time slots. Furthermore, the proposed hybrid generation scheme incorporates a 15% carbon tax on diesel generator usage which could be aggregated and used in increasing the penetration of renewable energy (RE). The flexible billing system and centralized operations of the proposed hybrid generation scheme creates a platform for incorporating and experimenting a range of pricing and generation mix options which are capable of enhancing delivery and the robustness of the scheme. Additionally, the ability of the proposed hybrid generation scheme to compensate for excess solar irradiance through a re-adjustment of households monthly contribution can be deemed an off-grid feed in tariff system. The proposed hybrid generation scheme thus guarantees sustainability in terms of frugal utilization of resources and carbon emissions reduction by providing a platform that can make it accommodate government policies on emissions target and RE penetration.

7. Conclusions and policy implications

This paper offers the following conclusions. First, our study has argued that the Non Grid Electrification Policy may be practically and as a result, ethically flawed. As demonstrated based on an analysis using selected principles from the energy justice framework, the Non Grid Electrification Policy does not incorporate values into its delivery. Moreover, it does not adequately consider the effect of weather variations across and within the provinces on SHS output. Our simulated results have shown that solar irradiance stochasticity impacts heavily on the output of these SHS and deprives households their intended benefits. Moreover, the varying figures of 7.5 kWh/month/household for off-grid poor rural homes when compared to the FBE of 50 kWh/month/household for grid connected poor homes, 45 kWh/month/household from [34] and 50–100 kWh/person/year from [35] shows that it is quite inadequate in even fully dispatching the basic needs of lighting, entertainment and communication. In contrast, the proposed hybrid generation scheme we have presented has been shown to meet the requirements of the adopted principles from the existing energy justice framework and the ethical ideas of sufficientarianism, egalitarianism, libertarianism and utilitarianism in a realistic utopia.

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[6] The Free Basic Alternative Energy (FBAE) policy is a variation of the FBE and is aimed at supplying indigent off-grid households without SHS limited quantities of alternative energy fuels at no cost to meet their basic energy needs (see [39]).

Secondly, our study has shown that the Non Grid Electrification Policy inadvertently creates or reinforces poverty. Considering the poor contribution of the SHS to the QoL of households based on poor QoS and limited delivery of SHS, households spend more of their income in meeting their energy needs from alternative fuel sources since investments made toward the SHS scheme offer no additional value (see Fig. 5). This thus exposes households to price volatility of these alternative fuel sources. Since productivity is linked to electricity access [37], declining electricity per capita as shown in [10] and our arguments on the negative contribution of the SHS to QoL of off-grid poor rural households find support in [36] which shows increasing poverty across the country despite increasing generation capacity. Furthermore, the fixed nature of the SHS capacity prevents houses from transiting to higher energy levels through purchase of electrical appliances due to the inability of the existing SHS system to accommodate such. The proposed hybrid generation scheme however has been shown to guarantee productivity through provision of energy transition opportunities for households, stable and sufficient electricity supply and the adoption of a flexible billing and centralized operations system (that incorporates artificial intelligence tool (MGA) in optimally dispatching high energy loads).

Third, our study has shown that the Non Grid Electrification Policy is unsustainable. According to [41], a re-organization of the entire off-grid electrification programme is being proposed to improve system delivery. This resonates with simulation results obtained and arguments presented in this paper that (1) resources have been poorly utilized and deployed without proper sizing, adequate consideration of spatial variations and solar irradiance stochasticity; (2) upgrading the SHS to support energy transition of households is not sustainable (since it is capital intensive); (3) the long term operation of the SHS shows no consideration of depreciation and inflation indices which can potentially increase government's subsidy, decimate SHS performance and increase households contribution. The proposed hybrid generation scheme however improves on the conventional SHS scheme by providing a platform that can accommodate inflation and system depreciation and evolve a billing system to compensate for these (through the Q-point determination).

Fourth, our study has argued that the Non Grid Electrification Policy does not offer a platform for sufficient community engagement due to the isolated (per household) nature of SHS installations. Community engagement has been shown to be a contribution to the failure of the Lucingweni project and success of the solar-diesel Tsumkwe hybrid mini-grid project in Namibia [4,37]. We have thus presented arguments supporting community-led management in contributing to decision making as regards the proposed hybrid generation scheme. Furthermore, we have argued that incorporating the community from the beginning and in all decision making processes creates a sense of 'shared ownership' which makes adoption of resolutions easily binding on all connected households.

Overall, this paper pioneers the incorporation of energy justice into off-grid electrification policy formulation for South Africa. Considering the planned overhaul of off-grid electrification programmes in South Africa, our proposed hybrid generation scheme offers a roadmap for off-grid electrification policy formulation especially in mitigating the impact of weather variations and guaranteeing a basic level of electricity supply that is available, affordable, sustainable and supports energy transition.

Finally, our paper has exposed the scarcity of sufficient research on the incorporation of values in power expansion programmes for South Africa, which thus necessitates further research. Considering the huge investments being made by Eskom in order to increase electricity supply capacity far beyond demand increase (see [10]), the worsening poverty (see [36]) which we have argued is tied to decreasing electricity per capita (both for off-grid and grid connected households) and the capital intensive nature of off-grid electrification, ongoing research aims at creating a sustainable supply capacity expansion framework for Eskom that would lead to a significant reduction in planned electricity price increases, guarantee investment return for Eskom and free up resources for off-grid electrification projects.

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Appendix I

Eq. (3) presents the computation process of output (utilizable) power $P^{o/p}(t)$ at time t while Eq. (4) shows the relationship between ambient temperature (T) and T_c (i.e. conversion from °C to Kelvin).

$$P^{o/p}(t) = \text{evaluate}(T,\ V,\ G) \times V \times U_f \tag{3}$$

$$T_c = T + (0.2 \times G) + 273.18 \tag{4}$$

where T is the hourly average weather station temperature (in Celsius), V is the fixed output voltage of the converter (12 V), G is the hourly average weather station irradiance (in $\mathrm{W\,m^{-2}}$) and U_f is the utilization factor (fill factor). The term '*evaluate*' used in Eq. (3) is a function that computes hourly current (I in amperes) by utilizing the Newton-Raphson method.

For this paper, we assume that all solar power gets dumped into the battery first before utilization. Eq. (5) shows the constraint on the battery state of charge $SOC(t)$ at any time t.

$$\mathrm{SOC}_{\min} \le \mathrm{SOC}(t) \le \mathrm{SOC}_{\max} \tag{5}$$

where SOC_{min} described in Eq. (6) is the minimum state of charge of the battery and is a function of battery's depth of discharge (DOD) and SOC_{max} is the battery's maximum state of charge. At maximum battery charge C_{batt}, $SOC(t) = SOC_{max}$.

$$\mathrm{SOC}_{\min} = (1 - \mathrm{DOD}) \times C_{\mathrm{batt}} \tag{6}$$

The law of energy conservation guides the battery charging and discharging operations and is described in Eq. (7).

$$\mathrm{SOC}(t_{\mathrm{initial}}) = \mathrm{SOC}(t_{\mathrm{final}}) \tag{7}$$

where $SOC(t_{initial})$ is the battery state of charge at start of simulation and $SOC(t_{final})$ is battery state of charge at end of simulation. Given $P^{o/p}(t)$ as the PV output power at time t, n_{batt}, n_{inv} as efficiency of the battery and inverter respectively and σ as the battery discharge rate, then the equivalent of $P^{o/}$

$^{p}(t)$ dumped into the battery is given in Eq. (8). Given $D(t)$ to be real time demand, then its battery equivalent ($\overline{D(t)}$) is defined as $\overline{D(t)} = \frac{D(t)}{n_{\text{batt}} \times n_{\text{inv}}}$ where n_{inv} is inverter efficiency. If $\overline{D(t)} \leq \text{SOC}(t-1) \times (1-\sigma)$ then Eq. (9) describes the battery discharge.

$$\text{SOC}(t) = \text{SOC}(t-1) \times (1-\sigma) + (P^{o/p}(t) \times n_{\text{batt}}) \tag{8}$$

$$\text{SOC}(t) = \text{SOC}(t-1) \times (1-\sigma) - \overline{D(t)} \tag{9}$$

Appendix II

The aim of MGA [10] during generator operations is to constrain the allocation of loads (LP5–LP7) at any instant to less than 50% of the generator capacity. In doing this, time slots are pre-allocated to houses with loads LP5, LP6 and LP7 while every other load LP1, LP2, LP3 and LP4 gets dispatched with $df = 0.8$. Thus, if $slot^{max}$ is the maximum slot demand for any duration, Eq. (10) describes the MGA operation on the slot objective function (Z_{slot}).

$$Z_{\text{slot}} = \min(\text{slot}^{\text{max}}) \tag{10}$$

Such that $slot^{max} = max(P_D)$, $P_D = \{P_D^k | k = 1\!: k = 144\}$, $P_D^k = \sum_{i=1,k,j}^{i=10} \{\text{LP5}_k^{i,j}, \text{LP6}_k^{i,j}, \text{LP7}_k^{i,j}\}$ and $slot = \{k | k = 1 : k = 144\}$.

Where *slot* is a 10 min interval, P_D is the set of all slot power demands, P_D^k is the slot k power demand (W), k is the index of all slots and *max* is a function that finds the maximum value in a set. $\text{LP5}_k^{i,j}$, $\text{LP6}_k^{i,j}$ and $\text{LP7}_k^{i,j}$ are the households slot k dispatch value as computed by MGA. It must be pointed out that the slot k value for $\text{LP5}_k^{i,j}$, $\text{LP6}_k^{i,j}$ and $\text{LP7}_k^{i,j}$ are expressed by their power rating.

The artificial intelligence (AI) tool used for optimally allocating LP5–LP7 during hours 05:00–08:00 and 17:00–22:00 (for weekdays and weekends) and 11:00–14:00 (for weekends only) is the modified genetic algorithm (MGA) presented in [10]. In solving the dispatch problem (which is a minimization problem) as shown by Eq. (10), MGA is used to obtain the allocation of the varying combination of LP5–LP7 owned by the connected houses to obtain the minimum demand per time slot (10 min interval) possible. The results obtained are presented in Tables 11 and 12.

Appendix III

The billing of each household is as follows:

- PV cost: A flat rate of ZAR 60/month is billed each house for PV supply. This rate assumes the full cost due each house under the current SHS scheme for off grid houses by transferring the ZAR 48 cost paid by government (in form of subsidy) to the households.
- Generator cost 1: A special billing is applied to households owning any combination of loads LP5–LP7. Thus for any single ownership, a monthly flat rate of ZAR 20 is billed while ZAR 30 is billed for combination of any two (LP5/LP6, LP5/LP7or LP6/LP7). ZAR 48 is billed any house owning the three electrical appliances (LP5/LP6/LP7).
- Generator cost 2: In billing for generator use, houses owning none of LP5-LP6 are charged ZAR 0.65/kWh while houses owning either LP5, LP6 or LP7 are charged at ZAR 0.75/kWh. Houses owning either LP5/LP6 or LP5/LP7 or LP6/LP7 are charged at ZAR 0.94/kWh while houses owning LP5/LP6/LP7 are charged at ZAR 1.00/kWh.
- Generator cost 3: A 15% flat rate is applied on the billing for generator use (Generator cost 2) for all houses as environmental surcharge. This is the penalty due emissions from the diesel generator.
- Generator cost 4: A maintenance cost of 10% is applied on Generator cost 2 for all houses.

The implication of the strategy adopted for billing the houses means that monthly about ZAR 1435.20 is recouped from the connected houses. However, the monthly expenditure on electricity generation (maintenance and operations) is ZAR 4052.53. This means that the deficit of about ZAR 2617.33 would be borne by the government in form of subsidy. Considering the increased expenditure by government in subsidizing off-grid electricity generation from the proposed hybrid generation model, we thus propose a quiescent point (Q-point) which defines the year at which contribution from the connected houses matches government's contribution. The establishment of a *Q*-point helps in determining the rate at which contributions from the houses would increase yearly. In modelling the *Q*-point, the following assumptions are made:

- The monthly cost of generator maintenance has 0% yearly growth throughout the modelling period.
- Power output from the generation station depreciates by 1.1% yearly.

Eqs. (11) and (12) model the yearly depreciation of generation power and combined household monthly contribution for each year.

$$P_n = P_{n-1}(0.989)^n \quad \text{kWh/month} \tag{11}$$

$$C_n = C_{n-1}\left(1 + \frac{\text{rate}}{100}\right)^n \quad \text{ZAR/month} \tag{12}$$

where, P_n and P_{n-1} are the present year n and preceding year $n-1$ power available for distribution while C_n and C_{n-1} are the present year n and preceding year $n-1$ combined monthly contribution from all the houses.

Tables 14 and 15 present the standardized monthly allocation (kWh/month) and monthly electricity bill (ZAR/month) for each household across the years under consideration using *Q*-point = 4 while Fig. 7 presents the Duration-Comfort plot for $n = 0$. Fig. 8 presents the progression of C_n and G_n (government monthly counterpart funding in form of subsidy for year n) for *Q*-point = 4.

Appendix IV

Table 17 presents the appliance ownership schedule for the houses under consideration. From Table 17, the houses can be grouped into 6 classes. The weekday and weekend demand profile for each house class is shown in Tables 18 and 19 respectively. Furthermore, Tables 20 and 21 show the pre-set time for the dispatch of the LP5–LP7 load points for weekdays and weekends respectively. The weekday and weekend energy allocation per house is shown in Tables 22 and 23 respectively while Table 24 presents the battery profile under the proposed hybrid generation scheme. Table 25 presents the monetary cost and equivalent carbon emissions for a typical household under consideration in meeting the needs LP1–LP7. It is observed from Table 25 that a typical household with a SHS and with a monthly income of R2000/month will expend about 18% (R357.61) monthly in

Table 17
Electrical appliance ownership for the houses under consideration.

House	TV LP1 53 W	Radio LP2 2 W	Lighting LP3 6 W	Phone charging LP4 10 W	Cooker LP5 750 W	Electric kettle LP6 1000 W	Iron LP7 700 W
1	✓^{1}	✓^{1}	✓^{4}	✓^{1}	X	X	✓^{1}
2	✓^{1}	✓^{1}	✓^{4}	✓^{1}	X	X	X
3	✓^{1}	✓^{1}	✓^{4}	✓^{1}	✓^{1}	X	X
4	✓^{1}	✓^{1}	✓^{4}	✓^{2}	✓^{1}	✓^{1}	✓^{1}
5	✓^{1}	✓^{1}	✓^{4}	✓^{1}	X	✓^{1}	X
6	✓^{1}	✓^{1}	✓^{4}	✓^{1}	X	X	X
7	✓^{1}	✓^{1}	✓^{4}	✓^{2}	✓^{1}	✓^{1}	X
8	✓^{1}	✓^{1}	✓^{4}	✓^{2}	✓^{1}	✓^{1}	X
9	✓^{1}	✓^{1}	✓^{4}	✓^{1}	X	X	X
10	✓^{1}	✓^{1}	✓^{4}	✓^{1}	X	✓^{1}	X

X – implies not owned.
✓^{V} – electrical appliance owned with v indicating quantity.

Table 18
Weekday demand profile per group (per house).

Group	Number	Time			
		05:00–08:00 df = 0.8	08:00–17:00 df = 0.6	17:00–22:00 df = 0.8	22:00–05:00 df = 0.6
1	3	213.6 Wh	480.6 Wh	712 Wh	373.8 Wh
2	1	1893.6 Wh	480.6 Wh	6312 Wh	373.8 Wh
3	1	2013.6 Wh	480.6 Wh	6712 Wh	373.8 Wh
4	2	2613.6 Wh	480.6 Wh	8712 Wh	373.8 Wh
5	2	4437.6 Wh	534.6 Wh	14792 Wh	415.8 Wh
6	1	6117.6 Wh	534.6 Wh	20384 Wh	415.8 Wh
Total (Wh)		24768 Wh	4968 Wh	82552 Wh	3864 Wh

Table 19
Weekend demand profile per group (per house).

Group	Number	Time					
		05:00–08:00 df = 0.8	08:00–11:00 df = 0.6	11:00–14:00 df = 0.8	14:00–17:00 df = 0.6	17:00–22:00 df = 0.8	22:00–05:00 df = 0.6
1	3	213.6 Wh	160.2 Wh	213.6 Wh	160.2 Wh	712 Wh	373.8 Wh
2	1	1893.6 Wh	160.2 Wh	1893.6 Wh	160.2 Wh	6312 Wh	373.8 Wh
3	1	2013.6 Wh	160.2 Wh	2013.6 Wh	160.2 Wh	6712 Wh	373.8 Wh
4	2	2613.6 Wh	160.2 Wh	2613.6 Wh	160.2 Wh	8712 Wh	373.8 Wh
5	2	4437.6 Wh	178.2 Wh	4437.6 Wh	178.2 Wh	14792 Wh	415.8 Wh
6	1	6117.6 Wh	178.2 Wh	6117.6 Wh	178.2 Wh	20384 Wh	415.8 Wh
Total (Wh)		24768 Wh	1656 Wh	24768 Wh	1656 Wh	82552 Wh	3864 Wh

Table 20
Weekday pre-set duration.

Load	05:00–08:00	17:00–22:00
Cooker	LP5	60 min
Electric kettle	LP6	10 min
Iron	LP7	30 min

Table 21
Weekend pre-set duration.

Load	05:00–08:00	11:00–14:00	17:00–22:00
Cooker	LP5	60 min	60 min
Electric kettle	LP6	10 min	10 min
Iron	LP7	30 min	20 min

Table 22
Weekday energy allocation per house.

		05:00–08:00	08:00–17:00[a]	17:00–22:00	22:00–05:00	Sub–total	Total
House 1	LP1–LP4	213.60 Wh	378 Wh	356 Wh	373.80 Wh	1321.40 Wh	2021.40 Wh
	LP5–LP7	350 Wh	0 Wh	350 Wh	0 Wh	700 Wh	
House 2	LP1–LP4	213.60 Wh	378 Wh	356 Wh	373.80 Wh	1321.40 Wh	1321.40 Wh
	LP5–LP7	0 Wh	0 Wh	0 Wh	0 Wh	0 Wh	
House 3	LP1–LP4	213.60 Wh	378 Wh	356 Wh	373.80 Wh	1321.40 Wh	3196.40 Wh
	LP5–LP7	750 Wh	0 Wh	1125 Wh	0 Wh	1875 Wh	
House 4	LP1–LP4	237.60 Wh	378 Wh	396 Wh	415.80 Wh	1427.40 Wh	4669.07 Wh
	LP5–LP7	1266.67 Wh	0 Wh	1975 Wh	0 Wh	3241.67 Wh	
House 5	LP1–LP4	213.60 Wh	378 Wh	356 Wh	373.80 Wh	1321.40 Wh	1988.07 Wh
	LP5–LP7	166.67 Wh	0 Wh	500 Wh	0 Wh	666.67 Wh	
House 6	LP1–LP4	213.60 Wh	378 Wh	356 Wh	373.80 Wh	1321.40 Wh	1321.40 Wh
	LP5–LP7	0 Wh	0 Wh	0 Wh	0 Wh	0 Wh	
House 7	LP1–LP4	237.60 Wh	378 Wh	396 Wh	415.80 Wh	1427.40 Wh	3969.07 Wh
	LP5–LP7	916.67 Wh	0 Wh	1625 Wh	0 Wh	2541.67 Wh	
House 8	LP1–LP4	237.60 Wh	378 Wh	396 Wh	415.80 Wh	1427.40 Wh	3969.07 Wh
	LP5–LP7	916.67 Wh	0 Wh	1625 Wh	0 Wh	2541.67 Wh	
House 9	LP1–LP4	213.60 Wh	378 Wh	356 Wh	373.80 Wh	1321.40 Wh	1321.40 Wh
	LP5–LP7	0 Wh	0 Wh	0 Wh	0 Wh	0 Wh	
House 10	LP1–LP4	213.60 Wh	378 Wh	356 Wh	373.80 Wh	1321.40 Wh	1988.07 Wh
	LP5–LP7	166.67 Wh	0 Wh	500 Wh	0 Wh	666.67 Wh	

[a] Insufficient battery capacity resulting in reduction in pre-set allocation.

Table 23
Weekend energy allocation per house.

		05:00–08:00	08:00–11:00	11:00–14:00	14:00–17:00	17:00–22:00	22:00–05:00	Sub-total	Total
House 1	LP1–LP4	213.60 Wh	160.20 Wh	213.60 Wh	160.20 Wh	356 Wh	373.80 Wh	1477.40 Wh	2410.73 Wh
	LP5–LP7	350 Wh	0 Wh	233.33 Wh	0 Wh	350 Wh	0 Wh	933.33 Wh	
House 2	LP1–LP4	213.60 Wh	160.20 Wh	213.60 Wh	160.20 Wh	356 Wh	373.80 Wh	1477.40 Wh	1477.40 Wh
	LP5–LP7	0 Wh	0 Wh	0 Wh	0 Wh	0 Wh	0 Wh	0 Wh	
House 3	LP1–LP4	213.60 Wh	160.20 Wh	213.60 Wh	160.20 Wh	356 Wh	373.80 Wh	1477.40 Wh	4477.40 Wh
	LP5–LP7	750 Wh	0 Wh	750 Wh	0 Wh	1500 Wh	0 Wh	3000 Wh	
House 4	LP1–LP4	237.60 Wh	178.20 Wh	237.60 Wh	178.20 Wh	396 Wh	415.80 Wh	1643.40 Wh	6243.40 Wh
	LP5–LP7	1266.67 Wh	0 Wh	1150 Wh	0 Wh	2183.33 Wh	0 Wh	4600 Wh	
House 5	LP1–LP4	213.60 Wh	160.20 Wh	213.60 Wh	160.20 Wh	356 Wh	373.80 Wh	1477.40 Wh	2144.07 Wh
	LP5–LP7	166.67 Wh	0 Wh	166.67 Wh	0 Wh	333.33 Wh	0 Wh	666.67 Wh	
House 6	LP1–LP4	213.60 Wh	160.20 Wh	213.60 Wh	160.20 Wh	356 Wh	373.80 Wh	1477.40 Wh	1477.40 Wh
	LP5–LP7	0 Wh	0 Wh	0 Wh	0 Wh	0 Wh	0 Wh	0 Wh	
House 7	LP1–LP4	237.60 Wh	178.20 Wh	237.60 Wh	178.20 Wh	396 Wh	415.80 Wh	1643.40 Wh	5310.07 Wh
	LP5–LP7	916.67 Wh	0 Wh	916.67 Wh	0 Wh	1833.33 Wh	0 Wh	3666.67 Wh	
House 8	LP1–LP4	237.60 Wh	178.20 Wh	237.60 Wh	178.20 Wh	396 Wh	415.80 Wh	1643.40 Wh	5310.07 Wh
	LP5–LP7	916.67 Wh	0 Wh	916.67 Wh	0 Wh	1833.33 Wh	0 Wh	3666.67 Wh	
House 9	LP1–LP4	213.60 Wh	160.20 Wh	213.60 Wh	160.20 Wh	356 Wh	373.80 Wh	1477.40 Wh	1477.40 Wh
	LP5–LP7	0 Wh	0 Wh	0 Wh	0 Wh	0 Wh	0 Wh	0 Wh	
House 10	LP1–LP4	213.60 Wh	160.20 Wh	213.60 Wh	160.20 Wh	356 Wh	373.80 Wh	1477.40 Wh	2144.07 Wh
	LP5–LP7	166.67 Wh	0 Wh	166.67 Wh	0 Wh	333.33 Wh	0 Wh	666.67 Wh	

Table 24
Battery profile under the proposed hybrid generation model.

5–6	6–7	7–8	8–9	9–10	10–11	11–12	12–13	13–14	14–15	15–16	16–17	17–18	18–19	19–20	20–21	21–22	22–23	23–24	24–1	1–2	2–3	3–4	4–5
Battery capacity (%) without generator																							
10.00[a]	10.00[a]	10.00[a]	10.00[a]	10.02	10.06	10.12	10.17	10.24	10.29	10.32	10.33	10.32	10.31	10.30	10.29	10.28	10.27	10.27	10.00[a]	10.00[a]	10.00[a]	10.00[a]	10.00[a]
Weekday battery capacity profile (%) with generator																							
20.00	30.00	40.00	40.00	40.02	40.06	40.12	40.17	40.24	40.29	40.32	40.33	48.32	56.31	64.30	72.29	80.28	80.27	80.27	80.20	80.14	80.07	80.01	79.95
battery charging – generator only						battery charging – PV only						battery charging – generator only							utilization and derating only				
Weekend battery capacity profile (%) with generator																							
20.00	30.00	40.00	40.00	40.02	40.06	43.12	46.17	50.24	50.29	50.32	50.33	58.32	66.31	74.31	82.31	90.31	90.27	90.27	90.19	90.12	90.05	89.98	89.91
battery charging – generator only			battery charging – PV only			battery charging – PV and generator			battery charging – PV only			battery charging – generator only							utilization and derating only				

[a] Battery maximum depth of discharge.

Battery capacity is 1050 Ah.

Table 25
Energy needs cost and emissions computation under SHS configuration.

Energy need	Alternative	Cost (ZAR)	CO_2 emissions ($kgCO_2$)
LP1	kWh (est.)	41.95	
LP2	kWh (est.)	41.95	
LP3	Candles[a]	58.73	5.13
LP4	kWh (est.)	33.56	
LP5	Paraffin[b]	151.02	0.54
LP6	Wood[c]	8.40	6.05
LP7	Coal[d]	10.00	252.51
Monthly surcharge		12.00	
Total		357.61	264.31

[a] CO_2 emission is taken to be 10.69 gCO_{2e} from [42]. 2 candles per household for 8 hours duration daily is assumed. 1 Month is taken to be 30 days.

[b] Cost is taken from [33] and adjusted at 1.6779% cumulative inflation rate. CO_2 emissions is taken to be 2.58 $kgCO_2$/L.

[c] Cost is taken from [33] and adjusted at 1.6779% cumulative inflation rate. CO_2 emissions is taken to be 1.8 $kgCO_2$/kg.

[d] Cost is assumed and CO_2 emissions taken to be 2419 $kgCO_2$/Tonne.

Table 26
Monthly operations cost for diesel generator and SHS maintenance cost.

Weekdays	8 h × 22 days = 176 h
Weekends	11 h × 8 days = 88 h
Total monthly hours	264 h
Diesel cost	ZAR 11.50/L
Hourly diesel rate	1.2 L/h
Monthly diesel cost	ZAR 3643.20/month
Monthly generator maintenance	ZAR 400
Monthly SHS maintenance	ZAR 9.33
Total monthly cost	ZAR 4052.53

Table 27
Energy cost and emissions for the hybrid generation scheme.

Class	Houses	Cost (ZAR)			Emissions ($kgCO_2$)		
		Hybrid scheme	Others	Total	Hybrid scheme	Others	Total
1	2,6,9	75.27	169.42	244.69	42.00	259.10	301.10
2	1	110.07	159.42	278.49	65.49	6.59	72.08
3	3	158.80	18.40	177.20	109.02	258.56	367.58
4	5,10	116.28	161.02	277.30	62.54	253.05	315.59
5	7,8	214.74	10.00	224.74	133.32	252.51	385.83
6	4	269.28	0.00	269.28	156.81	0.00	156.81

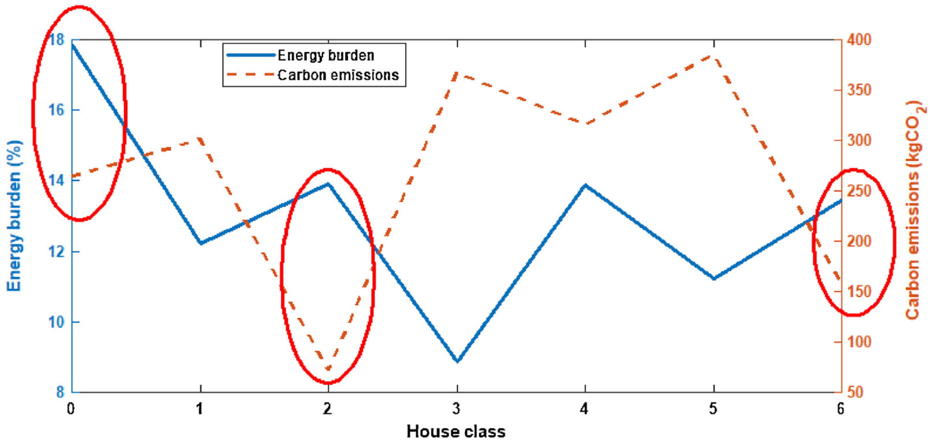

Fig. 9. Energy burden versus Emissions variation for the various house classes.

dispatching LP1–LP7 with a monthly carbon emission 264.31 $kgCO_2$/house.

However, for the hybrid generation scheme, Table 26 presents monthly associated cost for running the diesel generator and servicing the PV panels while Table 27 presents the equivalent monthly energy cost and equivalent carbon emissions for all the house classes. Fig. 9 presents a pictorial representation of the variation of energy burden with carbon emissions for the various house classes. From Fig. 9, house class "0" represents a typical household with a SHS. A significant observation from Table 27 shows that if all houses belong to class 2, the hybrid configuration will result in a 73% drop in emissions over the SHS configuration. Similarly, all houses belonging to class 6 for the hybrid generation scheme will result in a 41% drop in emissions over the SHS configuration. It must be pointed out that the associated emissions from the SHS (i.e. PV and battery) have been ignored. Also, a typical summer month has been assumed (to account for the non-consideration of space heating).

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CHAPTER 9

DISCUSSION OF RESULTS AND CONCLUSION

9.1 Introduction

This chapter presents the discussion of the overall results across this thesis. Considering the multidisciplinary nature of this thesis, this chapter harmonises the results obtained to show how issues raised have been addressed. First, a summary of issues raised from the literature review is presented while subsequent sections present a summary of attempts made at resolving the issues raised.

9.2 Summary of findings from literature review

Chapter 2 presented the paper entitled ***A just and sustainable smart grid approach for mitigating energy poverty and reducing climate change in South Africa***. This paper undertook a crucial review of South Africa's smart grid 2030 vision. Key findings from the literature review which underscored the need for this research revealed the following.

Issue 1: There is lacking for South Africa, significant research that quantifies the demand side management (DSM) potential of household loads such as dishwasher, cloth washer and cloth dryer for varying levels of participation. Such research must be capable of informing policy makers on the potential impact of varying DSM participation levels in mitigating energy poverty and generally minimizing supply capacity expansion costs.

Issue 2: There is lacking for South Africa, significant research that shows an integrated approach to DSM application within South Africa. Such research should show how interconnected aspects of the electricity grid (for example home energy management system (HEMS), supply-side energy management systems (SSEMS) and transmission line management system (TLMS)) can achieve their individual objectives without compromising on grid technical constraints.

Issue 3: There is limited literature and research for South Africa and by extension sub-Saharan Africa (SSA) that presents a comprehensive socio-economic and environ-technical analysis for households that are interested in adopting solar home systems (SHS). This research should be capable of presenting exhaustive results on the return of investments (RoI) for households seeking to adopt SHS while also highlighting the impact of tariff on RoI. Furthermore, associated issues like quality of life (QoL), carbon emission reduction and technical design should also be evaluated.

Issue 4: There is no comprehensive framework for South Africa which provides an avenue through which all active electricity players within the electricity sector can interface and assess the potential impact of their policy directions on the various aspect of the electricity sector and also on the economy (growth, development, poverty etc.)

Issue 5: Smart grid research for South Africa has isolated off-grid communities. Comprehensive and detailed research is thus lacking that shows how electricity access to off-grid communities can be improved without compromising on sustainability. Furthermore, proposed electrification options must be capable of reducing the energy burden of households and improving their QoL.

9.2.1 Resolving Issue 1

The paper entitled ***Demand Side Management potentials for mitigating energy poverty in South Africa*** in attempting to resolve Issue 1 for South Africa presented the following significant findings.

1 Residential electricity consumption is on the decline within South Africa. This research is foremost in methodologically showing that contrary to demand consumption projections, there has been a steady decline in electricity consumption.

2 Supply capacity was exceeding demand significantly. This finding was instrumental as it raised issues over the ability of the utility (Eskom) to recoup investment costs and associated expenditure from weakened consumption.

3 DSM potential of 6938.34 MW, 3469.18 MW and 2081.51 MW was computed for 100%, 50% and 30% participation of cloth washers and cloth dryers only.

4 In mitigating energy poverty, additional electricity of 247 Wh/day, 299 Wh/day and 577 Wh/day was computed as savings accrued for 100%, 50% and 30% household participation of cloth washers and cloth dryers only.

5 This paper presented a modified genetic algorithm (MGA) which was used in optimally dispatching the participating loads (cloth washers and cloth dryers).

9.2.2 Resolving Issue 2

Considering the wide span of Issue 2, two papers where presented that attempted to contribute significantly to research for South Africa and SSA. The first paper entitled ***Integration of demand side and supply side energy management resources for optimal scheduling of demand response loads - South Africa in focus*** attempted to integrate HEMS and SSEMS for South Africa and presented a combined energy management system. CEMS achieved the following.

1 Integrated HEMS for 100, 000 random residential houses having cloth washers, cloth dryers and dish washers with SSEMS (for the Medupi power plant).

2 Results showed that savings ranging from 6.5% to 44% were obtained for some houses participating in DSM with the households being in control of dispatch time.

3 On average, the no direct load control (DLC) option achieved 519.48 Wh/day for participating households and 135.24 Wh/day for households participating in full DLC.

4 Full DLC achieved 1.6% reduction in operations cost for the supply side along with a minimized DSM window and higher plant capacity utilization.

5 Presented a standard deviation biased genetic algorithm (SDBGA) which was used in scheduling the dispatch of participating DSM loads.

The second paper that attempted to address the Issue 2 was entitled ***A smart grid framework for optimally integrating supply-side, demand-side and transmission line management systems***. This paper advanced the earlier paper by adopting a dynamic thermal line rating (DTLR) for the incorporated TLMS. An IEEE 30 bus network was used in validating the proposed coordinated centralized energy management system (ConCEMS). Key results from this research include:

1 The development of an externally constrained genetic algorithm (ExC-GA) that was used in scheduling the dispatch of participating DSM loads.

2 The development of a dynamic thermal line rating (DTLR) algorithm that was used in determining the real time ampacity of the transmission network. This was useful in ensuring that the transmission network could be maximized without the need for regular upgrades.

3 The development of a modified economic and environmental dispatch (MEED) algorithm for optimal generator dispatch. MEED was further improved by the the development of a genetic algorithm based economic and environmental dispatch (GA-EED) algorithm. GA-EED was benchmarked against standard algorithms and found to perform optimally.

4 For the totally integrated system, ConCEMS achieved 3.6% cost reduction for electricity users, slight savings for the utility and obtained no violation of the TLMS using GA-EED and Price3 (dynamic pricing option 3).

9.2.3 Resolving Issue 3

The paper that attempted resolving Issue 3 was entitled ***A Biased Load Manager Home Energy Management System for Low-cost Residential Building Low-income Occupants***. This paper in addressing the incorporation of solar home systems (SHS) for residential homes obtained the following key results:

1 34% reduction in electricity cost for the household.

2 26% reduction in carbon emissions.

3 4% increase in comfort level for the household.

4 Return on Investment (RoI) is significantly influenced by electricity tariff and varied from 8.4 years to 25 years with annual electricity savings of 64% to 34% respectively.

9.2.4 Resolving Issue 4

The paper entitled ***Policy discussion for sustainable integrated electricity expansion in South Africa*** was presented in Chapter seven and attempted to resolve issue 4. The key results from the paper include:

1 The development of an integrated electricity expansion model (IEEM) for South Africa's electricity sector. This was used in evaluating the impact of DSM on every aspect of South Africa's electricity grid.

2 Policy discussions (especially on pricing, quality of service, quality of life, poverty mitigation etc.) were also provided that contribute significantly to growing smart grid research for South Africa.

9.2.5 Resolving Issue 5

In resolving Issue 5, the paper entitled ***Energy (in)justice in off-grid rural electrification policy: South Africa in focus*** was presented. Key findings from the paper include the following:

1 100% renewable energy projects for poor off-grid communities like the SHS are unsustainable, costly, exacerbate rural marginalisation, deepen poverty and create injustice.

2 The utilisation of hybrid generation schemes is capable of reducing carbon emissions by over 70%.

3 Hybrid generation schemes also meet sufficiently justice requirements such as affordability, availability and security.

4 Hybrid generation schemes also reduce the energy burden of households significantly.

The Figure 9.1 shows in more detail the linkage between the smart grid tools employed and the issues addressed (expanded).

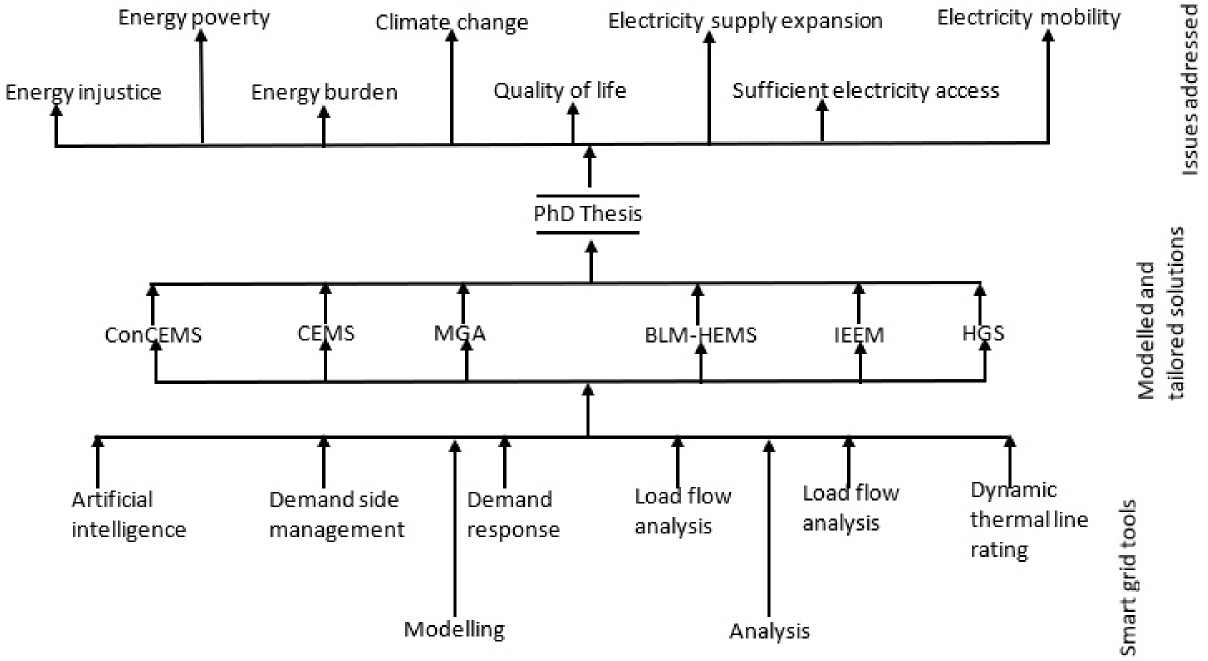

Figure 9.1: Expanded linkage diagram showing linkage between issues addressed and smart grid tools employed.

9.3 Brief on data analysis and interpretation

Data utilized for this thesis was mostly secondary data from Statistics South Africa (STATS SA). Such data covered aspects of South Africa such as population and population growth, electricity access, inflation, poverty levels, utilization of alternative energy sources etc. Furthermore, publications from Eskom especially the Transmission Development Plan (TDP) and its financial statements provided additional data on sales, losses associated with transmission and distribution, expansion plans and cost etc. This data was appropriately collated in a spreadsheet format and analyzed using common statistical functions (average, mean, median, standard deviation, variance, etc.). Furthermore, data from these sources were also utilized directly in models created to validate such models and also assist in benchmarking results from the models proposed with real-life case scenarios. It must be highlighted that all sources for data used in this thesis were duly acknowledged.

9.4 Conclusion

This thesis has explored significantly the social, technical, environmental, economic and policy aspect of South Africa's proposed smart grid. In critically examining the proposed smart grid for South Africa, pertinent issues relating to the development and direction of the proposed smart grid have been identified as well as their impact on poverty mitigation and emissions reduction. In critiquing smart grid research for South Africa, this research work has shown that current measures and drive towards improving South Africa's electricity grid are capable of further impoverishing households. Furthermore, this research work has underscored the need for increased integration of every aspect of the electricity grid. In advocating for more integration, this research work has proven that savings could also be achieved across the entire electricity network.

Technically, artificial intelligence (AI) based algorithms have been developed and used in optimally scheduling DSM loads and generator dispatch for reduced electricity costs. DTLR has also been incorporated into the design to improve grid flexibility and minimize transmission expansion costs.

For off-grid communities, this research work has proposed a hybrid generation scheme which has been modelled and shown to reduce significantly carbon emissions and energy burden. This has been achieved through the localisation of smart grid technologies at the rural level.

This research work is timely as well as necessary considering the fact that South Africa currently finds itself at the cusp of a major dilemma - mitigating climate change by reducing carbon emissions and mitigating energy poverty. This thesis shows that both can be sustainably achieved and provides elaborate design and policy concepts for realising a sustainable smart grid that is just and capable of reducing emissions as well as mitigating energy poverty for South Africa.

9.5 Future work

While this research work has significantly contributed to the growing research on improving electricity access for South Africa and developing a smart grid framework that is capable of mitigating energy poverty and reducing carbon emissions, the following are possible areas that could be researched upon to better improve on the findings from this thesis.

1 Additional research is needed to evaluate the potential impact of electric vehicles (EV's) on the entire electricity network. Considering the potential of EV's to be used in reducing peak demand and also balancing the grid, IEEM can be improved by evaluating varying case scenarios for EV participation in the electricity grid.

2 There is a need for further research on the potential impact of various levels of renewable energy sources (RES) penetration into South Africa's electricity grid. This is necessary to guide the development of the renewable energy independent power producer procurement programme (REIPPPP) considering declining electricity consumption and South Africa's huge DSM potential.