# Synthesis of an off-grid solar thermal cogeneration and intelligent smartgrid control system for rural applications

by

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# Declaration

This dissertation includes three (3) original papers published in peer reviewed journals or books and one (1) unpublished publication. The development and writing of the papers (published and unpublished) were the principal responsibility of myself and, for each of the cases where this is not the case, a declaration is included in the dissertation indicating the nature and extent of the contributions of co-authors.

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Declaration with regard to parts of the dissertation in which, in addition to the candidate, other authors were involved. With regard to the following chapters in the dissertation, the nature and scope of my contribution were as follows:

| Dissertation Chapter | Contribution Nature | Extent (∼%) |
|---|---|---|
| Chapter 2 | Main Author & Primary Researcher | 80 % |
| Chapter 3 | Main Author & Primary Researcher | 85 % |
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### Declaration by co-authors:

The undersigned hereby confirm that:

1. The declaration above accurately reflects the nature and extent of the contributions of the candidate and co-authors to the Chapters as indicated in the table above,
2. No other authors contributed to Chapters as indicated, besides those specified above,
3. Potential conflicts of interest have been revealed to all interested parties and that the necessary arrangements have been made to use the material indicated in the table above in the relevant Chapters of this dissertation.

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| R.T. Dobson | | Stellenbosch University | March 2018 |
| A.A. Mammoli | | University of New Mexico | March 2018 |

# Abstract

Access to reliable, affordable, and modern energy services has a vital role to play in attaining the Sustainable Development Goals promulgated by the United Nations, since this factor directly impacts on 74 % of their associated overall targets. With 80 % of the global energy-impoverished population living in rural areas, it is crucial to reach these communities to solve the global energy access problem. Sub-Saharan Africa is of particular concern as 16 of the 20 high-impact countries (lowest electrification rates) are located in this region, with current endeavours not able to keep up with population growth. Microgrids are critical in solving this problem, with about 44 % of the rural Sub-Saharan Africa population gaining access to electricity by 2040 expected to be connected by microgrids. This study identifies the need for advanced village microgrid control governance to fulfil the role of smart energy systems of future Smart Villages. While R&D pathways for future Smart Grid microgrids in the Global North are well defined, there are no definitive pathways for the development of advanced microgrids in the rural village landscape of the Global South. This dissertation hypothesises that rural village microgrids should adopt their operating principles from state-of-the-art future Smart Grid developments, and tailor these to address the knowledge gap pervading in the rural village microgrid landscape. This hypothesis is based on observations of global energy market trends that indicate a likely convergence in operating methods between Smart Village and Smart City energy systems. This study applies a model-based design-thinking methodology to the conceptualisation process of a proposed microgrid platform suitable for future Smart Village microgrids. This steered the development process to observe the challenges to rural electrification from the perspective of the village energy user as the primary stakeholder while formulating a concept platform based on future Smart Grid operating principles. This study combines state-of-the-art microgrid control principles, based on transactive energy management, with innovative methods that allow for functional interaction between the microgrid system and energy prosumers in the rural village. This dissertation thus establishes the interactive-market-based-control (i-MBC) approach at the core of the proposed next-generation Smart Village microgrid platform. The feasibility of this unique approach is demonstrated in synthesis experiments, using rural Smart Village case-based challenge scenarios. In addition to the current energy market drivers and trends that support this hypothesis, this research presents additional evidence to support the philosophy that Smart Village microgrids and Smart City microgrids can, to a large extent, share the same developmental pathway. A firm standpoint on the future of rural village microgrids is taken, as reflected and confirmed in the proposals for the Smart Village microgrid platform. This standpoint gives clear directives on the overlapping principles of Smart Cities and Smart Villages that will help researchers and energy access practitioners to select aspects of a Smart Grid R&D development program that is relevant to Smart Village microgrids.

# Uittreksel

Toegang tot betroubare, bekostigbare en moderne energiedienste speel 'n belangrike rol in die Verenigde Nasies se Volhoubare Ontwikkelingsdoelwitte, veral omdat 74 % van die doelwitte se teikens direk deur energie toegang beïnvloed word. Ten einde die wêreldwye energie-probleme aan te spreek is dit noodsaaklik om afgeleë gemeenskappe te bereik, aangesien 80 % van huishoudings sonder moderne energie in landelike gebiede voorkom. Die populasie groep in Afrika, suid van die Sahara, is van besondere belang aangesien 16 van die 20 lande met die laagste elektrifiseringsyfers in hierdie streek geleë is. In hierdie konteks is mikrokragnetwerke ("microgrids") van kritieke belang, omdat 'n beraamde 44 % van die landelike bevolking van Afrika na verwagtig voor 2040 deur middel van mikronetwerke van krag voorsien sal moet word. Hierdie proefskrif identifiseer die behoefte vir gevorderde bedryfs- en beheerstelsels om in die vraag na landelike mikronetwerke vir toekomstige Slim Nedersettings ("Smart Villages") in Afrika te voorsien. Daar bestaan reeds navorsingsplanne vir die ontwikkeling van Slim Kragnetwerke ("Smart Grids") vir toekomstige Slim Stede ("Smart Cities") in ontwikkelde lande ("Global North"), maar daar is feitlik geen sodanige planne vir Slim Nedersettings in ontwikkelende lande ("Global South") nie. Hierdie proefskrif formuleer die hipotese dat, gebaseer op waarnemings van globale energiemarktendense, daar waarskynlik 'n konvergensie in bedryfsmetodes vir toekomstige mikro-energiestelsels van Slim Nedersettings en Slim Stede gaan plaasvind. Volgens hierdie hipotese kan gevorderde bedryfs- en beheerstelsels van toekomstige Slim Kragnetwerke dus aangepas word vir mikrokragnetwerke in landelike gebiede om sodoende die kennisgaping te vul. en gebruik 'n rekenaar-model-gesteunde ontwerpsbenadering (design-thinking) vir die konseptualisering van geskikte mikrokragnetwerk platvorm opsies. Hierdie metodologie het die voordeel dat dit die uitdagings vir landelike kragvoorsiening vanuit die perspektief van die landelike energebruiker as die primêre belanghebbende benader. Die proefskrif ontwikkel die interaktiewe, mark-gebaseerde, beheer benadering ("interactive market-based control", i-MBC) vir volgende generasie mikrokragnetwerke in Afrika. Hierdie benadering kombineer moderne intelligente mikrokragnetwerk beheerstelsel beginsels met innoverende metodes om voorsiening te maak vir funksionele interaksie tussen die mikrokragstelsel en landelike energie verbruikers. Die uitvoerbaarheid van hierdie unieke interaktiewe-tipe transaktiewe energie bestuursbenadering word in senario-gebasseerde rekenaar sintese-eksperimente gedemonstreer. Hierdie navorsing bevind dat sekere beheer metodes van toekomstige Slim Kragnetwerke wel vir landelike mikrokragnetwerke aangepas kan word om dit geskik te maak vir toekomstige Slim Nedersettings. Die studie gee ook duidelike riglyne rakende oorvleuelende beginsels van Slim Nedersettings en intelligente mikrokragnetwerke ten einde ander navorsers, energie-praktisyns en ontwikkelings-organisasies te motiveer om intelligente mikrokragnetwerke vir landelike gebiede in Afrika te help ontwikkel.

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# List of Papers

List of internationally and locally published journal articles and conference papers, for which the candidate was the main author and principal researcher, that forms part of the dissertation research activities (listed in sequence):

**1. Conference Paper** †
Prinsloo, G.J., Dobson, R.T., Brent, A.C., Mammoli, A.A. 2016. Modelling and control synthesis of a micro-combined heat and power interface for a concentrating solar power system in off-grid rural power applications. *AIP Conference Proceedings: SolarPACES2015*, Cape Town, Volume 1734, Issue 1. pp 130016-1 to 130016-9.

**2. Conference Poster** †
Prinsloo, G.J., Dobson, R.T. 2014. Evaluation of a dynamic sun tracking platform for autonomous solar heat & power generation in rural areas. *Sun New Energy Conference on Helionomics Made Real, SuNEC International 2014 Conference*, Sicily, Italy.

**3. Journal Paper** † ‡‡ §
Prinsloo, G.J., Dobson, R.T., Mammoli, A.A. 2016. Model based design of a novel Stirling solar micro-cogeneration system with performance and fuel transition analysis for rural African village locations. *Journal Solar Energy Elsevier*, 133, pp 315-330.

**4. Journal Paper** † ‡‡
Prinsloo, G.J., Dobson, R.T., Brent, A.C. 2016. Scoping exercise to determine load profile archetype reference shapes for solar cogeneration models in isolated off-grid rural African villages. *Journal of Energy in Southern Africa*, JESA 27(3), pp 11-27.

**5. Journal Paper** †
Prinsloo, G.J. and Dobson, R.T. 2017. Smart village load planning simulations in support of digital energy management for off-grid rural community microgrids. Bentham Science, *Current Alternative Energy: Peer Reviewed Special Issue on Standalone Renewable Energy Systems for Remote Area Power Supply*, 2018(2), pp 1-29. doi: 10.2174/2405463102666171122161858

**6. Conference Poster** †
Prinsloo, G.J., Dobson, R.T. 2014. Smartgrid topologies in autonomous CSP power generation with microgrid distribution for rural Africa. *Smart Electric Power Alliance, Solar Power International SEPA, SPI International 2014 Conference*, Las Vegas, USA.

**7. Conference Presentation** †

† Peer reviewed
‡‡ ISI/DHET Accredited
§ Chapter in dissertation

Prinsloo, G.J., Dobson, R.T. 2014. Combined solar heat and power with microgrid storage and layered smartgrid control towards supplying off-grid rural villages. *Sun New Energy Conference on Helionomics Made Real, SuNEC International 2014 Conference*, Sicily, Italy. *Wiley Energy Science and Engineering*, Volume 3, Issue 2. pp 135-144.

**8. Journal Paper** † ‡‡ §
Prinsloo, G.J., Mammoli, A.A., Dobson, R.T. 2016. Discrete cogeneration optimization with storage capacity decision support for dynamic hybrid solar combined heat and power systems in isolated rural villages. *Energy Journal*, 133(1), pp 1051-1064.

**9. Conference Poster** †
Prinsloo, G.J., Dobson, R.T., Mammoli, A.A. 2016. Solar micro-CHP system with intelligent microgrid control for smart rural villages. *Smart Electric Power Alliance, Solar Power International SEPA, SPI International 2016 Conference*, Las Vegas, USA.

**10. Conference Paper** †
Prinsloo, G.J., Mammoli, A.A, Dobson, R.T. 2016. Participatory Smart Grid control and transactive energy management in community shared solar cogeneration systems for isolated rural villages. *IEEE Global Humanitarian Technology Conference GHTC 2016*, Seattle, USA, pp 1-8.

**11. Conference Poster** †
Prinsloo, G.J, Mammoli, A.A., Dobson, R.T. 2016. Transactive Energy Management: A different approach to energy management in rural off-grid microgrids. IEEE Special Interest Group on Humanitarian Technology SIGHT, *IEEE Global Humanitarian Technology Conference GHTC2016*, Seattle USA.

**12. Journal Paper** ‡‡ † §
Prinsloo, G.J., Dobson, R.T., Mammoli, A.A. 2017. Customer domain supply and load coordination: A case for smart villages and transactive control in rural off-grid microgrids. *Energy Journal Elsevier*, 135(1), pp 430-441.

**13. Journal Paper** ‡‡ † §
Prinsloo, G.J., Dobson, R.T., Mammoli, A.A. 2017. Synthesis of an intelligent rural village microgrid control strategy based on Smart Grid multi-agent modelling and transactive energy management principles. *Energy Journal Elsevier*, in press, pp 1-39. doi: 10.1016/j.energy.2018.01.056

Co-authored publications by the author for research of this dissertation:

**14. Internet Publication**
Asare, P., Broman, D., Lee, E., Prinsloo, G.J., Torngren, M. and Sunder, S. 2017. Cyber-Physical Systems. In: *Cyber-Physical Systems (CPS), integration of computation, networking, and physical processes*. Available at: http://cyberphysicalsystems.org/

**15. Conference Presentation** †
Prinsloo, F.C., Prinsloo, G.J. 2017. Development of a custom designed GIS-based envi-

† Peer reviewed
‡‡ ISI/DHET Accredited
§ Chapter in dissertation

ronmental decision support tool to address water energy nexus issues in floating solar environmental impact assessment. *International Association of Environmental Impact Assessment SA*, Integrated Environmental Management using GIS & Remote Sensing, Cape Town, 2017.

**16. Journal Publication** †

Uddin, K., Prinsloo, G.J. Marcoa, J., Jennings, P. 2017. Techno-Economic analysis of the viability of solar home systems using lithium-ion batteries in Sub-Saharan Africa. *Energy Procedia*, Alternative Energy in Developing Countries and Emerging Economies, pp 267-272.

**17. Promotion Article**

Prinsloo, G.J., Mammoli, A.A., Dobson, R.T. 2017. Discrete cogeneration optimisation with storage capacity decision support for dynamic hybrid solar combined heat & power systems in isolated rural villages.*Global Renewable Energy Innovations*, May 2017.

# Definitions and Terminology

The following definitions and terminology shall apply in this dissertation:

⇒ **Agent** or **Software Agent** means a configurable agent, or a self-contained software program module in object-oriented programming, configured to act as the representative of a registered microgrid network participant or prosumer device.

⇒ **Cogeneration** refers to Combined Heat and Power (CHP), an energy conversion system that uses combined energy cycles in the concurrent production of useful heat and electric power.

⇒ **Design-thinking Investigation** refers to a creative investigative strategy for innovation, involving the application of design-thinking principles to find pragmatic smart energy system solutions for rural communities through an investigative methodological research approach using theoretical modelling and simulations.

⇒ **Distributed Market-based Control (DMC)** emphasises the distributed nature of control elements in a distributed energy network that operates on the theoretical principles of Market-based Control (MBC).

⇒ **Energy Management System (EMS)** means a system of computer-aided tools to control an energy grid network by monitoring, controlling and optimising the performance of the generation and/or dispatch system. It includes mathematical functions using a method and means of operating procedures based on numerical optimisation and computational intelligence.

⇒ **Global North** denotes the generic socio-economic and political divide separating more economically developed countries from less economically developed countries also known as the rich-poor divide.

⇒ **Global South** is an extension of the metaphor for underdeveloped countries in the geography of globalisation and everyday living in human settlements, generally referring to developing countries, less-developed-regions or less-developed groups-of-countries.

⇒ **Interactive Market-based Control (i-MBC)** is a novel concept defined by this dissertation. It describes a newly defined *Interactive-Market Based Control* model that is an extension of the modern theoretical concepts of pure Market-based Control (MBC). As a rural microgrid concept relating to control automation, i-MBC emphasises direct interactive customer engagement in the micro-economic e-market for energy.

⇒ **Market-based Control (MBC)** describes a variant of a Multi-agent System (MAS), in which software agents are competing for resources in an energy market that strives toward equilibrium while performing local control tasks that require the traded resources as input (i.e. classical feedback control of physical processes).

⇒ **Microgrid** means a small-scale localised energy network with its own generation and energy storage units that are independently operated and automatically controlled to supply energy to a group of one or more single-family rural village/eco-estate household loads. The power sources could include hybrid solar Stirling engines, photovoltaic (PV) panels, renewable energy power plants, diesel-powered generators or a hybrid of such technologies.

⇒ **Multi-agent System (MAS)** refers to a computational energy system where software agents may either compete or cooperate with participants to perform individual or collective tasks or to achieve individual or shared energy goals.

⇒ **Smart City** defines a modern community in which citizens participate in developing plans towards the future development of buildings, the infrastructure, and operations that intentionally optimise efficiency, economics, and quality of life.

⇒ **Smart Grid (SG)** refers to an energy supply and distribution platform (such as a microgrid network), characterised by digital technology in a two-way communication system and automation, with distributional sensors, and (supervisory) control systems that automatically monitor and control changes in local energy usage.

⇒ **Smart City microgrid** or **Smart Grid microgrid** defines a particular class of advanced microgrids that include commercial development and transaction traceability pathways through cascaded control intelligence envisaged for use in future Smart City-type Smart Grid microgrid environments and applications (utility distribution, campus, military, community, industrial).

⇒ **Smart Village** refers to a development model aimed at access to sustainable energy services as a catalyst for development, thus enabling the provision of access to clean water, sanitation, nutrition, education, healthcare. It includes the growth of productive enterprises to boost incomes and to enhance security, gender equality and democratic engagement through the provision of energy services, the last-mentioned often driven by a Smart Energy System.

⇒ **Smart Village microgrid** refers to a particular class of smart rural village microgrids, defined by this dissertation, which envisions a more intelligent microgrid suitable for future IEEE Smart Village applications. It describes a microgrid based micro-utility system that operates independently of national-grid power and can run on multiple fuels, including renewable and fossil sources.

⇒ **Transactive Energy Management System (TEMS)** refers to a system of economic control mechanisms that allow the dynamic balancing of supply and demand through the application of transactive controls. Its operational transaction-based energy systems are based on real-time or day-ahead defined transactive positions.

# Nomenclature

## Abbreviations and Acronyms

| | |
|---|---|
| AI | Artificial Intelligence |
| ANN | Artificial Neural Network |
| BOP | Bottom of Pyramid |
| CAM | Customer Adoption Model |
| CES | Community Energy Storage |
| CHP | Combined Heat and Power |
| CPS | Cyber-Physical System |
| CSP | Concentrating Solar Power |
| DEM | Distributed Energy & Microgrid |
| DER | Distributed Energy Resources |
| DG | Distributed Generation |
| DR | Demand Response |
| DSM | Demand Side Management |
| EM | Energy Management |
| EMS | Energy Management System |
| GPS | Global Positioning System |
| HIL | Hardware-in-the-Loop |
| HMI | Human Machine Interface |
| IBT | Incline Block Tariffs |
| ICT | Information Communication Tech |
| i-MBC | Interactive-Market Based Control |
| IoE | Internet of Energy |
| IoT | Internet of Things |
| ISGT | Innovative Smart Grid Technologies |
| ISV | IEEE Smart Village |
| LAN | Local Area Network |
| LCOE | Levelised Cost of Energy |
| LPG | Liquefied Petroleum Gas |
| MAS | Multi-Agent System |
| MBC | Market-based Control |
| MBD | Model-Based Design |
| MEMS | Micro Electrical Mechanical System |
| MILP | Mixed Integer Linear Programming |
| MOO | Multi-Objective Optimisation |
| MPC | Model Predictive Control |
| OAS | Open Automation Software |
| ODE | On Demand Energy |
| OOP | Object Oriented Programming |
| P2P | People to People / Peer to Peer |
| PAYG | Pay-As-You-Go |
| PoS | Point of Sale |
| PLC | Programmable Logic Controller |
| R&D | Research and Development |
| RAMI | Ref. Architectural Model Industry |
| RAPS | Remote Area Power Supply |
| RE | Renewable Energy |
| SDG | Sustainable Development Goal |
| SE | Stirling Engine |
| SES | Smart Energy System |
| SGAM | Smart Grid Architectural Model |
| SGIP | Smart Grid Interoperability Panel |
| SHS | Solar Home System |
| SV | Smart Village |
| sv-TEMS | Smart Village TEMS |
| TAS | Transactive Aggregator Scheduler |
| TC2 | Transactive Control Coordination |
| TCB | Transactive Control Block |
| TCS | Timing-Centric Software |
| TEF | Transactive Energy Framework |
| TEM | Transacative Energy Management |
| TEMS | Transacative Energy Mngmt System |
| TES | Thermal Energy Storage |
| TFS | Transactive Feedback Signals |
| TIS | Transactive Incentive Signals |
| TMY | Typical Meteorological Year |
| TOU | Time of Use (energy tariff) |
| VPP | Virtual Power Plant |

## Companies, Institutions, Countries

| | |
|---|---|
| ARE | Alliance for Rural Electrification |
| BRICS | Brazil Russia India China South Africa |
| CEET | Center for Emerging Energy Technologies |
| CSIR | Council for Scientific & Industrial Research |
| DOE | Department of Energy (SA, USA) |
| DHET | Dept. Higher Education and Training |
| DST | Dept. of Science & Technology (SA) |
| EPRI | Electric Power Research Institute (US) |
| ESKOM | National Grid Supplier (SA) |
| ESRI | Enviro Systems Research Institute |
| GWAC | GridWise Architecture Council |
| IEA | International Energy Agency |
| IEEE | Institute for Electrical & Electronic Engineers |

| | |
|---|---|
| IRENA | International Renewable Energy Agency |
| ISA | International Society of Automation |
| ISES | International Solar Energy Society |
| MEC | Microgen Engine Corporation |
| NEMA | National Electrical Manufacturers Assoc |
| NERSA | National Energy Regulator of SA |
| NPC | National Cleaner air Production Centre |
| NIST | Nat. Institute of Standards Technology |
| NPC | National Planning Commission (SA) |
| NREL | National Renewable Energy Laboratory |
| NRF | National Research Foundation (SA) |
| OPAL-RT | Real-Time simulation Real-Time Solutions |
| OpenEI | Open Energy Information Organisation |
| PES | Power Engineering Society (IEEE) |
| SA | South Africa |
| SADEC | Southern African Development Community |
| SANS | SA National Standards Organisation |
| SANAS | SA National Accreditation System |
| SABS | South African Bureau of Standards |
| SANEDI | SA National Energy Development Institute |
| SARS | South African Revenue Services |
| SEIA | Solar Energy Industries Association |
| SEPA | Smart Electric Power Alliance |
| SNL | Sandia National Laboratory (USA) |
| SPI | Solar Power International |
| SUN | Stellenbosch University |
| UN | United Nations |
| UNDP | United Nations Development Program |
| UNIDO | UN Industrial Development Organisation |
| UNiLAB | Virtual International Lab for Collective Intelligence in Applied Energy |
| UNM | University of New Mexico |
| US, USA | United States of America |
| USAID | United States Aid Organisation |

## Mathematical Symbols

| | |
|---|---|
| $A_a$ | Stirling aperture area opening (m$^2$) |
| $a_x$ | Stirling engine heat coefficients |
| $b_y$ | Stirling engine electrical coefficients |
| $\phi$ | Latitude of installation (h:m:s) |
| $\zeta$ | Longitude of installation (h:m:s) |
| $p_e(t)$ | Electric power output (kW) |
| $q_t(t)$ | Thermal power output (kW) |
| $n$ | Discrete simulation time-steps |
| $N$ | Total simulation time-steps |
| $t$ | Simulation time-steps (s) |
| $P_e$ | Aggregate electrical energy (kWh$_e$) |
| $T_a$ | Stirling daytime ambient temp (°C) |
| $T_{in}$ | Temperature of the Stirling fluid (°C) |
| $DNI$ | Direct Normal Irradiance (W/m$^2$) |
| $\Delta T$ | Stirling head temp difference (°C) |
| $P_e$ | Electrical energy generated (kWh) |
| $Q_t$ | Aggregate thermal energy (kWh) |
| kW$_e$ | kilo Watt electrical (kW) |
| kW$_t$ | kilo Watt thermal (kW) |
| $H_x$ | Village size households service capacity |
| $P_l$ | Annual household energy demand (kWh) |
| $NCV$ | Energy equivalence for dry fuelwood (kJ/kg) |
| $E_h$ | Energy required to increase water temp (kJ) |
| $W_h$ | Mass of wood required to heat water (kg) |
| $S_m$ | Stirling engine hot water produced (kg) |
| $c_p$ | Specific heat capacity of water (kJ/kg°C) |
| $\mu_{wood}$ | Estimated moisture content of fuel wood (%) |
| $\eta_{fire}$ | Heat transfer efficiency open wood fire (%) |
| $P_{e_s}$ | Solar supply source time series |
| $P_{e_g}$ | Gas hybrid supply source time series |
| $L$ | Microgrid demand Loads (kW) |
| $S$ | Microgrid energy Supplies (kW) |
| $B$ | Demand-side transactive Bids ($) |
| $O$ | Supply-side transactive Offers ($) |
| $p$ | Controllable load priority layer level |
| $x$ | Energy price control variable parameter ($) |
| $x'_t$ | Transactive market clearing price ($) |
| $S_{n_t}$ | DER discrete-time supply time-series (kW) |
| $L_{m_t}$ | Load demand consumption time-series (kW) |
| $x_{n_t}$ | Optimiser control variable time-series ($) |
| $P_{B_t}$ | Battery energy storage level (kW) |
| $P_{B_c}$ | Battery storage capacity level (kW) |
| $P_{B_d}$ | Battery discharge constraint levels (%) |
| $C_T$ | Mathematical optimisation Cost function |
| $p_n$ | Priority on multi-bus in multi-bid topology |
| $S_{m_t}$ | Supply quantity discrete time-series (kW) |
| $L_{n_t}$ | Demand order discrete time-sequence (kW) |
| $O_{m_t}$ | Supply offer price-quantity time-series ($) |
| $B_{n_t}$ | Demand bid price-quantity time series ($) |
| $S''_{n_t}(x)$ | Supply offer for supply source $n$ at time $t$ |
| $S_{n_t}$ | Supply quantity for source $n$ at time $t$ |
| $O_{n_t}$ | Supply offer price for source $n$ at timeslot $t$ |
| $y_p$ | Supply bid function cut-off characteristic |
| $z_p$ | Demand offer function cut-off characteristic |
| $S''_t(x)$ | Aggregated supply offer function |
| $L''_t(x)$ | Aggregated demand bid function |
| $\mathbb{C}_x$ | Transactive optimisation cost function |
| $x'_t$ | Transactive market clearing price |
| $L'_{p_t}$ | Discrete-time demand response regulation |
| $S'_{n_t}$ | Discrete-time supply response regulation |

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# Chapter 1

# Introduction

This chapter presents an overview of the global energy scene in §1.1, specifically focusing on a discussion and a comparison of the technology trends in both the developed and developing energy markets. The problem statement, the purpose of the study, and the research hypothesis are presented in §1.2, which is used in turn as a basis for formulating the research questions, aims, objectives, and methodology of the study in §1.3. The scope for innovative iterations is presented in §1.4 where the opportunities for novel rural village microgrid contributions are discussed within the context of current Smart Grid trends, theories, market drivers, and technological developments. An overview of the research design process is presented diagrammatically in §1.5, while the significance of the research is discussed in §1.6. Finally, §1.7 presents an overview of the entire dissertation by offering a brief synopsis of each chapter and its contribution toward the research objectives and the overall research question.

## 1.1. Background Information

A seemingly unquenchable thirst for energy has driven the human race toward marvellous technological discoveries, each one of which opens the door for more innovation and a need for more energy to keep it all going. However, while the major innovations propel us from periods of stagnation and often crisis, they also bring times of rapid growth in economies and industries to relieve the pressure. Ironically, these cycles are becoming shorter, forcing us to keep innovating at an increasing rate to stay ahead. While energy has played a central role in enabling previous waves of innovation, it seems that we are in an era where the next breakthrough will directly impact on our energy systems. This section enters into a discussion on the current state of global energy developments in light of the trends that are driving change in this sector, and serves as an introduction to the challenges addressed in this research.

### 1.1.1. Sustainable development goals

Energy is viewed as the lifeblood of modern society as it drives productive activities, impacts on all economic sectors, and improves individual livelihoods through improved business development, healthcare, education, agriculture, infrastructure, and communication services [1]. The last century has demonstrated that every facet of human development is woven around a sound and stable energy supply regime [2]. Unfortunately, not all people have the same level of access to energy, something that has been at the core of many poverty and inequality alleviation endeavours over the past 50 years. The initial steps toward an equal global society were taken by the United States (US) during Lyndon Johnson's presidency (US President: 1963 - 1969), when he declared a global war on poverty. Labelling it as a war speaks to the seriousness of the matter and brings with it an urgency to resolve this problem. Over the years it has become clear that poverty is a complex phenomenon that needs to be approached from multiple angles, leading to what is known today as the United Nations (UN) Sustainable Development Goals (SDGs). While this title might not ignite the same sense of urgency as war, these goals still aim to address the devastation caused by all the forms of poverty. Every year millions of people (mostly women and children) lose their lives for reasons directly related to poverty, with energy poverty being one of the major challenges of our time [3, 4, 5]. Africa has the lowest energy per capita in the world, making energy poverty a root cause of underdevelopment in the continent [2].

Goal Seven of the SDGs is concerned with sustainable energy and is fundamentally linked to each of the other SDGs, as shown in Figure 1.1, which highlights the central role that energy is expected to play in this global undertaking [6]. The targets set for Goal Seven include gaining universal access to affordable and reliable modern energy services, increasing the use of renewable energy sources (RES) and hybrid renewable energy systems (HRES), and doubling the rate at which energy efficiency should be improved [7]. These targets require intervention and involvement from all nations, developing and industrialised alike, all of which are also facing local challenges of a changing energy environment. This necessitates a cultivation of new solutions that can address the challenges from all the sides to meet these targets of Goal Seven [7, 8, 9].

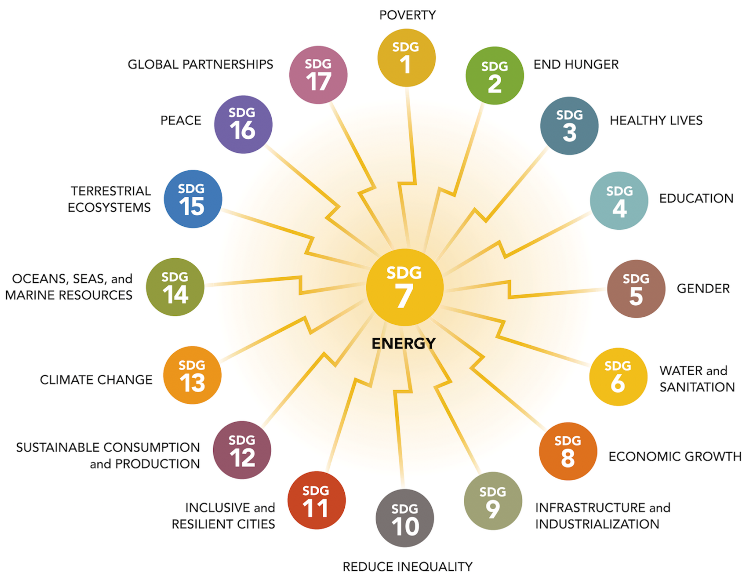



**Figure 1.1:** Interconnected nature of the United Nations' Sustainable Development Goals (SDGs), where Energy takes a centre stage role in the development strategy [6].

The Goal Seven target concerned with global access to reliable, affordable, and modern energy services emerges as a central theme in this study. It is further aligned with the objectives of the Stellenbosch University HOPE Program [10], especially in terms of the provision of energy access to poor communities.

### 1.1.2. Smart Grids and a smart energy future

Load shedding encounters over recent years have brought most South Africans face-to-face with the experience of living without electricity for extended periods of time [11, 12]. These events are not limited to developing countries, as proved by the fact that the United States (US) national grid experienced around 3500 outages in 2015 [13]. It is estimated that these outages, along with surges and spikes, cost the US economy around 150 billion US dollars (US$) annually in damages [13]. The problem of the ageing power infrastructure requires urgent attention, but should not be viewed in isolation. Rather, it requires a holistic asset management approach as part of the grid modernisation process.

The conventional electric utility grid was born as a district-oriented wire-grid and terminals approach. In its early days, the US grid existed in clusters, usually close to fuel resources, to serve the energy needs of local communities. Initially, the applications for electricity were basic, with few intense energy operations happening, but demand for electricity quickly grew as people developed new ways and technologies to be driven by this modern form of energy. Over time, these localised grids expanded and connected with other nearby grid networks which then continued to evolve and expand to become, what is known today as, the largest and one of the most complex engineering structures on the planet [14]. As shown in Figure 1.2, advances have been based on incremental improvements to the generation and distribution sides of the networks while operations beyond the substation only recently experienced change. The core grid computing concept and the operating principles of generating power to meet forecasted levels of demand without detailed feedback have not changed much from the early approach [15, 16, 17].

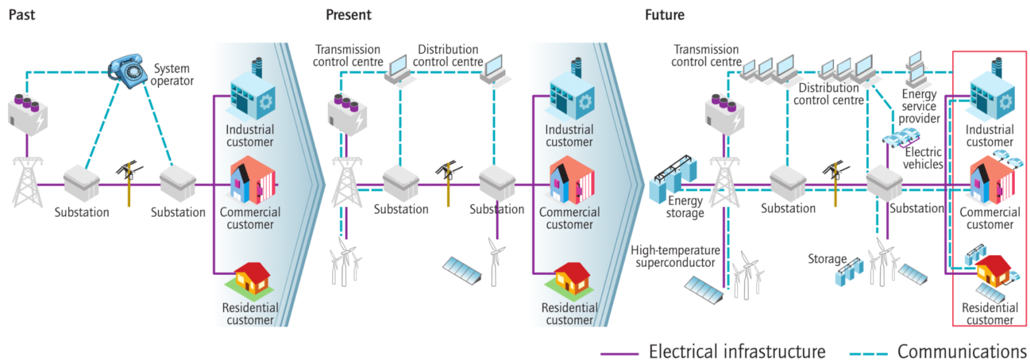



**Figure 1.2:** Evolution of the electricity grid in terms of past, present and future infrastructure and communication aspects, creating an increasingly smarter energy system [18].

A series of trends (brought on by technology, social, and policy drivers shown in Figure 1.3) have been driving the conceptualisation of new and radical approaches to grid design, operations, and management. In general, these trends include the increased integration of renewable energy resources into the grid, a significant growth in the market share of smart devices (which saw a rapid expansion of the Internet of Things (IoT)), and an increase in distributed energy resources (rooftop solar, behind-the-meter storage, and electric vehicles) [19, 20, 21]. In addition to the increase in functionality that these trends are bringing for energy producers and consumers, they have also added high levels of complexity to operations relating to grid management [19, 22, 23, 24]. This added complexity comes at a time when energy services are required to be more reliable, more resilient, more secure, more adaptable, and more efficiency, in the face of keeping up with the rapid growth in demand [22, 19]. The management and control of such a complex system using the current centralised control paradigm have rapidly reached the limits of scalability - which means that a more functional energy grid is needed to lead the world into a *smarter* energy future [19, 25, 26, 27].

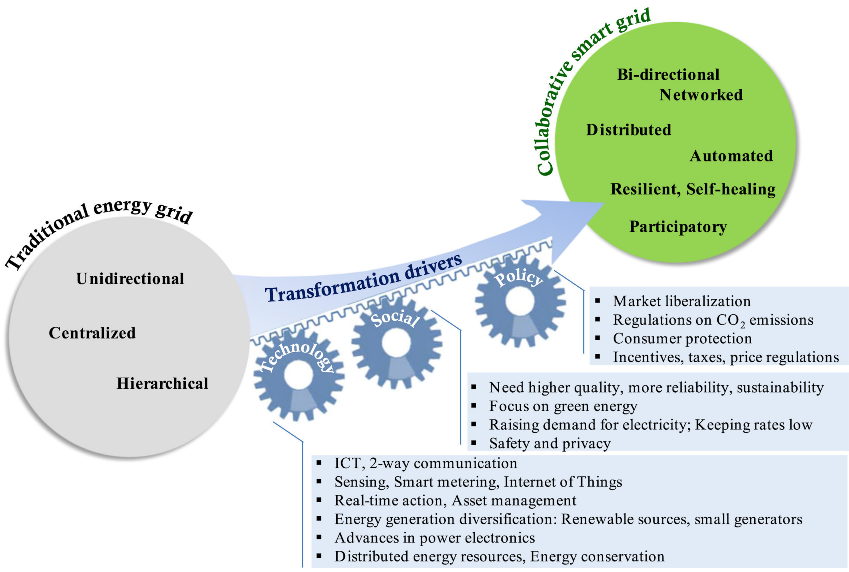
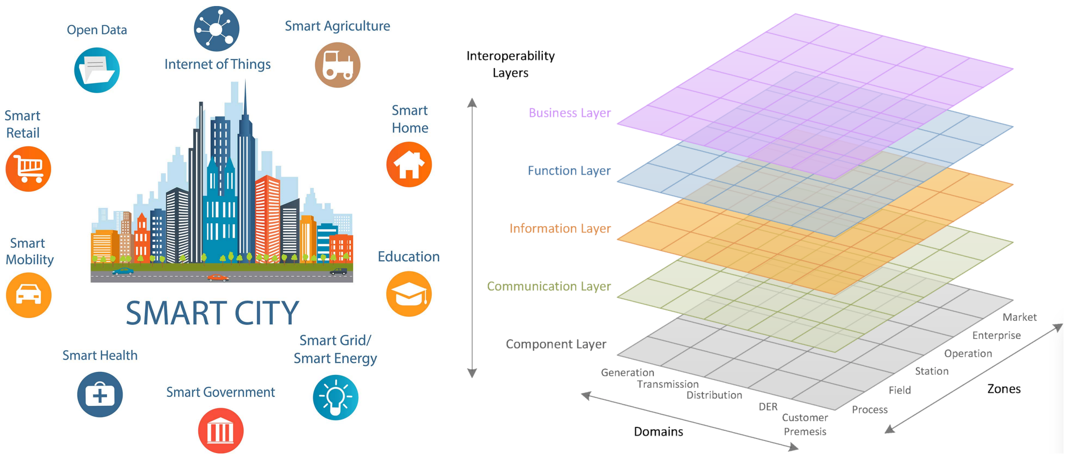



**Figure 1.3:** Transformation drivers for traditional energy grid to future Smart Grid [28].

The Smart Grid concept was established and provides a vision on how to adapt electricity networks to be effective in the 21st century. Smart Grid architectures are expected to modernise power systems through self-healing designs and by enabling two-way power flow and communication through the modernisation (digitalisation and intelligisation) of energy networks [28]. This will enable the intelligent automation of processes, the integration of renewable energy resources in a safe and reliable manner, and the implementation of dynamic control technology to ensure efficient use of energy resources, as shown in Figure 1.3 [27, 29, 30]. Energy networks are expected to evolve beyond their classical role as energy utilities to become user-interactive application development platforms and to take on a modern role as smart service providers [31]. The future Smart Grid is expected to become a distributed system that supports decentralised applications and services through modern trends and distributed system architectures, as shown in Figure 1.3 [32, 33]. This will offer new opportunities for energy prosumers (an energy producer and consumer) to play an active role in the operation of the utility business and the transfer of electrons [32, 33].

These Smart Grids are one of the critical components of the envisioned Smart Cities of the future, as shown in Figure 1.4(a) [30]. Smart Cities will rely heavily on the collection and processing of large volumes of data, which will aid in optimally managing energy, water, transportation, education, healthcare, and several other services and commodities as shown in Figure 1.4(a) [30, 34, 35, 36]. Smart Cities place particular emphasis on conservation and efficiency and are expected to play a vital role towards achieving current and future sustainability goals [24, 30].

In this urban Smart Grids context, nature-inspired metaheuristic algorithms are finding application in optimal voltage regulation [37]. Such emerging trends in municipal power systems bring new challenges in optimising energy grids, requiring more insight into vertically integrated control abstraction solutions in Smart City networks [26, 37, 38, 39]. Figure 1.4(b) illustrates the basic layout of the Smart Grid Architecture Model (SGAM) which has been developed to provide a framework to guide the development of the Smart Grid [34, 35, 36]. This architecture is IoT oriented and capable of facilitating machine-to-machine (M2M) interactions and promotes a more connected, device-driven, automated, and more intelligence grid [40, 41]. It is aimed at guiding the integration between various components of the Smart Grid by ensuring interoperability across all the layers of the Smart Grid control abstraction [40, 41, 42].




(a) (b)

**Figure 1.4:** Depiction of (a) Smart Energy as part of Smart City IoT concepts, with (b) an abstraction integration model of a Smart Grid SGAM hierarchical control system [43, 44].

The modern definitions of the digital Smart City concept are beginning to encapsulate universal machines and self-reproducing automata which were envisaged years ago by pioneering mathematicians in the scientific field such as Alan Turing and John Von Neuman [45, 46]. Some of their research on the use of computers in the development of critical algorithmic-based technologies (i.e. concepts of linear programming, stochastic computing, quantum logic, game theory and cellular automata) are today ideally suited to drive the digital Smart City model, especially from the perspective of a smart energy system platform.

### 1.1.3. The role of microgrids in the smart energy future

As part of the agenda to accelerate the integration of more advanced control, information, and communication technologies towards modern smart energy networks, the US Department of Energy (DOE) established the Smartgrid Research and Development Program [47]. The main goals of this project include optimising grid operations to accommodate a more robust, flexible, and interoperable electric grid, while also allowing for full integration of demand response and customer participation into grid management [47]. Much of the functionality expected of the future Smart Grid can be achieved by incorporating microgrids, and they have therefore earned a position as one of the key Smart Grid research and development (R&D) focus areas [47, 48, 49]. The planned timeline for microgrid development, shown in Figure 1.5, illustrates that more focus will be placed on operational optimisation and grid integration during these final stages.

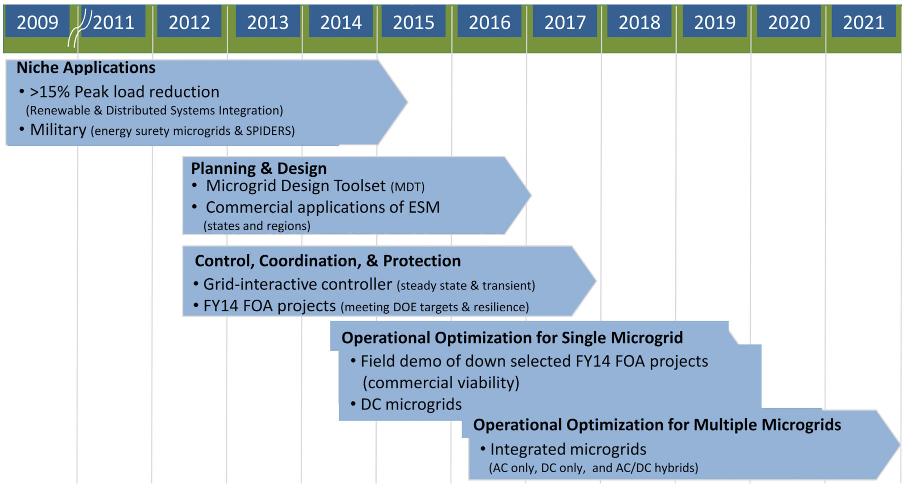



**Figure 1.5:** US Department of Energy Smart Grid R&D development focus areas, and Smart microgrid R&D roadmap timelines [50].

In addition to improving grid reliability and resilience, microgrids also improve energy efficiency, allow for the increased integration of distributed renewable resources, and for smart storage technology using the existing grid infrastructure [8, 32, 47, 51]. Microgrids also enable incremental reconfiguration of the existing distribution system towards smart energy networks [52, 53]. This enables more power to be delivered through existing infrastructure, thereby deferring additional transmission and distribution investment [52, 53]. These capabilities make microgrid technology directly applicable to both of the goals of the DOE Smartgrid Program and therefore a key component in the modernisation of the grid towards a future Smart Grid [47, 53]. This is not to say that microgrids can be deployed on a large scale without facing several operational and economic cost challenges.

Microgrids consist of a combination of various technologies and are typically designed to meet specific requirements, depending on the application [47]. As such, a microgrid can be seen as a system of systems instead of being viewed as a single technology [54]. The ability to integrate various resource types into a single system for a wide range of applications has led to a variety of implementations and a fragmented market [55]. Microgrids can, however, be broadly classified, based on their connection type, scale, users, objectives, and the loads that they serve [55], but a clear definition accepted by all stakeholders is still under debate [54]. The US DOE's definition is widely used and describes microgrids as an energy distribution system that contains loads and distributed energy resources (distributed generators, controllable loads, storage devices) that can be operated in a controlled, coordinated manner, either while islanded or while connected to another energy network [53, 55].

The current most prominent microgrid segments and their associated market share are shown in Figure 1.6 [54]. They include utility distribution, campus (university), community, commercial, military, and remote power system microgrids [54]. Because of the variety of microgrid definitions and classifications it is challenging to formulate the operational and design standards, which means that new microgrid projects are usually designed from scratch and require a lot of planning and resources, thereby slowing their adoption rate [52]. Other barriers include a lack of financing models, limited performance metrics, and a lack of all-in-one scalable prototypes [56].

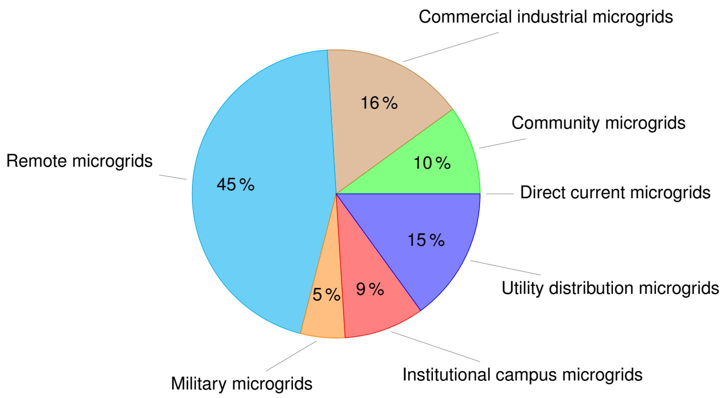



**Figure 1.6:** Global microgrid context in terms of market share by segment, 2017 [54].

The US DOE Office of Electricity Delivery and Energy Reliability has been leading the way in defining the role of microgrids in the future energy networks [47, 57]. As part of the DOE Smart Grid R&D project, a group of 170 experts representing leaders in industry, departments of energy (US, Japan, Korea, Canada, etc.), and other international stakeholders, have collectively devised a roadmap for research and development towards the future Smart Grid microgrid. The group defined twelve research focus areas, shown in Table 1.1, that could further be categorised into four major R&D areas (components, systems, planning and design, operations and control), which are all expected to play an important role in the future of smarter microgrids [47, 53].

Advanced control and resource management capabilities are believed to be a crucial component for microgrids to reach their full potential in serving the Smart Grid and future Smart Cities [59, 60, 61, 62]. These Smart Grid microgrids are expected to perform completely automated control that will be guided by advanced decision-making capabilities. The R&D timeline and key development phases, including the announcements of competitive funding opportunities (FOA), are shown in Figure 1.7 [53].

**Table 1.1:** Layout of microgrid technology focus areas envisioned as emerging technology elements in future smart microgrids [58].

**table 1. Key R&D areas identified from the DOE's 2011 and 2012 microgrid workshops.**

| 2011 Workshop | | 2012 Workshop | |
|---|---|---|---|
| R&D Areas | | | |
| **Components** | **Systems** | **Planning and Design** | **Operations and Controls** |
| **Switch Technologies** | **Standards and Protocols** | **System Architecture Development** | **Steady-State Control and Coordination** |
| • Legacy grid-connection technologies to enable connection and disconnection from the grid | • Universal microgrid communications and control standards | • Definition of microgrid applications, interfaces, and services | • Internal services within the microgrid |
| • Requirements based on customer and utility needs | • Microgrid protection, coordination, and safety | • Open architectures that promote flexibility, scalability, and security | • Interaction of the microgrid with utilities or other microgrids |
| **Control and Protection Technologies** | **System Design and Economic Analysis Tools** | **Modeling and Analysis** | **Transient State Control and Protection** |
| • Best practices and specifications for protection and controls; information models | • Microgrid multiobjective optimization framework | • Performance optimization methods and uncertainty in the modeling and design process | • Transient state control and protection |
| • Reliable, low-cost protection | • Designing an operations optimization methodology that takes uncertainty into account | | |
| • Switches to handle full fault current | | | |
| **Inverters/Converters** | **System Integration** | **Power System Design** | **Operational Optimization** |
| • Topologies and control algorithms so that multiple inverters can operate in a microgrid | • A common integration framework | • DC power | • Operational optimization of a single microgrid |
| • Advanced power electronics technologies | | • Microgrid integration | • Operational optimization of multiple microgrids |

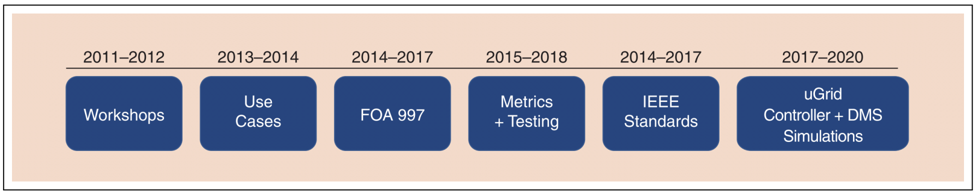



**Figure 1.7:** Timeline for the development of a smart microgrid controller [53].

To meet future Smart Grid requirements, the microgrid automation and control designers need to give particular attention to microgrid platform attributes that promote the following capabilities: (a) *controllability* (ability to reach desired status in response to customer-centric consumer demands), (b) *automated* (autonomous intelligent control functions with minimum human intervention/supervision), (c) *observable* (ability to determine microgrid holistic state from analytics and measurements), (d) *transactive* (enabling customer or merchant devices to participate in distributed energy market operations), (e) *enterprising* (sales enablement in automation to facilitate e-commerce and energy vendors), and (f) *security* (integrated multi-faceted energy and systems security) [23, 47, 63].

Microgrids are expected to play a key role in transitioning to a fully integrated Smart Grid since they inherently address the practical, architectural, and engineering challenges required to modernise the grid network [30, 54, 64]. Even with the current barriers, investment in microgrids is expected to proliferate with the increasing support of major government and industry stakeholders [54, 57].

### 1.1.4. The rural energy challenge

The importance of access to modern energy as a catalyst for sustainable economic growth, equality, and improved health and well-being is recognised by the UN [6]. Goal Seven of the UN Global Development Agenda on Sustainable Development Goals (SDGs), aims to ensure access to affordable, reliable, and modern energy services for all people by the year 2030 [7]. Owing to the synergy between the integrated strategies of the development goals (Figure 1.1), access to sustainable energy under Goal Seven is a necessary precursor to all of the other SDGs and directly affects 125 of the 169 combined targets [6].

Countries in the Global South face the challenges of bringing reliable, affordable, and modern energy services to all of their citizens while also having to meet other Goal Seven targets such as those of integrating renewable energy resources and improving energy efficiency [5]. Studies by the International Energy Agency (IEA) show that approximately 1.2 billion people (about 17 % of the total world population) currently have no access to electricity, while around 2.7 billion people (around 38 % of the global population) are without clean cooking facilities [65, 66]. This means that nearly one in five of the world's population does not have access to electricity [67], estimations that are supported by a combination of night-time lighting and day-time satellite imagery evaluation [68, 69]. As illustrated in Figure 1.8, people living in remote rural areas make up the largest part, 80 %, of the 1.2 billion people without access to electricity with Sub-Saharan Africa being the region facing the most challenges [4, 65, 66].

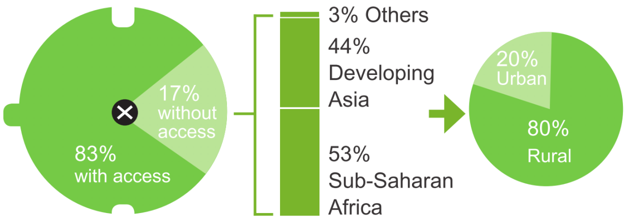
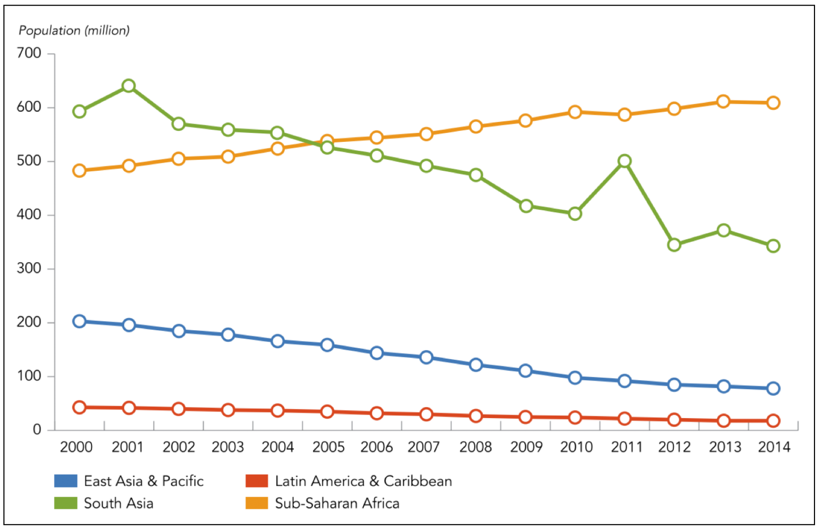
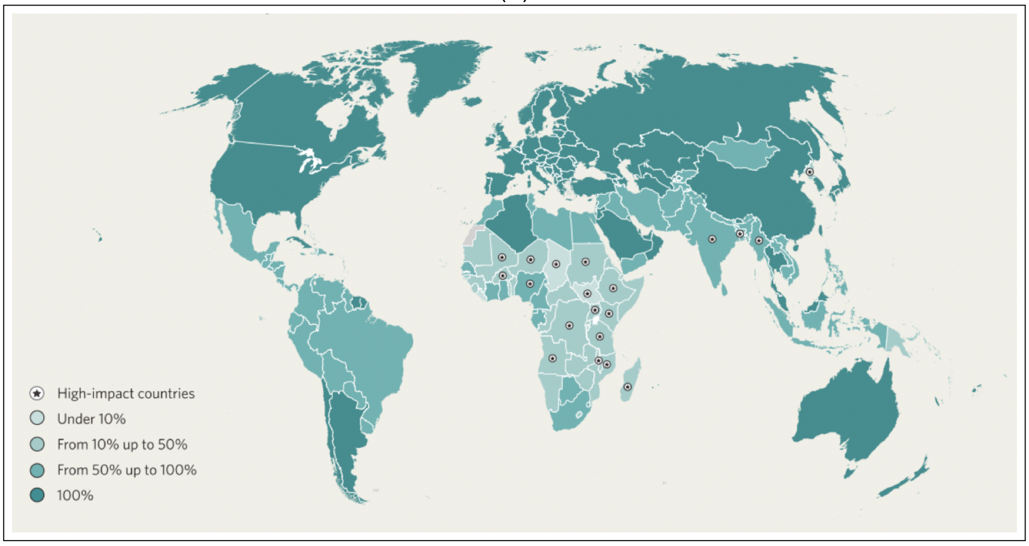



**Figure 1.8:** World electricity access and lack of access by region, 2013 [4].

Progress has been slower than expected, and under a business-as-usual case scenario, energy poverty in many countries is predicted to deteriorate by 2030 on account of rapid population growth (Figure 1.9(a)) [5, 65, 70]. The figure highlights the deteriorating situation of lack of electricity access (based on population in millions) in Sub-Saharan Africa compared to improvements observed in other developing regions of the world. This emphasises the fact that greater efforts are needed to solve the growing rural electrification problem in Africa. To make the greatest impact towards global energy access targets, it thus makes sense to focus on high impact countries with the lowest rates of access to modern energy [71]. Sixteen of the twenty high impact countries shown in Figure 1.9(b) are located in Sub-Saharan Africa, with Angola and the Democratic Republic of Congo causing major concern owing to their ever declining electrification rates [71]. In many of these high-impact countries, large percentages of the population without modern energy services live in rural areas that are characterised by low population densities and low rates of energy consumption [6]. This makes it difficult for




(a)




(b)

**Figure 1.9:** Depiction of (a) Sub-Saharan Africa not following Global South improvement in modern energy access trends, and (b) global electrification rates (high impact countries) 2014 [6, 71].

governments and utility companies to justify grid expansion projects that come at high installation and maintenance costs, caused by the often treacherous terrain, while at the same time facing uncertainty about the recovery of such costs [66, 72].

Figure 1.10 highlights the three major pathways that are available to gain access to modern energy services. These include top-down grid expansion, deploying community scale energy services (microgrids), or the use of fragmented installations (typically SHSs or solar lanterns) [21]. It is imperative to recognise the middle rural market segment a microgrid will be serving. The apparent over-reliance on centralised energy systems by the governments and financial institutions in developing countries appears to be one of the main factors contributing to the delayed delivery of modern energy services [5, 70, 73]. In addition to the high cost associated with these large infrastructural projects, it can take years to secure financing, finalise the design, and complete construction and commissioning, which do not fit the current timeline set out by the SDGs [66, 70, 73]. Even those who will eventually be connected to a large-scale grid network may face a waiting period of a decade or longer as population growth outpaces the expansion of the infrastructure [4, 65, 70].

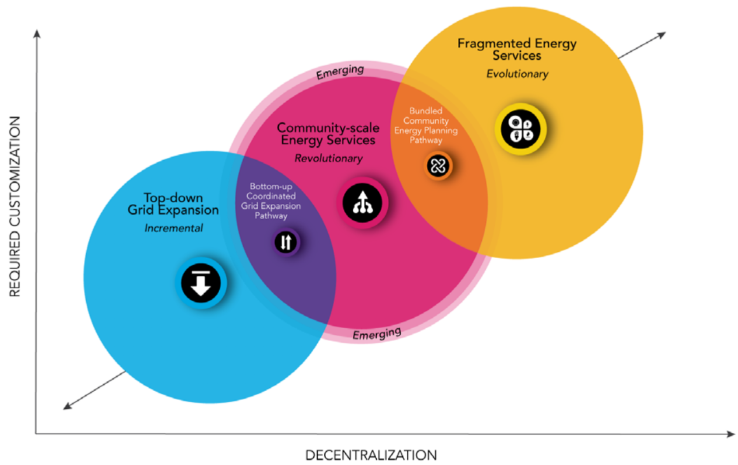



**Figure 1.10:** Continuum of energy access pathways arranged according to levels of decentralisation and required customisation under the microgrid imperative [21].

In developing countries, customers on the grid edge are often considered to have access to electricity based on their connection status, but are regarded as low priority users by grid operators. This leaves many rural village customers with energy delivery and energy quality challenges since the grid supply to these areas is often irregular and unreliable [5, 6]. This also occurs in South Africa where 43 % of the population is considered to be energy poor while 85 % is considered to have access to electricity [65, 74]. This supports the notion that a paradigm shift is required to move away from the centralised grid approach. In the South African context, microgrids are expected to play a significant role reaching isolated rural communities and cotetXu2013 offers a detailed review of rural electrification using a microgrid approach.

The UN Secretary General's Sustainable Energy for All (SE4ALL) campaign makes use of a Total Energy Approach to measure energy access based on a multi-tier system, as presented in Table 1.2 [5, 71]. On the lower end of the spectrum (Tier 1), users have enough power for a few light bulbs and to charge a cellphone, while Tier 5 is achieved when users have full access to grid electricity. The World Bank Group estimates that global access to Tier 1 would require US$ 1.5 billion annually over the next decade, while Tier 5 would require US$ 50 billion annually over the same period [6]. However, the Group's spending has often been described as "shallow and sporadic" as countries with low energy access rates received only 22 % of World Bank lending commitments and 6 % of the International Finance Institution investments from the year 2000 to 2014 [70]. It is alarming to note the low rates of energy access when considering that Africa alone is spending US $ 20 billion annually on fuel-based lighting, while cellphone-charging rates at a village charging station ranges from 5 to 10 US$

per kilowatt-hour (kWh) as opposed to that of the average 0.12 US$ per kWh in the US [75]. There is clearly enough capital to provide global Tier 1 access to energy, which would provide a higher quality of lighting as opposed to that provided by kerosene, with the added benefit of cellphone-charging [75].

**Table 1.2:** Elements of the multi-tier framework adopted by UN program SE4ALL as a benchmark for measuring remote and rural energy access [5].

| | | TIER 0 | TIER 1 | TIER 2 | TIER 3 | TIER 4 | TIER 5 |
|---|---|---|---|---|---|---|---|
| 1.Capacity | Power[1] | | Very Low Power Min 3 W | Low Power Min 50W | Medium Power Min 200 W | High Power Min 800 W | Very High Power Min 2 kW |
| | AND Daily Capacity | | Min 12 Wh | Min 200 Wh | Min 1.0 kWh | Min 3.4 kWh | Min 8.2 kWh |
| | OR Services | | Lighting of 1,000 lmhrs per day and phone charging | Electrical lighting, air circulation, television, and phone charging are possible | | | |
| 2.Duration | Hours per day | | Min 4 hrs | Min 4 hrs | Min 8 hrs | Min 16 hrs | Min 23 hrs |
| | Hours per evening | | Min 1 hrs | Min 2 hrs | Min 3 hrs | Min 4 hrs | Min 4 hrs |
| 3.Reliability | | | | | | Max 14 disruptions per week | Max 3 disruptions per week of total duration <2 hours |
| 4.Quality | | | | | | Voltage problems do not affect the use of desired appliances | |
| 5.Affordability | | | | | Cost of a standard consumption package of 365 kWh per annum is less than 5% of household income | | |
| 6.Legality | | | | | | Bill is paid to the utility, prepaid card seller, or authorized representative | |
| 7.Health and Safety | | | | | | Absence of past accidents and perception of high risk in the future | |

To improve the chance of reaching the SDGs of global access to reliable, affordable, and modern energy services, there needs to be a shift in approach away from the typical centralised generation and distribution models towards a more distributed generation approach [5, 66, 76]. To further increase the adoption rates of decentralised technologies and to reach rural off-grid communities, it will be important to develop standards based on scalable best-practice operations while gaining the support of local governments to create supportive policies in this resepect [77, 78].

### 1.1.5. The role of microgrids in rural energy systems

To achieve global access to reliable, affordable, and modern energy services by 2030, large financial institutions, such as the World Bank, need to increase their funding for rural microgrid installations with investments which need to grow from 4 billion to 50 billion US$ annually over the next decade [6]. Studies by the IEA predict that microgrids and off-grid installations, powered by distributed energy resources (DERs), will have to contribute around 55 % of additional generation capacity to be installed by 2030 if there is still to be any chance of meeting Goal Seven of the SDGs [72]. Figure 1.11 shows a breakdown of the most important regions to be targeted, and the expected contribution from each of the aforementioned energy access approaches shown in Figure 1.10 [79]. This specifically highlights the role of off-grid and microgrid installations in Africa and developing Asia [79].

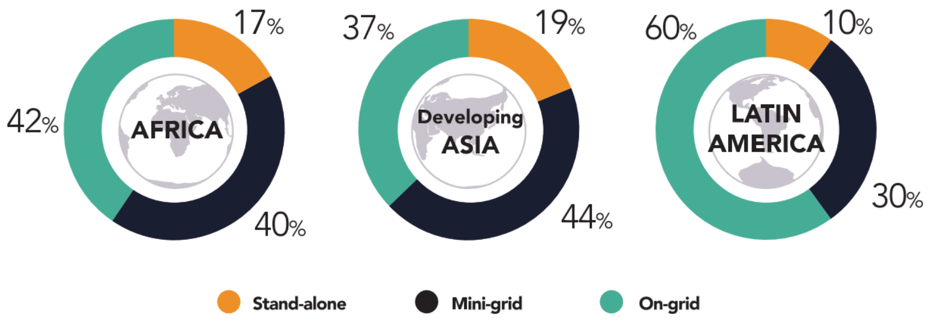



**Figure 1.11:** Estimated contribution from each of the various energy access approaches to attain global energy access by 2030 [79].

Focusing on rural communities in the high impact region of Sub-Saharan Africa, the IEA estimates that 70 % of this group gaining access to electricity by 2040 will be connected by microgrids and off-grid installations [76]. This means that between 100 000 and 200 000 microgrids will be built with the specific purpose of serving rural off-grid communities (140 million people) in Sub-Saharan Africa by 2040 [76]. Renewable energy resources are expected to account for 90 % of the DERs powering these new installations, which means that the microgrids and renewable DERs will play a major role in achieving energy access in Sub-Saharan Africa and other regions of the Global South [76].

Microgrids powered by diesel generators have a long history in the electrification of rural communities in remote areas that are out of reach of the main grid infrastructure [67]. However, this approach never reached the full potential of serving these communities, mainly due to high upfront investment and high operating costs due to supply chain challenges relating to fuel. The recent decline in the cost of renewable DERs, such as wind and solar, has been driving a resurgence in the rural microgrid market. Deployed in combination with modern energy storage technology, or in hybrid configurations that include dispatchable generation, such as diesel or micro-cogeneration, these microgrids can attain high levels of reliability and affordability [5, 80]. The main advantage of these renewable DERs is that they have limited to no running costs. Furthermore, they are not dependent on fuel transportation which makes them an ideal technology for isolated rural microgrids. In addition to the decline in renewable DER cost, the rural microgrid market is further driven by increased access to highly efficient direct current (DC) appliances and solid-state lighting [75].

Based on the SE4ALL tiered energy access approach, solar home systems (SHSs) are still more cost-effective for entry-level (Tier 1) electrification to power a few lights and cellphone chargers. On the other hand, as shown in Figure 1.12, microgrids are considered a better solution to bring modern energy services for productive use in order to foster poverty alleviation [5, 80]. However, research supports the idea that SHSs will eventually become interconnected (to other nearby off-grid systems) and that peer-to-peer power-sharing technology enabling them to grow into a unique class of off-grid microgrids [81, 82]. This phenomenon is also known as swarm electrification and it demonstrates the demand for higher levels of availability and reliability, on offer by microgrids, that prevails within these remote rural communities.

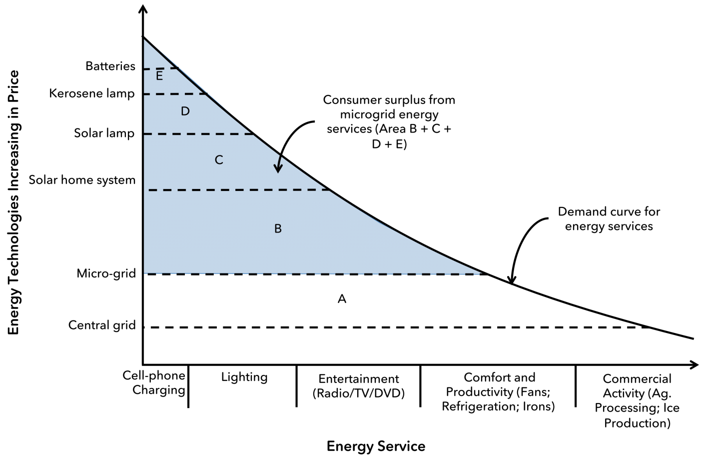



**Figure 1.12:** Price of energy services provided by energy fuels and energy distribution technologies in relation to user requirements [80].

Microgrids have many advantageous features that can make positive contributions in the rural energy environment, including:

⇒ Rapid deployment times and smaller upfront investment required as opposed to the expansion of the centralised grid [78, 83].

⇒ Better reliability as opposed to both grid connections and off-grid installations in developing countries [66, 71].

⇒ Modular designs allow for the integration of various types of DERs with combinations that can be customised to meet specific needs [84].

⇒ Adept at the integration of multi-fuel and multi-energy DERs, thus making microgrids an ideal platform from which to manage cogeneration resources for electricity, space heating and clean cooking [85].

⇒ Provisions being made for a wide variety of micro-utility type business models [80].

⇒ The delivery of productive levels of power at a reasonable cost for different purposes, as shown in Figure 1.12 [71, 80].

⇒ The potential to interconnect with future planned grid expansion projects [86].

⇒ The ability to inspire local direct investment [66]

The business community is just starting to consider the value of Smart Grid technology in developing world applications [87, 88]. Prominent drivers of rural microgrids and off-grid technologies include major funding and policy support, technology scalability, and the ability to incorporate mobile payment platforms [67]. This shows that the adoption rate of modern technology in the form of amongst others, mobile payment platforms and smart-metering, in rural village microgrids, will enable the level of user-device interaction required for these microgrids to become fully automated and capable of consistently reaching high levels of operational efficiency. In support of these views and the acknowledgement of the important role of rural village microgrids in striving towards the attainment of Goal Seven, the Institute for Electrical and Electronic Engineers (IEEE) has initiated the development of the new standards for remote rural DC microgrids [89].

The rise of the Smart Grid may offer exciting opportunities for rural electrification as it introduces features and operating principles that are much needed in rural village microgrids. The continued modularisation of Smart Grid energy systems, and the self-organising architectures for decentralised Smart microgrids under Smart Grid 2.0 and Smart Grid 3.0, as well as the future planned Smart Grid 4.0, are promising signs for a smart energy transformation in rural villages [90, 91, 92]. Many villages in Sub-Saharan Africa are already adding smart devices that are capable of data collection and storage, two-way communication, and varying levels of decision-making [67, 93]. In most cases, only the basic functionality of these devices is being utilised, and microgrids powering rural communities, remain for the most part, in the domain of being very simplistic, and therefore miss out on reaching their full potential. The idea of adopting these devices does not necessarily come from the rural energy users, but rather from the owners or operators of these microgrids. These smart devices allow improved accuracy and efficiency in assessing user consumption, remote activation and deactivation of services, remote monitoring for error detection, interactive human machine interface (HMI) support, and power limiting features [93].

The introduction of modern- control, communication, and payment technologies has led to a new rural energy landscape in some developing countries where the standalone microgrids and off-grid systems have levels of device and customer interaction that surpass most modern systems in developed markets [67, 75]. Many of these systems can be remotely de-activated if payments are not made and re-activated once payment has been received, while some even monitor customer data in real-time, thus allowing them to alert customers and operators in the event of high usage or system faults [67].

Microgrids powering off-grid communities in the Global South are expected to continue with the adoption of smart technologies to address local challenges [67]. Several organisations support research towards standardised scalable rural microgrid solutions that can operate on upper control tiers associated with more advanced smart microgrids as a part of Smart Villages [4, 78, 94, 95]. To this end, the IEEE Smart Village humanitarian empowerment program captures the value of a pragmatic Smart Village community energy system technology development in the vision **"Power a Village, and you Empower a Community"** [96].

Generally, a Smart Village is an analogy for an off-grid parallel to the Smart City model, and is based on the developmental ideas of the IEEE Smart Village Program (ISV) [95], the Oxford University Smart Villages Initiative (E4SV) [4], NREL's Power Systems of the 21st Century Power Partnership Program [21], and NREL's International Sustainable Village Power Program (ViPOR) for Township Electrification Programs for Informal Settlements [97, 98]. Smart Village thinking advocates energy justice and promotes quality of life, together with sustainable employment and energy provision, to offer a new sustainable type of developmental modelling paradigm able to support off-grid communities while helping to accelerate the momentum towards energy delivery and energy entrepreneurship, especially across the Global South [99]. The Smart Village approach also provides donors, policymakers, and development agencies with new insights on the real barriers to accessing energy (technological, financial, and political barriers) and how to overcome these barriers in rural villages in a practical manner to provide these communities with access to education, healthcare, clean water, information and communication technologies (ICT), entertainment, and a sustainable livelihood [4].

## 1.2. Problem Statement and Purpose of Study

This section introduces a more direct discussion on the specific field of energy development to be studied. The problem statement serves as a short summary of key factors from the background information and leads to the purpose of the study. §1.2.1 gives a description of the research problem, while §1.2.2 details the purpose of the study. The formulation of the research hypothesis, with supportive arguments, is presented in §1.2.3.

### 1.2.1. Problem statement

The global demand for energy is growing rapidly and for the sake of human well-being it has become necessary to devise more sustainable ways to harness the available resources, while at the same time also bringing affordable, reliable, and modern energy services to all people. Entering this new energy era brings a number of challenges that require attention from industrialised and developing nations alike.

On the one hand, the utility grids in industrialised countries with well-established energy systems need to be transformed in order to accommodate modern trends of renewable energy integration, DERs, and increased market penetration of IoT devices [19, 21]. These energy market trends in the Global North are driven by sustainability concerns and a desire for increased functionality and a higher standard of living, but are also causing some challenges for grid operators. The renewable energy resources are intermittent and cannot simply be dispatched when needed. They require the support of energy storage facilities supported by distributed energy resource management systems (DERMS) to carefully plan and schedule resource engagement. Privately owned behind-the-meter distributed generation, such as rooftop PV plus storage, further complicates grid energy management since it mostly operates beyond the management sphere of grid operators. Further complications arise when DERs with cogeneration capabilities become part of the district energy optimisation strategy since combined heat and power streams (often from multiple renewable and non-renewable fuels) are inter-dependent, and their generation needs to be optimised in a multi-carrier environment. Finally, the increase in the use of smart devices with two-way communication and decision-making capabilities is allowing for higher levels of functionality and controllability but results in increased complexity of the grid energy management processes [19]. Therefore, it is necessary to transform of the current energy systems to maintain reliability, resiliency, efficiency, and other operational standards under these rapidly changing conditions.

On the other hand, many countries in the Global South face challenges with their already fragile national energy networks which are being put under additional strain due to high rates of urbanisation. Further challenges are brought on by international pressure to expand these struggling networks to provide the energy-poor rural communities with reliable, affordable, and modern energy services. Until recently, their approach saw the bulk of investment going toward centralised generation with the classic transmission and distribution model with limited success [5, 70, 73, 76]. The narrative on the legitimacy of the ownership and control of centralised governmental electricity ownership and control is further limiting the appeal that of centralised grid power holds for to remote, isolated rural populations [100, 101]. The legacy of top-down electrification planning models and an over-reliance on centralised energy supply and delivery systems is thus considered to be one of the main barriers for rural electrification in Africa. With energy delivery being critical to the success of endeavours to address poverty, global sustainable development goals will thus be difficult to meet on the African continent with the use of centralised grid models [73]. While off-grid distributed generation is expected to have a big impact on the rural off-grid energy sector in developing countries, they also face a series of challenges. These include a lack of understanding on energy use in these off-grid rural communities, a shortage in operation and maintenance personnel for rural energy services, markets that are flooded low-quality generation technology, inefficient usage of energy, and challenges related to the financing of non-standardised solutions.

Microgrids have emerged as a promising technology solution that can address many of the challenges faced in both the Global North and Global South. In industrialised nations, microgrids offer improved reliability, resiliency, efficiency, and security for ageing power networks that under current trends are being placed under increased stress. In the off-grid markets of developing countries, microgrids offer a more reliable supply of affordable electricity by following a layout pattern which is more extensive and geographically balanced and presents a technology platform to accommodate trends of distributed generation, energy storage, and mobile payment methods [67, 71]. A technological component that is specifically important to both the rural off-grid African environment and the developed energy markets is the use of cogeneration systems which are already included in many installed systems [55, 71]. Cogeneration technology, as with other DERs, can benefit from the additional management capabilities on offer by microgrids.

The ability of more advanced microgrids to consistently manage available resources optimally through automated decision-making and control is a crucial component towards reaching its full potential [62]. Microgrid controllers with advanced resource management capabilities would permanently enable the microgrid to perform the same tasks as that of a central grid. These tasks include supply and demand balancing, optimised scheduling of dispatchable resources, and the maintenance of grid reliability [62]. Microgrids in the industrialised nations have a defined R&D pathway, as shown in Table 1.1 and Figure 1.7. This pathway leads to more advanced resource management capabilities that are expected in future Smart Cities where control platforms and energy management systems have increased intelligence and automated control capabilities [47, 53, 102].

For rural village microgrids, it seems to be a different case, with far fewer resources dedicated to the analysis of market drivers and the development of detailed R&D strategies. This leaves many researchers, project developers, and energy access practitioners in the rural village landscape in uncharted territory, as is evident from the wide variety and low level of complexity of current rural village microgrid designs [103, 104]. The IEEE standards for off-grid rural DC microgrids that are currently under development further supports this need for guidance in rural village microgrids to help establish the IEEE Smart Village vision [89].

The current technology adoption trends indicate that the use of microgrids with more advanced control and resource management capabilities are already an option in the rural energy landscape. However, due to a lack of more advanced rural microgrid technology platforms that are capable of integrating modern smart technology and legacy devices, rural microgrids are hindered from reaching their full potential. This deficiency is crippling an industry that is supposed to make a significant impact on the global energy crisis. Further research is required towards the development of smart rural village microgrid platforms, with similar operational capabilities as expected of Smart Grid microgrids, to unlock their full potential towards bringing reliable, affordable, and modern energy services to off-grid rural communities [67, 78, 94].

### 1.2.2. Purpose of the study

To address this *knowledge gap*, the purpose of this study is to conceptualise a next generation smart rural village microgrid platform using an engineering model-based design approach in a case-based design-thinking investigation. The conceptualisation of this platform is approached from the perspective of an energy user in a rural village in Sub-Saharan Africa. At the same time, consideration is also given to the interconnected nature of requirements amongst the stakeholders (the micro-utility owner, the NGO, government free basic electricity programs, etc.) in such a rural village microgrid project. This study also presents opinions that can translate into rural village microgrid development directives for the Stellenbosch University (SUN) solar cogeneration system.

This purpose supports the future planned research and development goals of our group, aligns with the Stellenbosch University community development HOPE program [10], and resonates with the objectives of the IEEE Smart Village empowerment program [96]. While addressing the knowledge gap for rural village microgrids, the purpose extends towards potential contributions to the development of a direction giving framework for what is envisioned by the IEEE as a future Smart Village, with recommendations towards future Smart Village microgrid R&D efforts.

### 1.2.3. Research hypothesis

At the core of this dissertation's **research hypothesis**, is the philosophy that next generation rural village microgrids will be based on state-of-the-art technology and operating principles of future Smart Grids. In doing so, these microgrids will be transformed into Smart Village microgrids to fulfil their role as the energy component in the envisioned Smart Villages of the future, as shown in Figure 1.13. *Smart Villages*, similar to *Smart Cities*, will need to be built on the basis of the integration and cooperation of various smart services and commodities, including smart energy. As no definitive developmental pathway currently exists to guide the future Smart Village energy transformation, this study further hypothesises that a conceptual Smart Village microgrid platform can be based on down-scaled Smart City microgrid plans in preparation for the envisioned convergence of their technological development trajectories in the foreseeable future.

Some of the global energy market drivers and trends that inspired this research hypothesis, as presented in Figure 1.13, have been discussed in §1.1. The list below contains a more concise overview of the current drivers and trends in the rural energy landscape that were gleaned from literature on rural microgrid design best practices, and from IEEE Smart Village program involvement [21, 80, 93, 105].

⇒ The need for a more intelligent resource management platform to meet the growing expectations of increased reliability and adaptability in off-grid rural village projects.

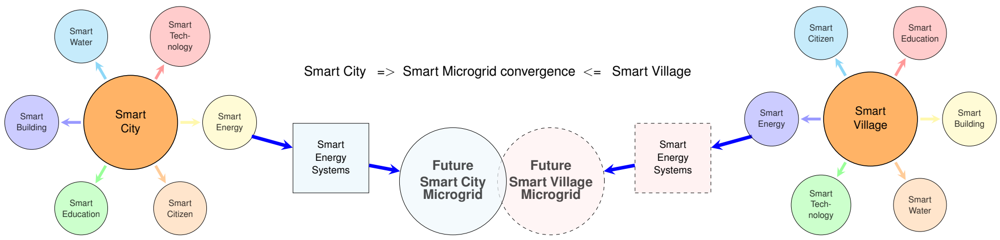



**Figure 1.13:** Envisioned smart microgrid platform convergence in an anticipated shared energy future of Smart Cities and Smart Villages, in terms of the hypothesis of the present dissertation.

- ⇒ The popularity of microgrid technology in the energy markets of the Global North and Global South.
- ⇒ The need for microgrids to have access to advanced resource management since it is an important feature to attain peak performance. This is important for realising the Goal Seven objectives.
- ⇒ The lack of a definitive R&D roadmap to acquire these advanced control capabilities in rural microgrids.
- ⇒ An increasing number of discussions on the use of smart meters in conversations with owners and operators of IEEE Smart Village energy systems [106].
- ⇒ Device-level interaction between village energy users and operators are exceeding those of many developed markets.
- ⇒ The notion of a Smart Village focused on *smart services* is already being envisioned [107, 105].
- ⇒ Supported by the IEEE P2030.10 Standard being developed for off-grid microgrids serving rural communities. These standards are expected to be extended for the use of smart devices and systems in rural electrification.

The presence of future Smart Grid phenomena in the Global North gives researchers the reason to believe that a potential forthcoming convergence may offer opportunities to piggyback on certain control principles of the Smart City microgrid:

- ⇒ The unbundling of the central grid into a coalition matrix of independent dynamic microgrids for disaster-contingency-planning purposes means a future developmental trajectory that overlaps with rural microgrid requirements [108].
- ⇒ Role of microgrids is becoming increasingly important in the grid modernisation process towards building and campus grids, leading to a more segmented and modular network. This is similar to the rural energy space where microgrids, off-grid SHSs, and interconnected off-grid systems are growing in popularity.
- ⇒ In the utility sponsored model (USM), next generation Smart City microgrids are making substantial progress by moving ahead with well-established microgrid R&D roadmap plans in preparation for an interconnected cloud-based network architecture.

Figure 1.14 offers an expanded perspective (bigger picture) of the research hypothesis and the purpose of the study. It contextualises the anticipated developmental pathway convergence between future Smart City microgrids and Smart Village microgrids, as presented in Figure 1.13. Figure 1.14 further highlights the potential significance of the hypothesis in respect of new rural electrification pathways for innovative energy systems to potentially leapfrog centralised grid electricity.

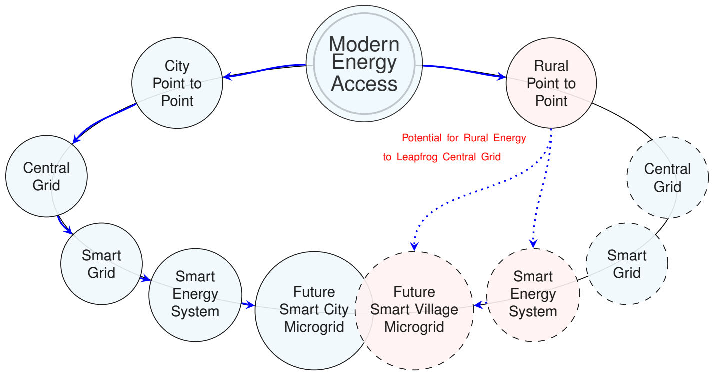



**Figure 1.14:** An expanded perspective of this study's hypothesis to contextualise the possibility of new rural electrification pathways.

The proposed research hypothesis enables the study to contribute to the discourse of next generation rural electrification systems through an investigation towards a next-generation off-grid rural energy platform that is suitable in future Smart Villages. The proposed research hypothesis reveals an opportunity for innovative and novel contributions to the body of knowledge and forms the basis for the main research questions and the investigation towards a next generation off-grid rural energy platform to serve future Smart Villages.

## 1.3. Research Design

This section presents the research design process that serves as a framework within which the study can systematically research scientific data and information in the field of rural electrification to critically appraise, make sound judgements, and creatively deal with complex issues around next generation rural village energy schemes. It presents the research process, including the formulation of the main research questions in §1.3.1, and a description of the research aim and objectives in §1.3.2. The research methodology is discussed in §1.3.3.

### 1.3.1. Research questions

The idea of introducing smart microgrids in rural African villages gives rise to challenges that can be used to formulate the research question: (a) Existing devices in circulation - In the case of existing but lower-tier energy access, rural village energy users need to be able to use the devices they already own while still having full interaction with the microgrid towards optimal smart grid energy use. This means that these legacy devices/appliances will need some way to be integrated with an intelligent microgrid to improve their limited capabilities; (b) User interaction with smart technology - There is uncertainty around the acceptability of the principle of demand response by a rural village energy user; (c) User interaction with smart technology - Upper control levels concerned with energy management usually involves optimisation and scheduling of resources. The concept platform should allow for the automated control/management of both generation and consumption sides. This means letting some levels control power flow to user devices within the bounds of acceptance of the user. User considerations tend to be influenced by both energy needs and budgetary constraints, resulting in a volatile operating environment; (d) Multi-energy optimisation - The integration of cogeneration needs to be considered as it constitutes a significant share of microgrids worldwide due to reliability and efficiency characteristics. Since the multiple energy streams are inter-dependent, careful consideration needs to be given to how these resources are managed; (e) Sharing in an islanded system - Since a finite amount of resources are available, community shared energy service interaction needs to be considered. This cooperation includes peer-to-peer energy trading and trading between interconnected microgrids; (f) Understanding rural energy use - Typical resource management used in upper microgrid control tiers might not resonate with an energy user in a rural village. Several factors could cause this as the consumption patterns of such users are not as well understood in the Global South, as opposed to those of a typical user in the Global North; (g) Communication limitations - Limited access to web and cloud services for optimisation owing to poor communication reliability or expensive rates of mobile phone data which causes concerns regarding the remote monitoring of smart meters in the rural village. (h) Cost recovery - Household income for these rural communities is notoriously volatile. The "buy-when-I-can" approach is typical of these communities when it comes to energy expenditure, and a smart microgrid platform should be able to accommodate payment models based on this.

The research hypothesis, and the practical considerations that have emerged from the above, lead to the following two main research questions:

The **first research question**: *Can a next generation Smart Village microgrid platform be conceptually based on future Smart City operating principles to serve off-grid rural villages in Sub-Saharan Africa?*

The **second research question**: *Could such an intelligent Smart Village energy system transformation have a meaningful impact on the needs and requirements of rural village microgrid stakeholders?*

The relevant research aim and objectives of the study can now be formulated within the context of the research questions posed above. This will facilitate the formulation of a scientific research methodology for investigating Smart Village automation phenomena.

### 1.3.2. Research aim and objectives

This research aims to investigate technology options that would enable the integration of legacy devices and future smart devices in the conceptual Smart Village microgrid in order to unlock Smart Grid capabilities of automated decision-making and control optimisation in an off-grid rural village environment. This aim is rooted in the combined need to address the knowledge gap discussed in §1.2.1, to answer the research questions in §1.3.1, and to enable further research toward the hypothesis in §1.2.3.

As part of the approach, stakeholder requirements will be formulated using a design-thinking methodology to guide the conceptualisation of a Smart Village microgrid control platform. Computer modelling and simulation instruments will be used to generate engineering models for experimenting with proposed next generation microgrid platform concepts in simulated rural village environments. To this end, the **research aim** is to follow an integrated model-based design-thinking approach to conceptualise the options for next generation digital Smart Village microgrid control platforms by exploring Smart Grid principles in a vertically integrated rural village microgrid. The final synthesis of the concept Smart Village microgrid platform, combines principles from best practices of rural microgrids with theoretical tenets from future Smart City microgrids. The investigation aims to take a standpoint on research development directives intended to guide future research operations on rural Smart Village microgrids.

Towards the research aim of this study, the following research objectives are defined:

**Objective 1**: *Rural village microgrid supply side modelling*, including the computer modelling of a hybrid thermal solar/gas cogeneration system, harnessing a model-based predictive analysis method to conduct performance evaluation simulations, and conducting site-specific performance analyses with the hybrid solar/gas cogeneration system at various rural African village locations to determine potential fuel reform and fuel transition implications.

**Objective 2**: *Rural village microgrid demand side modelling*, including an investigation into rural energy consumption (thermal and electrical) profiles that can be expected in newly-electrified rural African villages, and creating archetype computer load profile models that emulate device disaggregated load profiles representative of a typical future Smart Village in Africa.

**Objective 3**: *Conceptual rural Smart Village microgrid platform modelling*, including the computer modelling of a conceptual Smart Village microgrid, proposing theoretical concept platforms for microgrid control automation, developing engineering models for integrating Smart Grid principles, computer modelling of proposed solutions through mathematical formulations, and engaging case-based scenarios to evaluate the performance of the platform model concept in simulated rural African village conditions.

These research objectives jointly support the research aim of conceptualising a rural Smart Village microgrid platform which, in turn, serves to investigate the research questions in the context of the research hypothesis. The next section will describe the methodology that will be used to research aspects of the Smart Village microgrid within the context of the above-mentioned research aim and objectives.

### 1.3.3. Research methodology

From a scientific methodology perspective, this dissertation employs a combination of design thinking, model-based design, and computer synthesis techniques to perform quantitative multi-disciplinary applied research that explores pathfinding directions toward a next generation rural Smart Village microgrid control platform. This section describes the research methodology and procedures to be followed in facilitating new knowledge construction within the context of the Smart Village energy paradigm. To ensure that the IEEE Smart Village mission drives the microgrid technology platform design, the present study proposes a modern design-thinking approach for a simulated model-based design method as a means to explore strategic microgrid control concepts on the platform level. §1.3.3.1 introduces the design-thinking steps in approaching the research aim from an IEEE Smart Village paradigm point of departure. Design-thinking in a Smart Grid architecture environment is discussed in §1.3.3.2. §1.3.3.3 describes the model-based design aspects of the method and highlights the benefits and support from computer modelling and simulation instruments. Finally, §1.3.3.4 describes the framework for integrating design thinking with model-based-design methods in preparation for scenario-based experimental synthesis in rural African Village cases-study narratives.

#### 1.3.3.1. Design thinking method within the IEEE Smart Village paradigm

The design of a rural Smart Village microgrid system's operating platform faces a multi-dimensional problem in the quest for rural electrification. According to the IEEE Smart Village approach, platform considerations should go beyond a techno-economic viewpoint, and should also investigate the strategic social and business enterprise contexts [67, 80, 95]. An envisaged next generation Smart Village microgrid design should thus offer a digital software application platform with smart meter, data analytics and computational intelligence capabilities that can automate energy management tasks through cascaded control intelligence that is dynamically integrated into microgrid control operations. To achieve this goal and to emphasise the role of the end-user in innovating towards the design of a control approach for a system (that is positioned midway between a home-energy-system and a grid-energy-system), this dissertation engages a design-thinking methodology in the reasoning cycle of the research. In this strategic research development process, the aim is to develop an innovation strategy with a relevant method, instruments, and process steps, through which to explore microgrid platform technology options towards a next generation Smart Village microgrid.

In this context, this research identified the value of a human-centred design-thinking methodology as a framework for innovation in exploring new value propositions for Smart Village microgrids. Design thinking is a holistic design method that, like design science and ergonomics, helps to determine cooperative design decisions in business process and industrial design [109]. It offers a hands-on inspirational research ideology that specifically involves the application of creative design processes to strike a balance between customer requirements and what technology has to offer [110]. As a human-centric design approach, it is often used by leading companies in the Information Technology and Services industry (Microsoft, Apple, Google), where the approach has proven itself to be an invaluable market-product differentiator [111, 112]. While the design thinking process includes various thinking modes (cognitive and realistic thinking), it is driven by three underlying operational categories, namely to, *understand*, *explore*, and *materialise*. It supports stakeholder collaboration in value networks and combines the principles of user-centredness, customer co-creativeness, sequencing (mood of the customer), and customer awareness, as objectives in the holistic systems-level context [113, 114, 115].

The research method of design thinking integrates three focus elements in a design process that enables the designer to innovate towards desired solution objectives [116, 117, 118]. The design thinking Venn-diagram in Figure 1.15 shows the notional aspects of design thinking, highlighting the potential to integrate the aspects of *Human Desirability/Pleasurability*, *Business Viability* and *Technical Feasibility* in a people- or business-focused technology design. By *combining engineering model-based design* *with design-thinking, as proposed in the present study in §1.3.3.4*, the method offers the microgrid platform designer the potential to cognitively focus on *Process-, Functional-, or Emotional- innovation*, as highlighted in the Venn-diagram intersections shown in Figure 1.15. This approach resonates with the exploration of microgrid platform technology options for an envisioned Smart Village microgrid concept that should operate as a smart energy system (Technology) in a commercial business ecosystem (Business) suitable for the energy requirements of the customer and entrepreneurial model frameworks (Human/People).

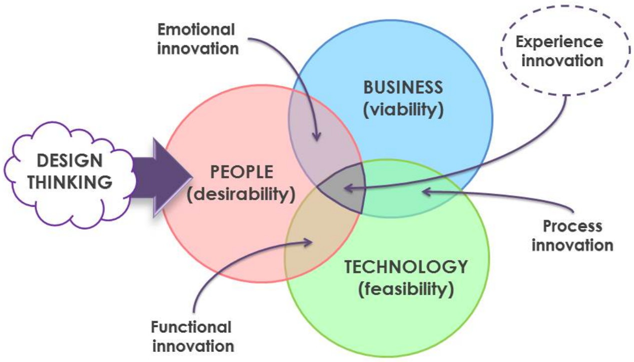
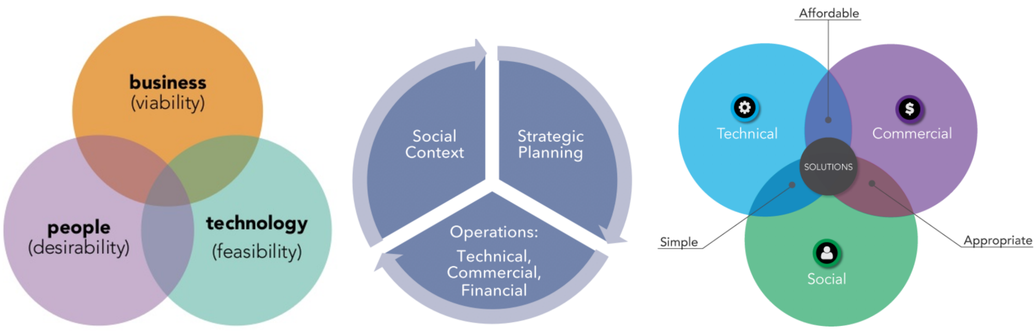



**Figure 1.15:** Elements of the integrated design thinking methodology [118].

In an IEEE Smart Village innovative environment, the design innovation process set out in Figure 1.15 permits the researcher to approach the challenge with a user-centric mindset. It will help to achieve a more balanced socio-technical-business innovation solution that caters for multiple perspectives, experiences, disciplines, and knowledge. Design thinking thus offers a new lens through which the Smart Village microgrid designer can look at the rural context to engage creative technologies and strategies able to bring microgrid technology closer to rural village community customers [111, 119]. As will be discussed later in this section, Figure 1.20 shows that design thinking is a phased iteration process that encourages the designer to progress through the phases of *Ideation, Inspiration, and Implementation*. It thus engages a chain of design thought processes towards the goal of achieving technological innovation suitable to unique circumstances (socio-technical and socio-economic circumstances for community microgrids).

The envisaged future Smart City models aim to increase device connectivity and machine-to-machine energy trading e-commerce, while their digital virtues have the potential to offer user-centric technology and service platforms for IoT interaction. They are thus able to host fitness for purpose, customer-directed solutions. The customer-focused developmental pathways of Smart Cities inherently offer synergetic opportunities for Smart Villages to adopt Smart City R&D pathways in their modelling visions. The interconnected nature of the end-user and other stakeholders requirements (micro-utility owner, NGO, government free basic electricity programs, etc.) must be taken into consideration when planning for market-based prosumer participation in the Smart Village microgrid [32]. This study identified interesting correlations between the design-thinking elements in Figure 1.16(a) and associated approach elements from the UN literature on *microgrid design best practices* in Figure 1.16(b) [80], and NREL's *microgrid determinants for success in energy-poor rural markets* in Figure 1.16(c) [21]. These concepts further correlate with elements identified by the Oxford E4SV *Smart Villages Initiative* [4] and NREL's *ViPOR village power program design guide* [97]. Such approaches are all aligned with the three pillars of sustainability (energy, enterprise, education) needed to qualify an IEEE Smart Village project [120]. In this study, these best practices will be used to conceptualise a more suitable and pragmatic Smart Village microgrid platform based on appropriate Smart Grid principles.




(a) (b) (c)

**Figure 1.16:** Elements of (a) design thinking [121] correlating with (b) rural microgrid best practice design elements [80], as well as (c) determinants for success in energy-poor rural markets [21].

The application of design thinking in this dissertation is initiated from a rural African village energy user perspective (the *People* aspect in Figure 1.16(a)). In this case, the *Village Energy User Requirements* (top layer in Figure 1.17) are gathered from literature [5, 7, 80], and from personal interactions with IEEE Smart Village micro-utility owners and operators [93, 106]. In light of these requirements, the analysis is shifted to the *Technology* aspect of design thinking (Figure 1.16(a)), from which the *Technology Considerations* (middle layer in Figure 1.17) are mapped to the User Requirements. During this process, the considerations include technology platform components that can meet and improve the Village User Requirements, while also being relevant to the *Business Requirements* (bottom layer in Figure 1.17). These Business Requirements are typically related to the microgrid owners, operators, or prosumers (examples include tariff collection, cost recovery, and rate structures) and constitue the *Business* aspect of design thinking (Figure 1.16(a)).

The interconnected nature of the various stakeholder requirements (some examples shown in the layers of Figure 1.17) become apparent during these stages of the Smart Village microgrid platform conceptualisation. These stakeholder requirements are discussed in more detail in §1.4.7).

#### 1.3.3.2. Design thinking in Smart Grid architecture context

A hierarchical control system is an intelligent type of control system in which governing software for a set of devices can be arranged according to a Purdue type hierarchical

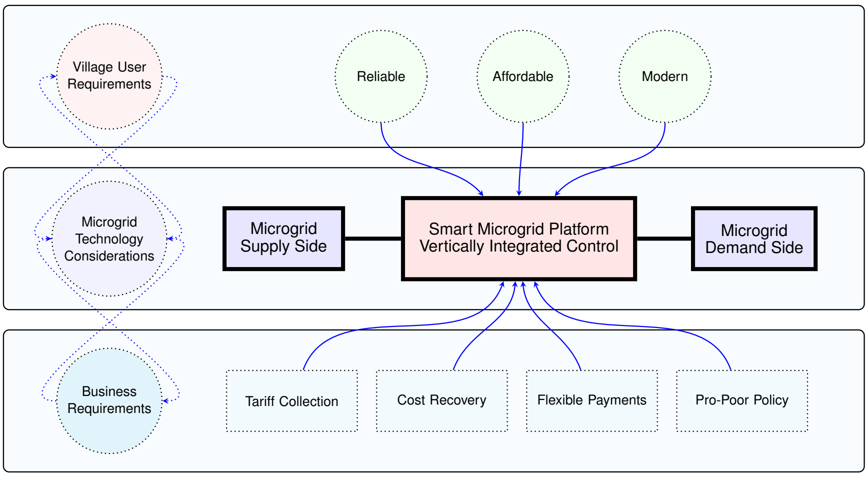



**Figure 1.17:** Depiction of the research methodology, showing design thinking elements in the Smart Village microgrid conceptualisation.

control tree [63, 122]. Design-thinking in terms of Figure 1.17 can thus benefit from designing Smart Village microgrid control in terms of the Purdue/SGAM Smart City hierarchical control architecture depicted in Figure 1.4(b). Cascaded Smart Grid control options in a vertically integrated microgrid concept platform can made smarter through *computational intelligence* locked up in (the upper control abstraction layers of) the control hierarchy. To this end, Figure 1.18 shows the Purdue/SGAM *control design process iterations* for Smart Grid design in terms of Zachman business architecture principles by NIST [42, 123]. The NIST Smart Grid design process steps (red arrows in Figure 1.18) interestingly starts from the business customer end, which relates closely to a customer-based design-thinking approach. It then selectively maps the logical control concepts and design flow decision sequences (iteration levels) into the Smart Grid (or microgrid) control architecture, as shown in Figure 1.18.

Hierarchical control algorithm development in the context of Figure 1.18 is one of the elements of the microgrid platform model-based design. Innovating towards new designs in the smart microgrid space calls for hierarchical modelling and data management in a logical control framework. The hierarchically arranged logical control framework of Figure 1.18 calls for cascaded ICT component integration to take responsibility for multi-temporal control of cascaded domains within the energy conversion chain [124]. In the Purdue/SGAM vertical integration control environment (the NIST/Zachman equivalent of Figure 1.18), software algorithm formulation is tasked with making appropriate design choices such choosing the appropriate control abstractions, selecting the proper control layers abstraction, and configuring the relationships across the set of control abstraction layers [125, 126]. It further means that control system elements and software algorithm components should be designed to operate on a variety of different functional, spatial, and temporal scales to exploit the various functionalities in the control abstraction space and layers, as depicted in the energy system layout Figure 1.18.

In this context, modern control algorithms enable innovation through processes of mathematical modelling, digital logic, or cognitive control procedures [127]. These aspects are dealt with the description of the model-based design considerations of the

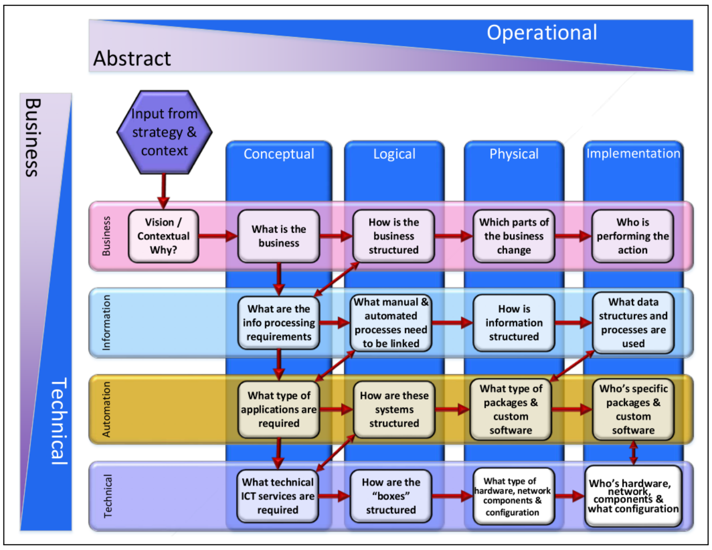



**Figure 1.18:** Smart Grid hierarchical system architecture layers, activity model and design iteration levels defined in terms of Zachman business process design principles [42].

next section.

#### 1.3.3.3. Model-based design towards Smart Village microgrid modelling

Design thinking links up well with methodological aspects of computer simulation as a research technique and is a well-established approach in empirical software engineering [112, 128, 129]. Combined with the above-mentioned design thinking, the theoretical foundations of a simulated model-based design environment offer a valuable basis for systems-thinking innovation in a theoretical building research approach [130, 131].

Design thinking also engages a model-based design (MBD) approach at the core of the development process and allows computer-aided design (CAD) techniques to be used in the simulated implementation of the microgrid controller [50, 57]. Computer-based design techniques in the modelling, simulation, and optimisation of the rural village distribution system can support a variety of microgrid research activities. These can range from technology selection, system sizing requirements, control requirements, technology evaluation, system integration, system testing, cost-benefit analysis, locational impact, benefit analysis, system suitability, and performance metric verification through discrete event simulations [57]. As such, MBD assists the design process from the requirement identification in the developmental stages, through to conceptualisation, design, implementation, and testing. The model-based design of the concept Smart Village microgrid will allow integration of the SUN cogeneration system computer models, to perform further evaluation and testing under the simulated operating conditions of a rural African village.

With the Smart Village microgrid requirements determined through design thinking in §1.3.3.1, MBD aims to model and evaluate a conceptual microgrid platform towards meeting system requirements in a consensus control strategy for rural energy system applications. The conceptual framework design for the *digital microgrid platform and community control algorithm modelling activities* are depicted in Figure 1.19. It offers an abstract representation of the proposed Smart Village microgrid platform development elements, wherein the layered SGAM reference framework plays a central role in engaging the different functionalities in the control abstraction layers [132]. By modelling a conceptual microgrid strategic control platform, through the process in Figure 1.19, the outcome will provide a set of component blocks that can be combined to offer a full model representation of a microgrid system. The discrete-event simulation model then allows for the system operation to be studied as a sequence of discrete events in time.

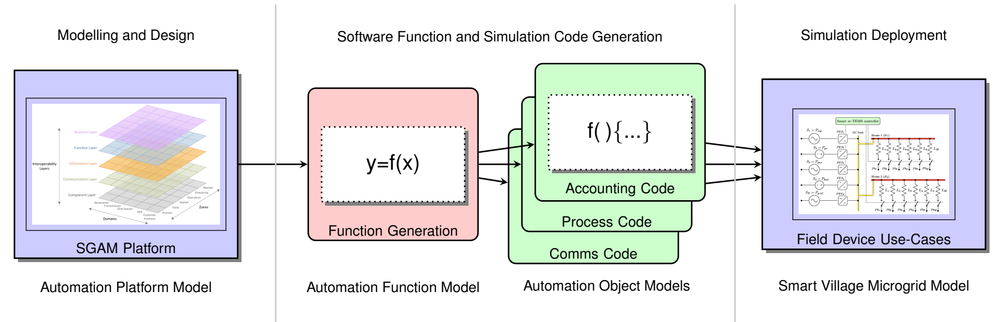



**Figure 1.19:** Methodological process layout for the proposed model-based development of a conceptual Smart Village microgrid platform.

In an engineering MBD approach, synthetic model representations are rooted in the sciences of the artificial, where dynamic systems may be re-created artificially to study aspects of the microgrid control model (as an artificially intelligent object) [133]. Design prototyping research conceptualises creative ideas and creates artefacts (algorithms, constructs, instantiations, libraries, methods, prototypes), by following an iterative process of modelling, simulation, data collection, analysis, and interpretation. Computer-based simulations in engineering control models are flexible as they imitate the behaviour of the system as a discrete model. Observations of the system behaviour can be observed to draw inferences about the operating characteristics or responses of the modelled energy management process in a microgrid system (microgrid platform artefact). Such model-based simulation experiments are valuable to test scientific proof-of-concept hypotheses.

In the model-based simulations of the present study, the quantitative dynamic simulation model framework of a proposed digital Smart village microgrid in Figure 1.19 can serve as one of the test benches for the evaluation of various conceptual microgrid strategic control model solutions [134]. In this context, computer simulation analysis on the model of Figure 1.19 will be useful in revealing how a rural village microgrid system will react, while case-based computer synthesis experiments enables the use of challenge scenario narratives to help reveal and explain why a system reacts and works the way it does [135]. This model thus supports scenario-driven microgrid model development, including structured model simulations for research data collection and management in verifying autonomous rural village microgrid driving functions.

Since computer modelling and simulation instruments emulate run-time system operation, it can facilitate the interconnected nature of end-user and other stakeholder requirements (micro-utility owner, NGO, government free basic electricity FBE) in a systems engineering approach (like SGAM). A multidimensional organisation such as a microgrid calls for interactive planning in a hybrid integrated systems thinking and quantitative data collection environment [136]. Computer modelling and simulation, as a flexible research instrument, provides the ability for model-based design to perform statistical mechanics, test hypotheses, or evaluate performance by way of simulating operations [137, 138].

#### 1.3.3.4. Integrated model-based-design-thinking in Smart Village concepts

The purpose of the study is based on the conceptualisation of a future Smart Village microgrid platform that would allow advanced resource management capabilities, needed in Smart Grids, in a rural energy environment. This calls for an integration of the model-based-design and design-thinking methods discussed above, a meta-modelling concept that applies the notions of design-thinking, software engineering and systems engineering in microgrid platform design and modelling. In the present study, this is inspired by the need for rural village microgrids to have more advanced control capabilities (and increased intelligence), driven by the hypothesis of future Smart City and Smart Village parity.

Integrated model-based-design-thinking in the platform conceptualisation space of Figure 1.20 offers an iterative approach to R&D problem solving that intentionally seeks solutions focused on applying creative thinking to meet customer engagement and client/shareholder needs. This is illustrated in the Smart Village energy platform investigation, where the overall design-thinking paradigm lifecycle process depicted in Figure 1.20 will continue to follow up with the full flow of model-based understanding, exploring, and materialising in a computer simulation environment [110, 116]. The design thinking process progresses through five phases empathising, defining, ideating, prototyping, and testing before entering the physical implementation phase to repeat all five phases in a physical modelling environment. In this circular organisation process (Figure 1.20), all parties are given equal representation in the democratic design hierarchy of Figure 1.15 [135].

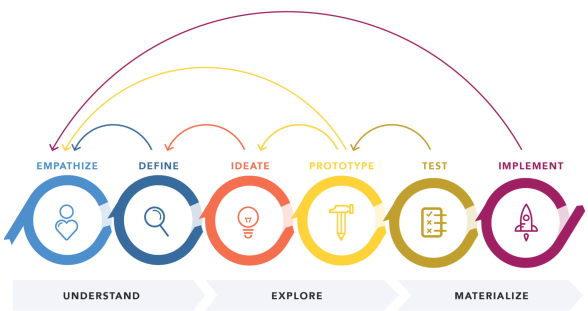



**Figure 1.20:** The design-thinking paradigm follows an overall flow of model-based understanding, exploring, and materialising in five phases empathising, defining, ideating, prototyping, and testing before entering the physical implementation phase [110].

In the development of conceptual platforms, designing optimisation philosophies can deliver better results when traditional engineering research methodologies consider interconnectedness philosophies [139]. Interconnectedness defines digital thinking as an integrated philosophy of engineering conceptualisation called digital thinking (Digital Thinking = Design Thinking + Systems Thinking + EcoSystem Thinking) [140]. It means that design thinking can further facilitate scenario thinking in systems thinking environment to combine the benefits [141]. Systems thinking [142] and case-based reasoning [141] can be integrated with design thinking as these are complementary approaches that can enhance the chances of creating better designs [131, 143]. In terms of engineering of Smart Grids for deployment, this present study adopts an integrated engineering design thinking approach as a research methodology to gain from these benefits in a computer modelling and simulation synthesis investigation modality.

In the iterative design context of Figures 1.18 to 1.20, the development of strategic control automation in a rural microgrid platform depends on the ability of the designer to *conceive and transform concepts into software algorithms*. Such conceptual automation algorithms are dependant on *computational intelligence* that forms the basis for automation of control abstractions [126]. In this computational control space, *applied algorithm design* needs to integrate with the model-design approach to create mathematical processes in the form of algorithms to solve process control challenges/problems. As the microgrid elements have to exhibit multiple and distinct behavioural modalities during their interactions, the software control algorithm(s) relies on computational thinking techniques [144]. Such computational intelligence is growing in the fields of Mechatronic Engineering, Energy Engineering, Software Engineering, and Computer Science [145, 146], and is becoming a fundamental requirement in modern *Cognitive Energy Management* applications such as the Smart Grid of the 21st Century [127, 147].

In summary, the design thinking methodology in §1.3.3.1 is used to identify the *operational requirements* for the concept microgrid platform, while a model-based design approach §1.3.3.3 provides a method to *create parametric computer-based representations of the microgrid components*. A model of the integrated resource coordination component (in Figure 1.17) required *special purpose computational intelligence* typically found in the Smart Grid control abstraction layers to elevate the microgrid model to the operational capability levels of Smart Grids.

## 1.4. Scope for Innovation

It is part of the IEEE Foundation vision to provide access to clean water, energy, nutrition, and sanitation on a universal growth path towards micro-enterprises that will improve the quality of living and boost village income [4, 96]. This IEEE mission must drive the microgrid platform technology design. The research hypothesis states that specialised Smart Village microgrids will play the role of the energy component in future Smart Villages and that these microgrids will have similar operational capabilities to those of the Smart City microgrids. This study further hypothesises that Smart Grid development can be used as a beacon to lead designers to the conceptualisation of the future Smart Village microgrid.

This section presents the foundations of current Smart Grid and Smart City developments in §1.4.1 to §1.4.5. It offers insights into the gaining of a better understanding of the developmental pathway that has led to the core Smart Grid concepts and operating principles that can support smart microgrids. It concludes with a scope of innovation towards next generation Smart Village microgrids in §1.4.6, re-iterating the context used to formulate the hypothesis, and giving a basis on which to conceptualise the future Smart Village microgrid in §1.4.7.

### 1.4.1. Sixth Kondratieff wave of Smart Grid automation

In analysing the automation trends for Smart City and Smart Village models from the perspective of technological intelligence and planning, the automation science community is drawing upon ideas proposed by Kondratieff [148]. Kondratieff and his followers studied significant socio-economic and socio-technical trends from the end of the 19th century and determined that there have been at least five well-defined long-wave innovation strings in world economies [149]. These so-called wave-excursions are driven by technological innovations (waves) that have transformed society through fostered economic development, triggered by a series of disruptive innovations [150]. Regarding these theories, it is believed that the world is currently in *the Age of the Internet*, or the *Fifth Kondratieff* [35]. The scientific community believes that the future sixth and seventh long waves (Kondratieff) will resonate with the *Smart City* concept, while studies on innovation strings concerning technological applications for the future are showing signs of great potential to support this view [35, 150, 151].

In this new wave, smart device and smart system enabled automation will exploit energy informatics and analytics within hierarchical control theory as a basis to ensure intelligent self-adaptive systems [152]. This will enable energy systems to dynamically operate under increasingly complex conditions, while adhering to constraints commanded by the operational environment, system dynamics, the availability of resources, and variations of user configurations and goals. System-wide diagnostics processing and predictive analytics (energy, pricing and quality performance factors) will promote distributed situational awareness - so necessary in smart energy systems of the so-called *sixth wave of automation* and in anticipation of the Age of the Smart City [153, 151].

### 1.4.2. Smart Grid trends and cycles driving Smart Cities

The evolution of Smart Grid concepts shows a rich history in the growth of computational intelligence in meeting energy system needs [154]. While digital grid modernisation efforts are poised to reconfigure the electric grid, evolutionary cycles of the Smart Grid shows four sequential implementation phases [42, 155, 156]. The first two phases include the formulation of Smart Grid 1.0 (meter-centric), and the Smart Grid 2.0 (operation-centric) phases [157, 158]. These phases led to the formulation of newer Smart Grid frameworks such as the forward-looking Smart Grid 3.0 (customer-centric) framework [156, 159] and the future envisaged Smart Grid 4.0 (agent-based cyber-physical grid) [160, 161].

With Smart Grid 3.0 and 4.0, the integration of a variety of distributed renewable energy sources, data mining and machine learning, the intermittent connection of electric vehicles, and the need for machine-to-machine applications to smart grids is bringing about more challenging issues in the realisation of future Smart Grids discussed later. In the digital energy system of the future, Smart Grid 4.0 envisions the development of smart energy management solutions for microgrid systems aimed at digital use cases for consumers and prosumers in smart houses [92, 162]. In this post-modern Smart Grid 4.0 environment, the development of cyber-physical grid systems will allow for a distributed grid with capabilities for integrated dynamic pricing and demand response management (DRM) capabilities - suitable to optimise decentralised solutions [160, 163, 164]. They will ensure a closer integration of various energy system elements and enable the exploitation of the combined capacities and flexibilities of electricity and thermal energy (cogeneration systems) [165]. To support neighbourhood energy management and smart electric vehicle charging, a more prominent role for IoT data is envisaged.

In the Smart Cities paradigm, a new Smart City model is showing the first signs of emerging. Unlike the technology-driven provider approach of Smart Cities 1.0, or the city driven model of Smart Cities 2.0, the emergence of Smart Cities 3.0 is leading Smart Cities to embrace activities of energy entrepreneurship in the so-called citizen co-creation model environment [166, 167]. According to the Smart City vision, the Smart Grid 3.0 developmental phases appear to be driven by the future Smart City 3.0 model, and *vice-versa*. The correlation between the *Smart Grid* and *Smart City* models highlights the fact that technology wave attributes are also driving the levels of "smartness" in the Smart City paradigm [37].

The industrial reference architectural automation model 4.0 (RAMI 4.0), brings a cascaded factory automation perspective, offering fresh options for automation to the energy industry [168, 169]. It aims to standardise production systems in a highly modular, multi-vendor environment by combining crucial control elements in a three-dimensional layer model [170]. It allows the energy industry to view the Smart Grid from the perspective of production automation whereby the balance between supply (production of electrons) and demand (orders for electrons) can be automated on the basis of RAMI 4.0 principles. This has created new opportunities for the modern Smart Grid digital transformation process, as energy-as-a-product management could be compared to the manufacturing process (a business system in a manufacturing system). This enables the advanced Smart Grid to apply the industrial Internet of Things (IIoT) to the control principles of the industrial process, control principles, as in the such as case of the just-in-time manufacturing of energy (electron production), as a means of leverage in modern automation science and process control theories in industrial control systems [171]. Smart Grid developers are adopting the process control principles of RAMI 4.0 aimed at guiding operational grid activities and used as leverage on its batch processing and supply chain management capabilities embedded in cascaded control [160, 172].

With RAMI 4.0 showing a close resemblance to the Purdue reference architectural model, which has already been successfully applied in this SGAM context, factory automation techniques have found its way into the modern Smart Grid in the form of process planning and resource coordination using such computer integrated manufacturing control techniques [44, 173, 174]. The latest Smart Grid research on pervasive "smart-energy manufacturing" applications is benefiting from modern automation science and change management principles offered by RAMI 4.0 in the development of industry microgrid platforms. In these factory automation operations, computer automated manufacturing execution systems (MES) achieve significant integration success with the practical application of the hybrid Purdue and Sixth Sigma manufacturing enterprise models within the ISA and RAMI regulatory frameworks [44, 175, 176]. Process control and collaborative manufacturing best practices have therefore influenced energy management principles based on industrial automation process control abstractions. This guides Smart Grid development towards adopting smart enterprise manufacturing operations management (MOM) and smart manufacturing operations (SMO) automation techniques [177].

Future Smart Grid operations can be engineered for service-oriented architectures or smart manufacturing operation automation. Such designs can benefit from modern automation science and change management principles based on manufacturing enterprise automation requirements. Such control automation principles have been developed by the GridWise Architecture Council (GWAC), specifically the framework development work concerning the Smart Grid GWAC logical control stack [42, 178]. This control stack enables cascaded control as a vertical cross-section of the levels of functionality, intelligence, and interoperability necessary for allowing the various interactions and transactions towards creating a logical unified Smart Grid reference architecture [42, 179, 180].

### 1.4.3. Smart City services vision driving the next generation Smart Grid

With IoT interconnectivity at the centre of the so-called *Smart Diamond of Smart Cities* in Figure 1.4(a), the ICT is a particularly important driver of the next generation Smart City [181, 182]. This paradigm anticipates smarter cities to be more connected (wireless mobile data), more electro-energy-driven (electrification of everything), more computable (smart devices, smart home services, artificial intelligence, big data), and more automated (cognitive, self-thinking, smart automation) [34, 35, 36]. In the digital transformation toward Smart Cities, modelling the grid for decentralised energy is concerned with solutions to process control in a connected enterprise chains, and to exploit hidden values over the entire value chain, as featured in Figure 1.21(a), ranging from suppliers to customers and from components to systems [183, 184].

With support from the IEEE interconnectivity (IEEE 1547 Standard) and the interoperability (IEEE 2030) Standards, it ensures the seamless integration of microgrid systems, components, and networks [185, 186]. In this stack, intelligent automated control is made possible on the core microgrid software platform. This platform, illustrated in Figure 1.21(b), elevates the strategic control capability towards the Smart City level functionality, and promotes the integration of DER through intelligent automated control. The digital transformation thus extends into the creation of vertically integrated enterprise control solutions to exploit microgrid intelligence value over the entire value chain (Figure 1.21(b)), ranging from suppliers to customers and from components to systems [183, 184].

The concept of a *Digital Energy System 4.0* (European Technology Platform for Smart Grids) is driven by the notion of the Fourth Industrial Revolution and serves as a beacon for the European strategy of moving towards the next generation Smart Grid [190]. The aim is to move the Smart Grid towards an energy enterprise eco-system that could better serve future Smart City concepts [36, 92, 181]. While the Smart Grid is an enabler of the new energy economy, the model presented in Figure 1.21(b) depicts the modern Smart Grid vision and represents this advanced framework of a cascaded control platform. This platform is intended to ensure a more connected network with higher levels of spatial intelligence that can pay digital dividends through knowledge-

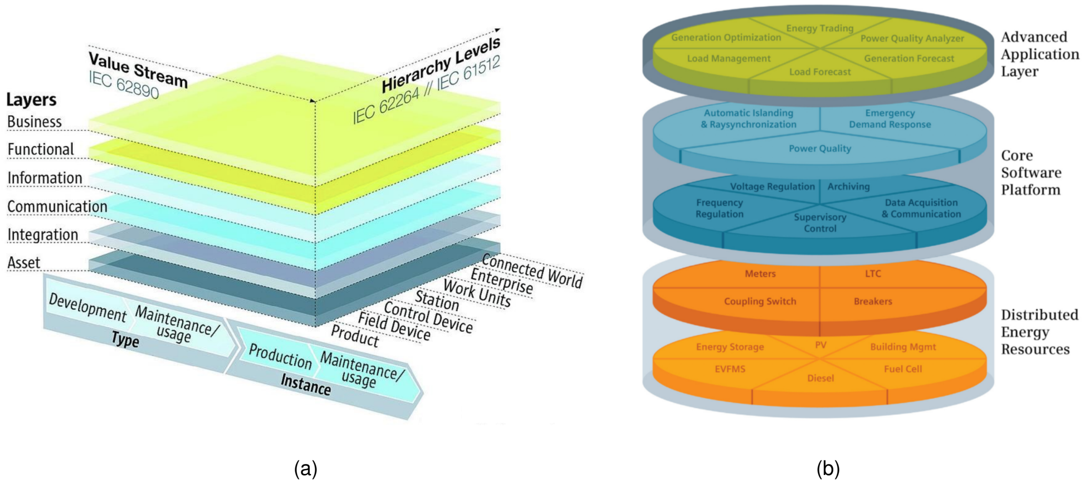



**Figure 1.21:** Smart City microgrid based on (a) the process-oriented reference architectural automation model [168, 187], with (b) a smart microgrid energy management control ecosystem [188, 189].

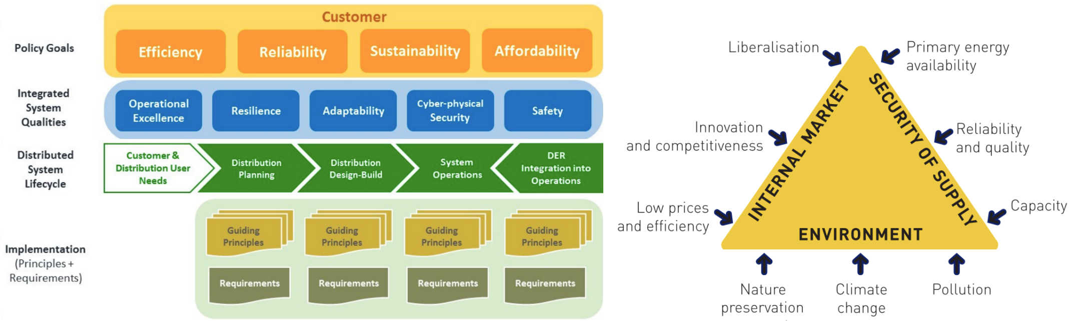
driven principles and machine-driven applications [191, 192]. Key technology enablers (and challenges) towards achieving such Smart City goals for the future include citizen engagement, business aspect development, big data and data analytics, improved approaches to machine learning, networking and communications, cloud and edge computing, the incorporation of software mobile agent objects, and cyber-physical systems technology on cellular automata models in multi-core embedded systems [24, 193, 194]. The *Digital Energy System 4.0* concept thus extends the strategy of the next generation Smart Grid as an energy enterprise eco-system able to serve the future Smart City concept [36, 92, 181].

The future Smart Grid is evolving to meet modern Smart City services, similar to the way in which the mobile internet allows for the flexible accessing and distribution of information. The future Smart Grid is progressing towards adopting similar aspects to those of the internet [195], thus pointing specifically to its qualities of decentralised intelligence, automated decision-making, and associated self-healing. In such Smart Grid models, resource coordination is changing from centrally managed power plants to the coordination of large numbers of smaller distributed generators and intelligent, controllable, and responsive loads. Smart microgrids fit this model and are expected to be prominent role-players in the future of Smart Grids.

### 1.4.4. Characteristics of next generation Smart Grid pathways

In the modern IoT era, a series of trends such as the increased integration of renewable energy resources, rapid growth in the smart device's share of the market, and an increase in distributed energy resources [19, 22, 43] have been driving the conceptualisation of new grid design plans and management approaches that are already changing the nature of future energy markets fundamentally. For example, in preparation for the next phase of the Smart City vision, the State of California developed an innovation strategy for a next generation Smart Grid platform as a *framework to make the distri-*

*bution grid more open, efficient, and resilient*. This strategy is based on the illustration in Figure 1.22(a) and, in the context of planning, highlights the policy goals of providing more reliable, affordable, and sustainable energy at affordable rates [196]. Along the same lines, Figure 1.22(b) depicts the driving factors in innovation planning for the European next generation Smart Grid [197]. Both the Californian and European innovation strategies for the next generation Smart Grid reflect how Smart Grid 3.0, and future versions, plan to accommodate a variety of Smart City stakeholder objectives on the cascaded SGAM control platform of Figure 1.4(b). In the above plans, for example, new approaches were needed to better manage the complex operations of Smart Grid 3.0, especially because the management and control of a centralised regulatory paradigm had reached the limits of scalability and flexibility towards IoT cloud-type grid models.




(a) (b)

**Figure 1.22:** Smart Grid platform development strategy in (a) California's preparation for the future Smart City vision [196], and (b) driving factors in Europe's future Smart Grid platform development [197].

Smart Grid R&D roadmap exercises, such as those depicted in Figure 1.22, stem from coordinated studies that plot smart energy system pathways for 21st century applications. In terms of smart energy transformation, such pathways play a central role in scenario-driven planning exercises as they act as guidelines in the compilation of frameworks for decision-making in developmental research roadmaps. Top-down grid expansion pathways are also valuable for evaluating investments and business decisions. The trends that are driving the power system pathway for other parts of the USA have been catalogued in a NREL report by Zinaman *et al.* [21]. These scenario driven pathways include (a) a *vertical-integration pathway* to prioritise the value of energy service delivery rather than to minimise energy and systems costs, (b) the *distribution system operator (DSO) pathway* that focuses on the development of regulatory and policy frameworks. This enables DSO technology and business innovation towards low-voltage distributed energy resources and on the strategic positioning of clean generation facilities for the mitigation of climate change, and (c) the restructuring of the energy market in the *reconstructive pathway* through engineering design features and renewable portfolio standards (RPS), which requires utilities to generate a specified amount of electricity from renewable sources. This pathway promotes top-down grid expansion that facilitates the generation of clean energy and the optimisation of an improved energy system.

The two remaining pathways by Zinaman *et al.* [21] are more relevant to this study. (d) The *federated microgrid pathway* aims to create a federated Smart Grid architecture in which intelligent microgrids (buildings, campuses, districts, factories, mines) can operate independently, or can become coalition elements of the main grid when intermittently associated or inter-mediated with the Smart Grid. This creates pathways for Smart Grid reconfiguration (hierarchical or layered grid unbundling, grid partitioning, grid segmentation, grid fragmentation or mesh grid creation), and (e) Bottom-of-the-Pyramid *BOP-pathways* (for utilities and micro-utilities) that aim at accelerating the rate at which energy access is provided through new technological configurations or business models. It supports new and innovative approaches for energy access, which are often linked to broader SDGs where there are chronic challenges pertaining to energy access. The last two energy pathways are of particular interest to this study, as they offer exciting opportunities for socially-customised solutions to energy access, such as adaptive bottom-up microgrid development, access services to bundled community energy, or coordinated Smart Grid interlinking once the grid infrastructure becomes available.

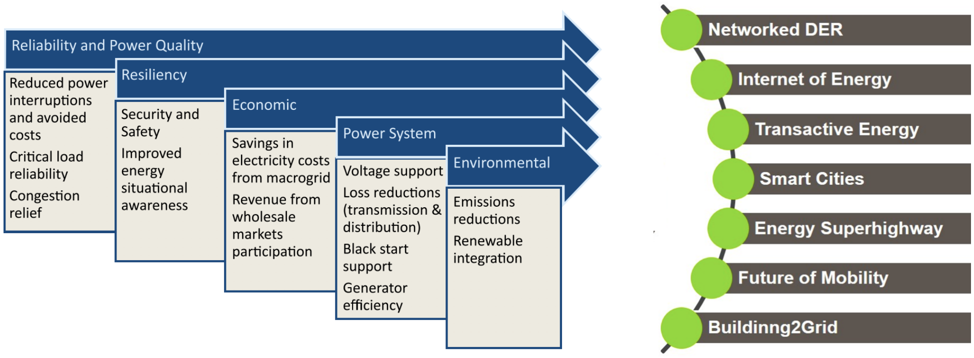
This discussion shows that there is value in studying the characteristics of next generation Smart Grid pathways, especially regarding developing R&D roadmap exercises derived from observed *market trends and drivers*. While utility-based Smart Grid R&D roadmap exercises include BOP-pathways and federated microgrid pathways, there is still a particular need as part of the quest for off-grid rural electrification to study stakeholder requirements. This further highlights the need to determine *user-requirements*, and the need for *rural village R&D roadmap exercises* toward off-grid rural village applications. Some of the conceptual strategies previously discussed are indicative of future Smart Grid features that are ideal for Smart rural village microgrid platforms that are included in the Smart Village vision.

### 1.4.5. Future Smart Grid and Smart City microgrid platforms

An analysis of the R&D roadmap for the future Smart microgrid, which is expected to serve the internet-driven Smart City model, shows that many of the planned Smart Grid technological concepts are envisioned to realise specific principles, features, and capabilities to create an all-inclusive environment. Figure 1.23 shows the value propositions in new microgrid designs, which are based on ten value streams for intelligent software modules to monitor, predict, manage and optimise energy supply and demand in small-scale energy systems [198, 199].

A better distributed and more intelligent dynamic microgrid-based Smart Grid network was in part inspired by a need for more reliable and resilient energy networks with the capacity to integrate DERs and smart technologies [48, 201, 202]. The US National Electrical Manufacturers Association (NEMA) supports this view in their White Paper that sets the goal for utilities to incorporate microgrids as fully controllable independent dynamic units with intermittent grid coupling and decoupling capabilities by 2025 [198]. These capabilities accelerate the microgrid goal of becoming the "fundamental building blocks" of the future Smart Grid in the 21st century [203, 204].

While the Smart Grid unbundling strategy creates significant challenges in terms of energy management since microgrid designs must include dynamic grid federation capabilities that enable it to operate as part of the grid. Such aspects of modularity




(a) (b)

**Figure 1.23:** Smart City and Energy Cloud microgrid value proposition (a) based on ten value streams for intelligent software modules to monitor, predict, manage and optimise energy supply/demand for small-scale energy systems) [198], (b) towards emerging combinatorial platforms [55, 200].

design make room to include customer engagement and development opportunities for business-orientated microgrids. Smart Grid microgrids mandate the selection and development of suitable software protocols to allow for demand response functionality, such as open source implementations of OpenADR protocols developed to standardise the demand response goal [205]. Furthermore, the integration of dynamic value-based parameters promotes new computationally-intelligent behaviour dynamics and dimensions of control that enrich the microgrid eco-system [44, 206]. Understanding and applying economic signals in the feedback loop fosters the optimisation of costs and balancing aspects that have become particularly important in current goal-orientated cost systems. Figure 1.24 shows the expected developmental timeline towards these more advanced microgrids with their integrated automation, analytics, and capabilities for market-based operations [56, 207].

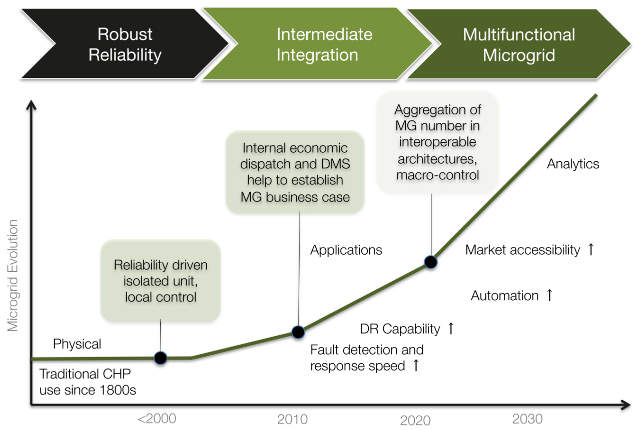



**Figure 1.24:** Microgrid localised energy optimisation with evolution timelines and elements for technological development [56, 207].

As such, next generation microgrids are proving to be complicated commercial ecosystems with many stakeholders and value exchanges [200, 208]. It is essential that stakeholders and designers view the microgrid system as a sum of discrete commercial elements and stakeholders, each able to perform value exchanges in different roles as part of the more extensive system in grid-connected microgrids. Navigant Research developed a product vendor-based *Commercial Microgrid Ecosystem Model*, shown in Figure 1.25, to help market players establish a universal language of understanding when discussing microgrids with multifaceted DER [55].

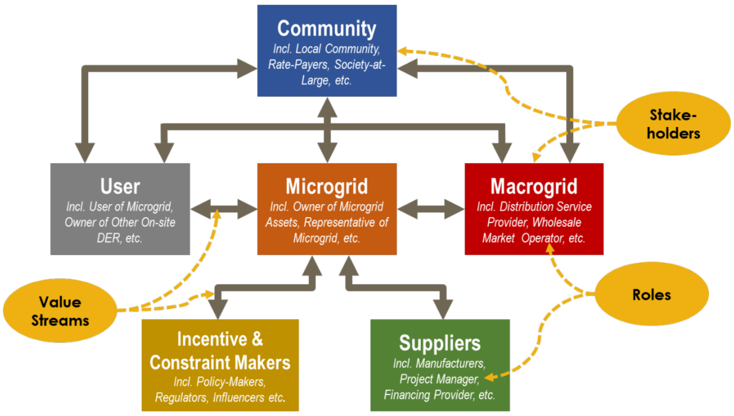



**Figure 1.25:** Microgrid commercial ecosystem and analysis components [55, 209].

A microgrid value compatibility matrix can help to select best options [210] since cost-control and integrated business model frameworks require enterprise intelligence in a the component analysis phase of a commercial ecosystem approach. These aspects in Figure 1.25 highlight the importance of the microgrid commercial developmental processes in the future strategic planning of microgrids. The new basics of modern Smart Grids and digital energy are thus set to bring about new relationships in a sharing energy economy that differs from those of the conventional economic models. It works towards the emergence of market models based on the transaction-based energy economy [211, 212]. In this context, both the development and orchestration of new Smart Grid technologies are transforming the utility sector toward a human-centric and market-based grid platform, while prosumers are further empowered by the capacity to actively participate in the energy market in a microgrid context. The next section describes possible opportunities for next generation rural microgrid systems design in the Smart Village context.

### 1.4.6. Scope of innovation towards Smart Village microgrids

The vision for Smart Cities and Smart Grids was long foreseen by pioneers and visionaries who recognised the value of electronic intelligence and automated processes. The current frameworks and pathways toward future Smart Grid developments are based on the communication and decision-making capabilities of machines which are expected to automate and operate almost all aspects of modern society to keep it running as smoothly and efficiently as possible. The role of microgrids in the Smart city context is well defined and being continuously updated, as it grows in popularity.

From an IEEE perspective, the Smart Village vision promotes access to sustainable energy systems, based on renewable energy resources, which are guided by modern digital information and communication technologies to allow for a more holistic environment for development. While the idea of Smart Villages already exists, there has been little formal development toward the future rural Smart Village microgrid and the technical and operational capabilities that it should include. This research argues that there is a possible opportunity to leapfrog to this more desirable microgrid concept by borrowing from the Smart City microgrid developmental roadmap and by making innovative adaptations for rural microgrids to be more relevant to the off-grid rural energy space. This vision leaves significant scope for innovation in terms of the conceptualisation of a future Smart Village microgrid since Smart Grid developments and future principles can be observed for inspiration.

The conceptualisation of a next generation Smart Village microgrid platform will consider the current and future operational features and capabilities of the Smart Grid, as presented in §1.4.1 to §1.4.5 as development cues:

- ⚠1 The Sixth Kondratieff wave in a Smart City and Smart Grid automation environment discussed in §1.4.1 is an essential consideration in the context of Smart Village microgrids. It highlights future trends in control automation as a means to unlock the inherent attributes of smart technology, such as computational intelligence (hosted by the cascaded control layers of Figure 1.21).
- ⚠2 Waves of transition from Smart Grid 1.0 to Smart Grid 3.0, discussed in §1.4.2, show that the Smart Grid and Smart City evolution phases have underlying effects on each other. The discussion in §1.4.2 continues in §1.4.3, showing that the service-oriented vision of the Smart City is driving next generation Smart Energy ecosystems [188, 189].
- ⚠3 Conceptualisations of the Village microgrid should consider the process-oriented aspects of the reference architectural automation model to lever supply chain management procedures and capabilities embedded in cascaded control (energy production, logistics, retail energy sales, bookkeeping, pricing, customer relationships, and management) [160, 172]. Future designs for Smart Village microgrid platforms could therefore consider additional functionality in the control architecture to allow for more advanced Smart Grid control automation, and even include this aspect in the control architecture that would allow for market-based operations. The upper control layers of energy management and market operations are essential and Smart Village microgrids should, in similar fashion to the Smart Grid, and, as propounded by the internet look to adopt structurally inspired qualities of decentralised intelligence, automated decision-making, and self-healing [195].
- ⚠4 Similar to the Californian and European next generation Smart Grid innovational strategies in §1.4.4, future versions of Smart Villages should plan to accommodate a variety of Smart City stakeholder objectives on the cascaded SGAM control platform, as featured in Figure 1.4(b). This discussion highlights the value in studying the characteristics of next generation Smart Grid pathways, especially regarding the development of R&D roadmap exercises based on observable market trends and drivers. Furthermore, it shows that specifically conceptualised utility-type Smart Grid

strategies and R&D pathways on future Smart Grid features are ideal for Smart rural village microgrid platforms that feature in the Smart Village vision.

- The federation of microgrids proposed by NEMA in §1.4.5, creates exciting options for smarter and cleaner energy systems [198, 213]. Such a federation would also create opportunities for more intelligent independent modular microgrids that would benefit Smart Villages. This modularisation allows for next generation Smart Village microgrids to engage in a mesh of inter-connected computing power, especially in situations where microgrids use hierarchical or layered Smart Grid principles to act in coalitions of utility architectures [214]. The modularisation of Smart Grid energy systems opens new pathways for distributed generation and control [90, 91], with different communication scheme requirements [215], thus offering exciting new opportunities for Smart rural electrification and self-organising architectures for decentralised Smart Microgrids. Smart City attributes in Smart Village microgrids can also allow for the integration of demand response functionality as part of the optimisation of control procedures and software protocols. Figure 1.25 explicitly highlights microgrid commercial ecosystems and the analysis of their components in the context of business since next generation Smart Grid microgrids under NEMA will be moving towards commercial ecosystems with many vendor capabilities and with stakeholders and value exchanges [55, 209]. The businessification of this village microgrid platform is an essential cue for microgrid designs for Smart Villages.

This scoping exercise for innovation shows that the future goals for the Smart Village correspond with the requirements of the Smart City concept. This overlap brings opportunities for bottom-up Smart Grid re-engineering and opportunities to fashion potential Smart Village designs around proven technological concepts. Such an approach offers opportunities for novel control paradigms in the domain of the microgrid system for rural village energy that can be computationally modelled and synthesised as an enabling environment to help realise (geographically-distributed) community sharing-based microgrid platforms. True to the Smart Grid approach and technology trends at the grid edge, the future Smart Village microgrid platform should build on the decision engineering concept of distributed intelligence to provide for a smart, application-based microgrid ecosystem.

Such a radical transformation is nothing new to the rural landscape as the field of telecommunications recently experienced a similar leapfrog event. Modular geographically-dispersed digital cellphone services have allowed remote rural communities to bypass analogue landline technology and enter the age of digital communication. In the same way, off-grid rural electrification schemes can focus on modular technological development towards modern sustainable rural energy services through establishing cellular microgrids at the community level to serve geographically-dispersed communities [4, 99, 216]. In terms of technological innovation, this calls for the integration of multi-disciplinary knowledge from the respective disciplines of Mechatronic Engineering, Decision Engineering, Software Engineering, Microeconomics, and Computer Science, with an information systems approach. Such an approach should ideally involve computational intelligence, energy informatics and energy cybernetics in embedded autonomic computing platforms to intelligently integrate the behaviour and actions of all users that are connected to coordinate micro-generators and prosumer devices. This would work efficiently towards the provision of a sustainable, economic and secure supply of energy through a next generation Smart Village-type microgrid network.

### 1.4.7. Smart Village microgrid considerations and requirements

With the current adoption trends of more intelligent devices in the rural village microgrid space leaning toward Smart Grid 1.0, smart meters with remote accessing capabilities are making their way into the rural energy markets [105, 106]. In Smart Grid 1.0, the introduction of smart meters was geared toward data collection for a better understanding of user energy consumption which would allow for better forecasting and the optimal dispatch of resources. From discussions with IEEE Smart Village microgrid operators, who added smart meters to their systems even though they were not included in the original design, the smart meters were not only used for data collection, but also to support basic energy management activities in microgrids. Depending on the specifics of the device, the acquired data provided more accurate and reliable billing and in some cases enabled mobile payment methods in small business models [106]. Additional outcomes included better tariff collection and, improved load managing capabilities for the operators, and there are even some reports of behavioural changes owing to the user's insight into their energy use. While still a long way from the full capabilities of integrating a more automated management platform, these are significant impacts compared to the initial impact of smart meters in some of the developed markets.

Microgrids are typically designed to meet specific operating requirements and even when different installations are lumped together in the same category (microgrid categories shown in Figure 1.6) the technology and control makeup can vary significantly. Essential functions of current and future Smart City microgrids include the autonomous balancing of the network supply and demand, the optimisation of resource engagement schedules. The list below presents a brief summary of the requirements to be considered in the conceptualisation of a next generation Smart Village microgrid platform:

- ▷ *Reliability* is based on the ability of the system to deliver the planned energy outputs. The SE4ALL Multi-Tier Framework in Table 1.2 presents some criteria for measuring reliability and has been adopted by the UN as the benchmark to measure energy access toward the attainment of Goal Seven [5]. A certain level of resilience is also expected under this criterion as these requirements complement each other [217].
- ▷ *Affordability* has multiple dimensions when considered in the rural village context. It includes upfront costs, total investment costs, and flexibility in payment [130, 218]. Flexibility in payment will be a key consideration during the conceptualisation of the microgrid platform since upfront, and total investment costs are absorbed by the micro-utility owner in future Smart Villages. Allowing flexible power purchases will be a familiar notion since the "pay-when-you-can" concept is already part of everyday life in these communities [219, 220]. In fact, this approach has seen people who live on less than US$ 1.25 per day, pay over 50 times the price of electricity in industrialised countries. There are examples of village kiosks reporting rates of between US$ 5-10/kWh for the charging of cellphones [75].
- ▷ *Adaptability* to changes in operating conditions, which are a common occurrence in rural village energy projects, is another important aspect to consider [80, 93, 221]. The critical failure of generation or storage equipment could cause prolonged downtime since replacement components are typically not readily available. Being able

to adapt to these situations and to serve the critical operations and infrastructure for these periods will be important. It could also includes adapting to new or changing regulatory requirements, such as the pro-poor governmental policies of Free Basic Electricity (FBE) and inclined block tariff (IBT) pre-payment schemes [74, 222, 223].

- ▷ *Scalability*, in the context of this study, means that an increase in controllable resources (generation, consumption, and storage) should not hinder the system in its capacity to perform its core functions.
- ▷ *Interoperability* , in the context of this study, considers the need for legacy devices (non-smart), that are already in circulation (§1.3), to communicate and interact with other devices. Further consideration should also be given to the possibility of interconnected Smart Village microgrids, and integration of off-grid systems such as solar homes.
- ▷ *Flexibility and replicability* refer to designs that are flexible enough to be replicated with minimal reconfiguration. These solutions are an important consideration for rural energy systems toward attaining Goal Seven of the SDGs, and see strong support from USAID who allocated four million US$ toward scalable solutions in Africa in the 2016/2017 financial year [78, 224].

Access to modern energy services, which includes access to electricity and clean cooking services, also forms part of the requirements owing to its role as an important part of Goal Seven [7]. Reliability and affordability, as indicated in this list, form the basis for fulfilling of the village energy-user's needs, while amongst others, adaptability and scalability, for example, are more important for other stakeholders. Some consideration must also be given to trade and supply functionality and privacy protection, both of which are fast rising in the expectations to grow Smart Microgrids through Smart Grid considerations. To ensure that future Smart Village requirements are also met in standalone (islanded) off-grid conditions, autonomous operation is also included in hardware and control considerations.

## 1.5. Research Design Layout

This section summarises the research design layout to illustrate the framework around which the study investigates a next generation Smart Village microgrid platform. The research design layout, shown in Figure 1.26, provide a visual guide to the research design formulation. It points to the prominent role of microgrids in the energy future of the Global North and Global South. It's investigation showed overlaps in the trends between the rural energy space and modern grid systems. From there, the similarities for microgrid operational requirements in both energy environments were identified, while cognisance was also taken of their drivers (and the challenges caused by them) which typically proved to be different. This study noted that more advanced microgrids are crucial in the rural energy space, as well as in the city energy environment. It noted that the future Smart City microgrids have definitive R&D pathways, while the rural village microgrids currently lack such guidelines. The study identified a gap in knowledge and stated that research is required towards a smarter microgrid platform to meet the current and future energy requirements for rural areas. The research hypothesis states that (a) there is convergence at a technical level of rural village microgrids and the microgrid elements of the macro-grid, and that (b) smart grid operating principles related to resource management will work well in rural areas owing to some overlap in the operatinal requirements (supply/demand balancing and optimal resource scheduling).

While this hypothesis may prove to be true or untrue, the Smart City microgrid development pathway was used as a guideline (based on the hypothesis) so that a future Smart Village microgrid could be conceptualised. A model-based design-thinking methodology (Figure 1.17) was selected to help identify research objectives towards the formulation of the conceptualised vertically-integrated Smart Village microgrid platform. A model-based design-thinking methodology specifically aims at customer needs of villages, that may typically be remote and often lack primary energy generation sources. The proposed methodology thus makes provision for the fact that village customer needs differ significantly from Smart Cities that evolve from the conventional model of modernisation of traditional grids into Smart-er grids fed from the major power stations through transmission networks.

## 1.6. Research Significance

The present research supports the future vision of *Smart Villages* which, like *Smart Cities*, are built on the integration and cooperation of smart energy systems and various other services and commodities. The study aims to develop a concept Smart Village microgrid platform in support of the hypothesis regarding the converging trends in energy markets, and the expected positive impacts of Smart Grid principles on the rural energy landscape. This investigation aims to take a standpoint, or development directive, that is intended to provide guidance in future operations of rural village microgrid development.

This study addresses the current lack of advanced resource management capabilities in rural village microgrids by initiating research towards a Smart Village microgrid platform. This means looking beyond the levels of resource management that would suffice in the current age, and looking instead at the future capabilities that will be required for these microgrids to support future Smart Villages. While the study focuses on Sub-Saharan Africa, its significance extends to off-grid rural communities in other regions of the Global South.

Regarding the significance for **researchers**, the concept platform can be used to investigate the interaction of DERs and other components in the context of this concept of a Smart Village microgrid. This could be of assistance in design decision-making in the early stages of microgrid R&D projects. For our research group, it will serve as a simulation-based testing platform to evaluate the interaction of DERs in a case-based rural village microgrid environment. It will also be used as a foundation for further conceptualisation and development toward a complete Smart Village microgrid. By conceptualising a village microgrid platform based on user-centric operating principles that is capable of automated control, decision-making, and the optimal engagement of available resources, it provides researchers and practitioners (in our research group and otherwise) with a foundation from which to progress to the next stages of development. The research aims to contribute to determining the practical value added in the use of more advanced strategic microgrid control in rural village environments which would be relevant to all **rural village microgrid stakeholders**.

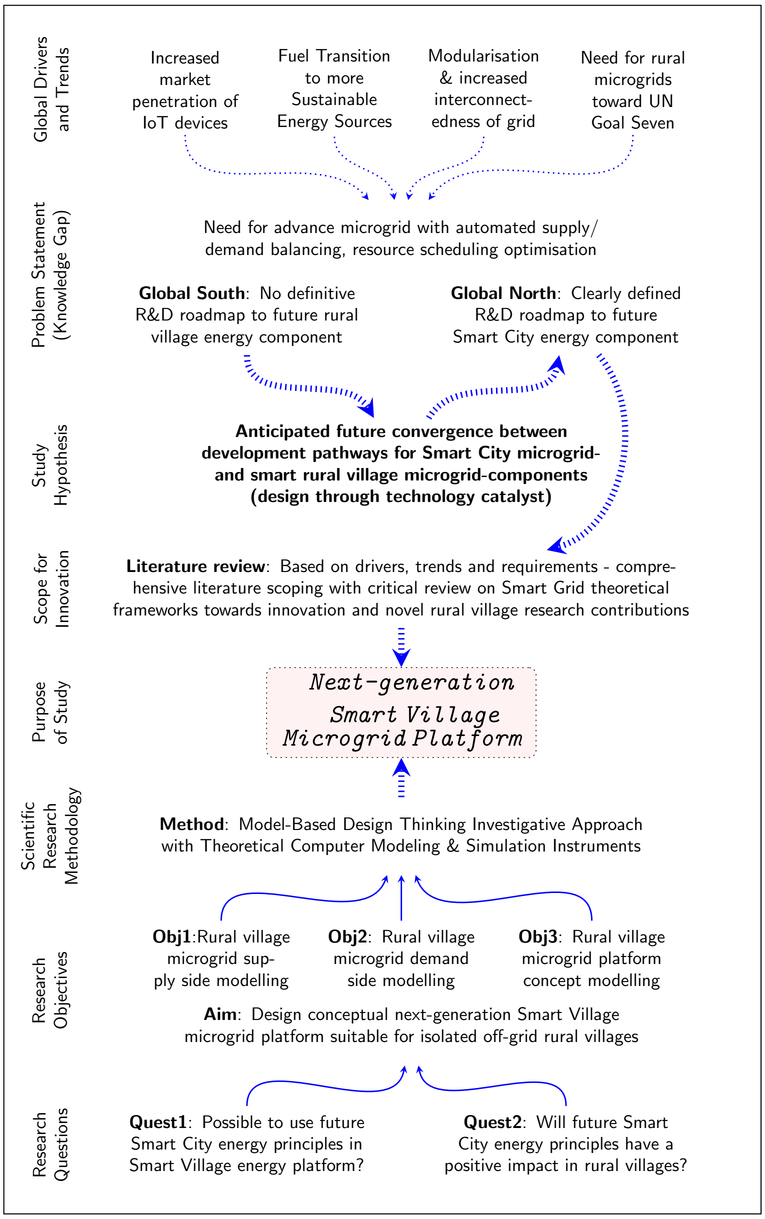



**Figure 1.26:** Visual layout of research design process for the present study; arrows denoting the direction of research progress from problem statement, research question, aims and objectives to methodology.

The aim of this research extends beyond the current discussions of rural village energy systems by initiating research towards Smart City-type microgrids in anticipation of future developments. As such, this research aims to provide direction for the development of smart microgrids in rural village energy projects which would benefit the **rural energy user**, as well as the **energy access practitioners, micro-utility owners and operators, governments entities, and other stakeholders**. The concept next generation Smart Village microgrid platform, considers the integration of cyber-physical devices towards an automated control future that would enable these microgrids to achieve peak serving capacity. This research could contribute points of discussion during policy development toward SDGs and future Smart Villages. The current dearth in design and developmental frameworks is creating additional de-risking challenges for financing and investment. This research could contribute toward exploring future standards by providing some insight into the interaction of Smart Village microgrids in case-based simulated experiments. The significance of the research extends to the IEEE Smart Village program since the concept platform aims to adhere to the typical technological expectations, but also gives significant consideration to enabling the business and user-centric components, which form the foundation for sustainable growth. The need for practical, user-oriented, rural village microgrid solutions, with strong scalability qualities, is seen as critical by the IEEE and USAID [78, 224]. The adoption of Smart Grid processes that originate from well-established production automation principles aims to achieve these scalability requirements in Smart Village microgrids.

The significance of this reserach also extends to the **rural village energy user**. The conceptualisation of a microgrid platform as the energy component of the envisioned Smart Village concept could identify the value of applying advanced technological approaches in these environments. Results could show whether a positive impact on the top priority performance indicators can be brought on by Smart Grid control strategies, thus promoting developmental pathways that could accelerate the adoption of high impact approaches. Considerations for the integration of legacy devices aim to provide insight and guidance that would be so necessary during the transition period when the current village microgrid energy landscape will be transformed into a future Smart Village microgrid landscape.

As the flagship program of the IEEE Foundation, the IEEE Smart Village program works toward exponential impact in empowering off-grid communities and therefore values research work in this field [95]. As the present scope of this dissertation aims to fill a knowledge gap in terms of community energy systems, it supports the extensive vision of the IEEE's ISV program in *seeking to bring basic electrical/energy and educational services to more than 50 million people from remote communities by 2025*.

## 1.7. Dissertation Layout and Structure

This dissertation consists of a compilation of journal papers and is structured to selectively include a sequence of papers that follow the pattern of research conducted during various phases of the project. As set out in Figure 1.26, the chapters follow a logical pattern of research activities detailed in the research design process. The document consists of six chapters, including an introductory chapter, four international research publications, and a chapter that presents the summary and conclusions. Chapter 1 offers an introduction to the research background, problem statement and purpose of the study, the research design, the scope for innovation and theoretical background, the significance of the research, the definition of terms, publications, and finally the dissertation layout and structure.

Regarding the first research objective, **rural village microgrid supply side modelling**, the journal papers in Chapter 2 and Prinsloo *et al.* [225], together with the poster presentation in Prinsloo *et al.* [226], start off with the development of parametric computer models for SUN cogeneration system components. It describes the characteristics associated with a theoretical simulation model for the micro-cogeneration subsystems (the thermal and electrical) of the concentrating solar cogeneration system under development at Stellenbosch University (see also [227, 228]). Chapter 2 in particular presents computer-based simulation experiments performed with the micro-cogeneration model from Prinsloo *et al.* [225]. It offers decomposition models for solar energy yield modelling and reports on the prospective performance and fuel reform capabilities predicted for the operation at various rural village locations in Africa [229]. This extends the application of this model into the parametric scenario case-based simulation arena for future computer simulation studies to be performed at such locations. It also demonstrates the model's ability to evaluate performance in terms of operational and economic feasibility predictions for future planned system installation sites.

Regarding the second research objective concerning **rural village microgrid demand side modelling**, the journal paper** in Prinsloo *et al.* [230] characterises energy consumption models representing rural Sub-Saharan Africa village conditions. It uses a scoping study to determine off-grid baseline load profiling for non-electrified and first-time electrified rural communities on the basis of an analysis of the relevant data from literature [230]. This aspect of the research continues in the journal paper featured in Prinsloo *et al.* [229], which describes the development of the load profile generator based on the electrical signature of appliance devices.

Regarding the third research objective on **conceptual rural Smart Village microgrid platform modelling**, Chapter 3 reports on the implementation of Smart Grid-type intelligent computational techniques to optimise resource utilisation and maximise balanced energy delivery in the energy network of a rural village [231]. The concept originates from an associated journal paper in Prinsloo and Dobson [232] with the poster presentations in Prinsloo and Dobson [233] and Prinsloo *et al.* [234] presenting these ideas. The focus of these publications is on developmental options for the rural Smart Village microgrid. This study investigates the potential solutions towards establishing an intelligent, smart microgrid topology for a micro-utility energy system through the integration of the SUN hybrid micro-cogeneration [235]. The digital parametric engineering model representation of the cogeneration system in Prinsloo *et al.* [225] enables this system to be modelled as anchor generator in the Smart Village microgrid platform.

With the focus remaining on the objective of **conceptual rural Smart Village microgrid platform modelling**, this dissertation advances an enterprise-oriented Smart Village microgrid concept based upon a self-organising paradigm. These ideas were sourced from findings presented at the IEEE Global Humanitarian Technology Conference, and detailed in the IEEE proceedings paper** and poster presentations of Prinsloo *et al.* [236] and Prinsloo *et al.* [237] respectively, where Ubuntu-type rural lifestyle principles were blended with re-configurable price-reaction type energy management and demand response concepts. The published journal paper in Chapter 4 continues with the investigation into the adoption of distributed market-based transactive control techniques in a system for decentralised generation. This was done to create opportunities for cooperative customer engagement in microgrid supply/demand coordination, and was accomplished through multi-choice buying decisions by customers. Methods are investigated to operationalise this concept of the transactive energy system towards the goal of more advanced microgrid control based on the modern Smart Grid automated

**Not as Chapter due to PhD length restriction

**Not as Chapter due to PhD length restriction

control platform.

This study continues the investigation towards modelling the **conceptual Smart Village microgrid platform** in the research paper of Chapter 5 where the research implements algorithmic formulations, using a distributed market-based control approach with programmable intelligence towards a future smart cyber-physical energy system. The research paper presents an *agent-based resource coordination system* where an agent-based smart village energy enterprise is modelled through the mathematical formulation of discrete transactive market-based principles (resource allocation, the multi-agent approach to systems modelling, machine to machine, distributed automation, energy management). Other co-authored engagements and publications in support of the research include the contributions to the cyber-physical systems model in Asare *et al.* [163], the development of a GIS platform module for an environmental impact analysis of the solar PV system in Prinsloo and Prinsloo [238], and a techno-economic analysis for battery storage in rural village energy systems in Uddin *et al.* [239].

This study closes with a summary of the research in Chapter 6. This chapter includes an extensive discussion of the findings, general conclusions, as well as the strategic research conclusions pertaining to the present study. It also includes a summary of contributions and directions for further research.

# Chapter 2

# Solar Micro-CHP Model Design and Analysis

**Paper:** Prinsloo, G.J., Dobson, R.T., Mammoli, A.A. 2016. Model based design of a novel Stirling solar micro-cogeneration system with performance and fuel transition analysis for rural African village locations. *Solar Energy*, 133, 315-330 [240].

## 2.1. Introduction

Open innovation humanitarian initiatives such as the Alliance for Rural Electrification [241] and the Smart Village Program [99] have been calling on engineers to engage in the design and development of custom designed small-scale sustainable energy and micro-CHP solutions for isolated off-grid locations. In terms of design orientation, this includes conceptual energy models for balancing renewables in energy transition regimes and design configurations that redirect rural infrastructure towards low-carbon energy transitions.

The proposed computer model explores the performance, feasibility, and fuel transition effects for the solar micro-combined heat and power system in terms of electricity and hot-water generation as well as fuelwood replacement at various locations in Southern Africa. This forms part of Objective 1 and is supported by additional publications, particularly in Prinsloo *et al.* [225]. The full introduction to this paper can be found in Prinsloo *et al.* [240].

## 2.2. Model for Custom Designed Micro-CHP System

To help overcome barriers to solar energy utilisation in isolated off-grid indigenous rural villages in Africa, the Solar Thermal Energy Research Group (STERG) at the Stellenbosch University have been designing a novel packaged solar Stirling cogeneration system to enable renewable energy access for low-income isolated rural areas. This standalone solar micro-CHP powerpack is capable of delivering around 1 kW power and 3 kW heat. With the addition of energy storage and adaptive digital control automation, the unit aims to achieve a 100 % renewable energy goal in isolated off-grid rural village microgrid and mini-grid configurations. This section introduces the basic elements of the newly designed solar micro-CHP system and its computer model in a model based design approach.

### 2.2.1. Solar micro-CHP model based system layout

Numerical simulation models capable of predicting the performance of the solar micro-CHP system and forecasting the resulting fuel transitions at specific off-grid rural locations are required. Funder approval ratings generally depend on location-based suitability of newly proposed solar technologies for remote area applications to help overcome barriers in the adoption of renewable energy technology in Africa. Convincing projections should be system specific, site specific, and dimension specific, making it expensive to base techno/socio-economic projections on physical pilot projects at isolated rural sites. This makes the NREL system developer proposal towards a model layout for quantitative assessment measurements in a model based design simulation approach very attractive to champion a developmental project.

Figure 2.1 gives a block diagram representation of the solar micro-CHP model. Here the "solar tracker subsystem" comprise of the point-focusing parabolic solar reflector and mechatronic solar tracking elements (two-axis motorised solar dish tracking). The "energy conversion subsystem" comprise of a Stirling micro-CHP engine with integrated waste heat recovery element. The "energy storage subsystem" includes thermal energy and power storage components that feed into the electrical and thermal distribution lines of a multi-carrier microgrid. The storage subsystem assists with balancing of demand and supply, which is critical in maximising operational efficiency and maintaining microgrid energy stability. Proper sizing of microgrid thermal energy storage and battery energy storage (battery bank, fuel cell) for rural electricity energy buffering is dealt with in separate papers to detail the shifting and smoothing of generated and consumed energy profiles.

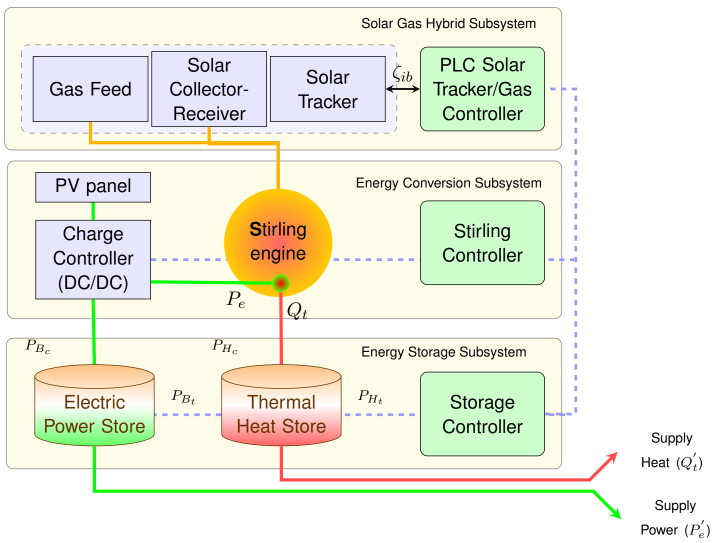



**Figure 2.1:** Block diagram representation of the model based design for the hybrid solar/gas micro-CHP system with added microgrid energy storage and sub-system components.

In the solar micro-CHP system of Figure 2.1, the solar receiver feeds solar energy into a hybrid micro-CHP Stirling unit manufactured by the Migrogen Engine Corporation (MEC) [242].This linear free piston Stirling engine (LFPSE) micro-CHP system has the ability operate in both *solar-mode* and *gas-hybrid-mode*. To accommodate the gas-hybrid-mode, the system includes an external gas-fired generation unit that allows for biogas or liquefied petroleum gas (LPG) as fuel. In the gas-hybrid-mode, the unit operates from a fixed thermal source to generate energy at unit capacities of 1 kW electrical 3 kW thermal. Its ability to meet domestic hot water demand from recovered waste solar heat makes the combined-cycle generation system a suitable technology selection for micro-power generation and residential hot water supply in community solar projects. Typical District Heating Systems can cover large areas, even entire cities (e.g. Stockholm), and are widely used across Europe since it features prominently in their energy policies. The distribution networks required in the case of this research is relatively small (village distribution network of 20-30 meters) and makes use of insulated pipes (about 25 mm diameter) that can either feed directly or make use of a heat-exchanger. A direct feed model is much more practical and is also used here.

Analytical modelling is a crucial element of system performance evaluation before engaging in costly exercises such as the manufacturing and deployment of newly designed micro-CHP systems at remote rural sites [243]. With a flexible model based design approach the performance and fuel transition effects of the experimental solar micro-CHP system can be theoretically predicted and evaluated at any arbitrary isolated off-grid rural microgrid location in Africa before the system is deployed in the field. A smart microgrid energy management and control automation architecture for renewable energy-based rural electrification systems are also being developed in collaboration with the Centre for Emerging Energy Technologies (CEET) at the University of New Mexico in the USA. Aspects of this control solution is described in a separate paper [231] and includes the functionality and intelligence to optimise solar micro-CHP storage capacity and operational costs in Figure 2.1, while balancing demand side load and supply generation in distributed energy resource based microgrids.

### 2.2.2. TrnSys simulation model for solar micro-CHP system

In this paper, the TrnSys 17 software simulation platform is chosen as basis for numerically characterising the solar micro-CHP design [244]. TrnSys is a flexible model based transient thermodynamic and electrical system simulation platform in which the user can specify components to constitute the system and the manner in which elements are connected. This platform is attractive for the design and modelling of micro-CHP systems as it includes libraries that describe most components regularly used in the characteristics of exergy-entropy processes for thermodynamic and electric energy systems [245]. The TrnSys model and objects are used to simulate location sensitive generation capacities for the standalone solar micro-CHP system intended to serve low-income communities through it's operation at off-grid rural villages in remote isolated regions of Africa.

Figure 2.2 shows the basic information flow diagram type layout of the micro-CHP system modelled using the TrnSys simulation software platform to determine location-specific micro-CHP performance data. It shows the functional objects for the parabolic dish tracking system, the linear free piston Stirling engine, and the TrnSys solar and meteorological weather data input components. TrnSys types as well as components that are not part of the standard software library types, such as Annex 42 models, are available for concentrated solar system components [246].The TrnSys platform further includes the component routines necessary to handle real-time pilot project characteristic inputs of solar irradiation and weather data for various locations throughout the world.

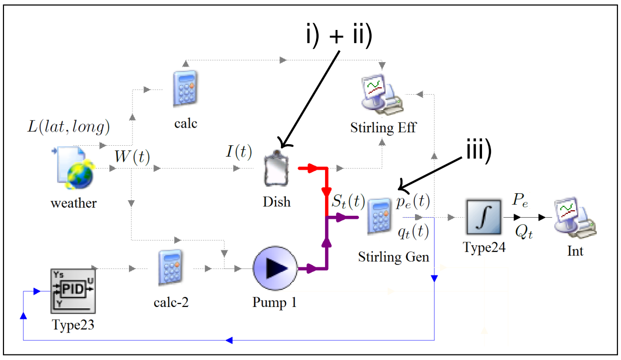



**Figure 2.2:** Proposed TrnSys model for our current solar micro-CHP powerpack.

Figure 2.3 further details the micro-CHP model through a sequential energy and information model flow diagram that includes a list of the prominent parameters, inputs and outputs for each of the TrnSys simulation model components. It shows the model characteristics for each of the micro-CHP components with sets of parameters that need to be specified during the model configuration phase. TrnSys use parameters along with components interactions to generate a set of digital numerical outputs as thermal and electrical energy outputs for the overall solar micro-CHP system.

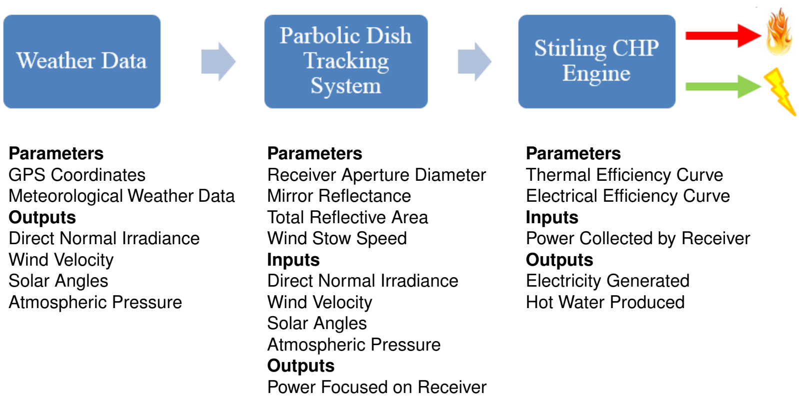



**Figure 2.3:** TrnSys sequential model flow diagram for solar micro-CHP powerpack.

Outputs from the "Weather Data" block in Figure 2.3 (i.e. energy atlas solar direct normal irradiance (DNI) I(t) in Figure 2.2), are inputs for energy conversion in the "Parabolic Dish Tracking System". This component uses the inputs received from the weather module W(t) in combination with its own characteristic set of parameters to generate a set of outputs. Outputs from this component become inputs to the "Stirling CHP Engine" $S_t$(t) to produce a set of Stirling electrical $p_t$(t) and thermal $q_t$(t) energy outputs. This exchange of signals are repeated by TrnSys at every time step of the simulation (incremental time steps $\Delta t = 36$ seconds) over the entire time-frame horizon of the simulation study. A summary of the list of parameters for each of the TrnSys components of the solar micro-CHP powerpack are presented in Table 2.1.

**Table 2.1:** TrnSys model parameters for solar micro-CHP system components.

| **Weather File** | **Parameter** |
|---|---|
| Data Source | Meteonorm |
| Simulation Location | GPS location |
| **Parabolic Dish** | **Parameter** |
| Dish Diameter | 3.75 m |
| Aperture | 9.58 m$^2$ |
| Ratio of Focal point/Diameter | 0.6 |
| Mirror Reflectance | 0.94 |
| **Stirling CHP Engine** | **Parameter** |
| Type | Free Piston Stirling |
| Designer | Microgen (MEC) |
| Electrical Output | 1 kW |
| Thermal Output | 3 kW |
| Transfer Function Equations | [242] |
| Annual Electrical Efficiency | 12 - 14 % |
| Annual Thermal Efficiency | 36 - 42 % |
| Receiver Diameter | 0.2 m |
| Receiver Distance from Focus | 3.75 m |
| Receiver Thermal Efficiency | 90 % - 95 % |

Table 2.1 includes the modular parameter specifications together with a description of each of the main components of the TrnSys model. The TrnSys parabolic dish tracking system component in Figure 2.2 and Table 2.1 is representative of the governing equations for the reflective parabolic dish and mechatronic control platform tracker. It simulates the actual refractive fresnel parabolic dish assembly optics and solar tracking precision control architectures [227]. It derives the amount of energy focussed onto the Stirling engine receiver head $S_t$(t) from the solar DNI I(t) it receives as input from the TrnSys weather forecast data file W(t).

The combined heat and power Stirling engine in Figure 2.2 and Table 2.1 uses concentrated solar power as a fuel source to generate electricity and heat in the form of hot water. In terms of mathematical notation, the Stirling engine component calculates the amount of thermal $q_t$(t) and electrical $p_e$(t) power output by the system at each time step. The Stirling engine and waste heat recovery calculations are based on the inputs received from the parabolic dish component and the performance curves from the engine developer [242]. The governing functions for the thermal and electrical performance and efficiency curves for the isothermal Stirling engine component are essential parameters that describe the functional operation of the Stirling engine during operation. The equations for these functions have been programmed into the customised TrnSys model dish Stirling user type for this component, but due to publisher copyright and proprietary confidentiality restrictions, these functions and curves are not illustrated in this paper.

In terms of active solar water heating, waste heat recovered from the Stirling engine to generate hot water during its power generation activity. Pump 1 in the TrnSys model of Figure 2.2 performs this function by circulating cooling water as heat-transfer fluid through the Stirling engine at variable flow rates. The pump is controlled by the TrnSys Type 23 PID control block, which essentially regulates the heat transfer fluid flow rates based on the temperatures of the cooling water at the Stirling engine outlet. In the TrnSys model, Equations 2.2.1 and 2.2.2 is applied to calculate the annual power and useful thermal energy generated by the solar micro-CHP system for each of the selected village locations. The results are discussed in Section 2.3.1.

$$P_e = \int_{t=0}^{N} p_e(t)\, dt \tag{2.2.1}$$

$$Q_t = \int_{t=0}^{N} q_t(t)\, dt \tag{2.2.2}$$

where:

$P_e =$ total aggregated annual electrical energy generated (kWh)
$Q_t =$ total aggregated annual thermal energy generated (kWh)
$p_e(t) = t^{th}$ time electrical energy variable (instantaneous electricity supply (kW))
$q_t(t) = t^{th}$ time thermal energy variable (instantaneous thermal supply (kW))
$N =$ total hours in annual simulation ($8760$ hours per year)

During operation, the TrnSys model uses weather data W(t) and direct normal incident radiation data I(t) based on global positioning system (GPS) coordinates in the simulation model of Figure 2.2. Weather prediction data sets from Meteonorm data exchange are considered a comprehensive meteorological reference, especially for site locations where actual measurements were taken by weather stations [247]. In cases where weather information may not be available for a specific location L, the weather patterns for a measuring station in closest proximity to that location is used. Meteonorm weather data are suitable for use as a TrnSys model function input to simulate the output of the micro-CHP model with the TrnSys mathematical model. The overall TrnSys model thus allows us to follow a virtual reality simulation approach to investigate the adaptive capacity of the micro-CHP combined-cycle solar system in peak supply planning and fuelwood energy resilience in the midst of long term fuelwood supply decline in Africa.

$$H_x = \left[\frac{P_e}{P_l}\right] \tag{2.2.3}$$

where:

$H_x =$ estimated rural village size (nr. households service capacity)
$P_e =$ annual electricity production of micro-CHP per location (kWh)
$P_l =$ estimated annual energy demand per rural household (kWh)

Given the performance for deployed solar micro-CHP systems, rural users also need to know the service capacity of the micro-CHP system. In this analysis, Equation 2.2.3 is applied to compute the average number of rural households that the micro-CHP system can supply with electricity in a single village. This computation is based on the estimated annual electricity supply and demand for a single household at that location as discussed in Section 2.3.2.

### 2.2.3. Energy transition analysis with micro-CHP system

Africa's contribution to global greenhouse gas (GHG) emissions per capita is much smaller than most of the other continents, but there is growing concern that the impacts of climate change are disproportionately affecting Africa's food and agricultural lifeline. Due to high consumption rates, the long-term supply of firewood in sun-Saharan Africa is further in jeopardy. In this context, system impacts can be studied using context sensitive simulation coupled modelling narrative approaches [248]. Energy transition engineering practitioners design for sustainability through audited stock-taking of current system design and operation to quantify the environmental risks through forward planning. The Global Association for Transition Engineering (GATE) further advocate policy regulation standards for changing fuel systems towards sustainable solutions (solar lighting, solar heater, solar domestic hot water, solar geyser, solar cooking) to avoid disaster management with catastrophic climate change impacts.

Presently, most indigenous rural African villages use fossil fuels for lighting and fuelwood as main source of energy for cooking, water boiling and space heating While the logistics of fossil fuels makes it expensive (often transported by taxi), natural fuel resources (fuelwood, biomass, wood chips, crop residues, animal dung, perennial grasses, perennial woody) are being depleted at unacceptable high rates [249]. In the absence of sustainable nature conservation and fuelwood production, over utilisation will totally deplete woody biomass resources. While wood and charcoal supply the majority of rural energy needs, solar energy is seen as solution towards sustainable development in the transition towards a low-carbon economy. A concerted and coordinated effort from distributed solar micro-CHP systems would help to reduce wood removal, constrain biomass harvesting and limit fuelwood use to cooking. Such clean energy replacement solution will accelerate forest and nature restoration as well as preservation of plants and trees in eco-systems such as villages, national parks and reserves.

International, regional and rural electrification authorities would therefore be interested to evaluate projections on the solar micro-CHP capabilities in terms of meeting thermal energy demands and hot water requirements for typical rural native African villages [250]. These typical village profiles are detailed in Chapter 6.2.2.Therefore, Equations 2.2.4 and 2.2.5 is formulated to calculate the amount of fuelwood that can be replaced by solar micro-CHP hot water production.

$$E_h = S_m \times c_p \times \Delta T \tag{2.2.4}$$

$$W_h = \left[\frac{E_h \times 100}{NCV_0 \times (100 - \mu_{wood}) - 2440 \times \mu_{wood}}\right] \times \frac{100}{\eta_{fire}} \tag{2.2.5}$$

where:

$NCV_0 =$ energy equivalence NCV for dry fuelwood (19000 kJ/kg)
$E_h =$ total energy required to increase the water temperature (kJ)
$W_h =$ total mass of wood required to heat water (kg)
$S_m =$ mass of hot water produced by Stirling engine per year (kg)
$\Delta T =$ defined water temperature increase (°C)
$c_p =$ specific heat capacity of water (4.186 kJ/kg°C)
$\mu_{wood} =$ estimated moisture content of fuelwood (%)
$\eta_{fire} =$ heat transfer efficiency of open wood fire (i.e. 5 % [251])

Given the importance of wood fuel, Equations 2.2.4 and 2.2.5 are valuable elements in studying fuel transition affects of the current solar micro-CHP system within the context of fuel usage in the domestic energy use ladder for a rural African village. The energy or fuel transition prediction results will be detailed in Section 2.3.3 where graphs illustrate how waste energy management can effect fuelwood saving for a number of rural villages in Africa.

In summary, TrnSys simulations for our solar renewable energy micro-CHP system can now be used to navigate developers through performance evaluation of the micro-CHP system in a virtual desktop environment by running computer simulations for various hypothetical rural locations in Africa. Since the characteristic models integrate TrnSys weather forecasts from weather station locations worldwide, the simulated performance provide realistic and accurate predictions about thermal and electrical power generation. Generation capacity of this system will be GPS location sensitive and based on the available solar resource in each of these regions. The discrete digital TrnSys models is also ideal for microgrid and distributed generation power system design and micropower optimisation in standalone power systems (SAPS or SPS) for tactical power, safari cottages, private lodges, game and nature reserves or remote area power supply (RAPS) applications in Africa.

## 2.3. Performance and Fuel Transition Experiments

This section details case-based simulation scenarios wherein the proposed TrnSys parametric model for our solar micro-CHP unit will be used in a soft-computing approach to evaluate the dynamic system performance at different locations in Southern Africa. The aim of these experiments are to use computer simulations to predict the performance of the solar micro-CHP system at isolated off-grid rural microgrid locations in Africa to forecast the potential generation capacity with associated energy and fuel transitions that can be affected with solar as pre-dominant power source at each location.

This paper mainly considers the micro-CHP outputs in Figure 2.1, meaning the assumption is made that the hot water and battery energy storage is 100 % efficient and of sufficient capacity to transfer the full solar renewable energy charge into later hours of the day as per village load demand cycles. The energy storage elements will later be incorporated into the microgrid cost optimisation solution, where it will serve as grid stabilising generator to improve the network's risk tolerance and energy flexibility as part of power flow and hot water draw optimisation [231].

### 2.3.1. Solar micro-CHP energy generation capacity

In this experiment, a rural village near Giyani in the Limpopo Province of South Africa is used as a typical reference site. Such a reference site may for example have been identified as a potential target site for deployment of micro-CHP systems as part of a rural off-grid energisation project. Viability decisions in terms of selecting this particular solar cogeneration system for a rural upliftment project generally depends on an a-priori confirmation of the generation capacity and potential fuel transition requirements that should be effected by a micro-CHP system at the target village location.

By using the Giyani rural area as a reference site, it is possible to determine the power outputs ($p_e$(t) and $q_t$(t)) of the solar micro-CHP model from TrnSys solar DNI and weather pattern data W(t) for this northern part of the Limpopo Province. Figure 2.4 shows the TrnSys model simulated micro-CHP output energy curves for a single week in March, computed in simulation time increments of 0.01 hours ($\Delta t = 36$ seconds) for the Giyani area.

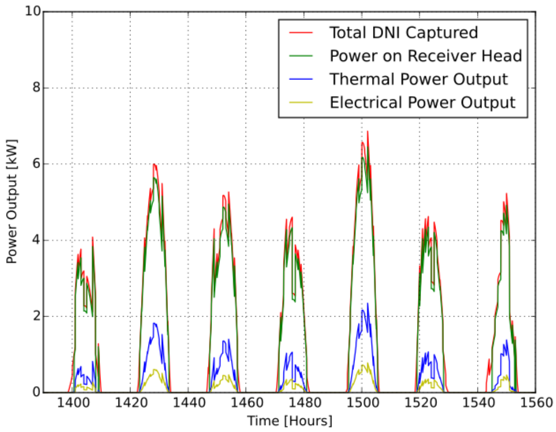



**Figure 2.4:** Simulated power output for the Stirling micro-CHP system for a week in March. Region: Giyani, Limpopo Province, South Africa (23 16'49.5"S 30 42'13.2"E).

The red and green time-series plots in Figure 2.4 represent the solar resource characterisation and solar energy flows in the "Weather Data" and "Parabolic Dish Tracking System" components of the TrnSys model of Figure 2.2. The blue and yellow time-series plots represent the simulation predicted thermal and electrical energy outputs of an autonomous micro-CHP unit at that location, as computed by the TrnSys "Stirling CHP Engine" component. The production for this week in March represents the typical 8th week of the year for the Giyani rural African site (Autumn season in Southern Hemisphere).

More specifically, the red plot in Figure 2.4 represents the instantaneous amount of direct normal irradiance (DNI) energy I(t) in kW that is theoretically available for solar collection by the parabolic dish when operating under the TrnSys predicted weather conditions W(t) for the chosen hours and days in March. This graph reflects the available amount of solar DNI collected at that particular location site L(lat,long). These are computed from the instantaneous time dependent TrnSys weather data W(t), in combination with the parabolic dish reflective area (9.58 $m^2$). The green plot in Figure 2.4 represents the instantaneous concentrated solar energy time sequence and shows the solar energy collected by the parabolic dish and focused onto the Stirling engine receiver head $S_t$(t) in kW at any given time.

Of particular importance to this study is the blue and yellow graphs in Figure 2.4. The blue graph represents the predicted instantaneous electrical power generated by the TrnSys Stirling engine model $p_e$(t) for that particular site. The simulated values are computed from the TrnSys model at regular time intervals ($\Delta$t = 0.01 hours). The yellow graph in Figure 2.4 represents the TrnSys predicted instantaneous waste heat output collected $q_t$(t) from the Stirling engine during the power generation operation using the time step ($\Delta$t). The instantaneous waste heat collected graph $q_t$(t), thus reflects the energy value for the thermal energy that is potentially available for water heating at this particular target village location L(lat,long).

In general terms, the TrnSys simulated time-series outputs given in Figure 2.4 represents the energy output profile for an individual solar micro-CHP system installed at a specific hypothetical target location in Africa. It illustrates how the TrnSys simulation model can generally be used to determine the prospective instantaneous electrical power $p_e$ and thermal energy $p_t$ output of the micro-CHP system at any particular time instance and location. In the same way, the TrnSys model simulations in Figure 2.4 can further be used to simulate the daily energy output time-series for all 52 weeks of the year (365 days of the year, 0-8760 hours). Then, by applying the mathematical expressions formulated in Equations 2.2.1 and 2.2.2 to integrate the instantaneous thermal $q_t$(t) and electrical $p_e$(t) energy output sequences over time, the TrnSys model is able to estimate the total aggregated annual thermal energy $Q_t$ in $kWh_t$ and electrical energy $P_e$ in $kWh_e$ generation potential for the solar micro-CHP system at any particular location site L(lat,long) in Africa.

In this way, the application of the TrnSys simulation model is extended to compute the cumulative annual energy harvesting outputs of standalone solar micro-CHP units for a number of hypothetical installations at rural sites throughout Southern Africa. The site specific cumulative annual micro-CHP energy output simulated results for a number of rural African sites are presented in Figure 2.5. In this illustration, the blue bars represent the aggregated annual amount of electricity ($P_e$) generated by the micro-CHP system at each of the different listed locations in Southern Africa. On the same graph, the red bars represent the aggregated annual thermal energy generated ($Q_t$) by the Stirling micro-CHP system at the same locations.

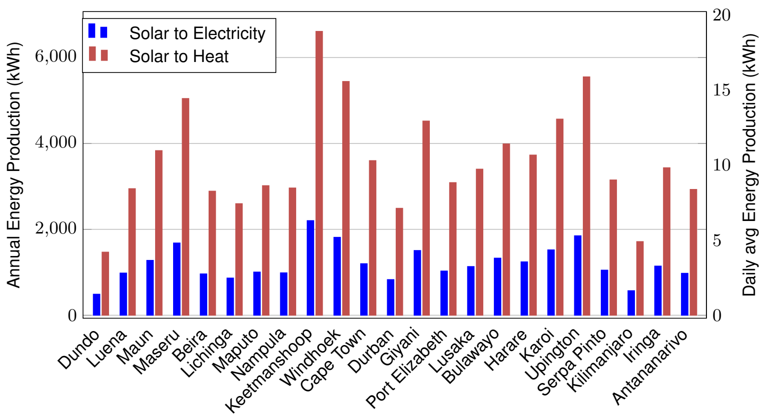



**Figure 2.5:** TrnSys simulated solar micro-CHP hot water and electricity generation for selected rural locations in Southern Africa. Units in $kWh_e$ (blue) and $kWh_t$ (red).

In general, the amount of energy generated by the system will increase in areas with a higher DNI exposure since those sites essentially have more "solar fuel" available. Moreover, from the TrnSys operating curves of the Stirling CHP engine it is known that a higher DNI exposure will also increase the overall system efficiency of the Stirling engine [242], thus allowing for more of the solar DNI to be converted into useful energy (exergy). Results in Figure 2.5 therefore show that the generation capacity for the micro-CHP system is fairly low in the northern parts of Angola where the DNI is fairly low. The low DNI exposure can force the electricity generating efficiency of the Stirling engine component down to about 10 % in extremely low DNI site cases like this. On the contrary, system integration at rural locations around Keetmanshoop in Namibia where the solar DNI is high, the Stirling engine electricity generating efficiency increase to levels around 15 %.

The unfolding of the energy transition to renewable electricity generation (wood fired to solar electricity and hot water generation) of solar micro-CHP can be viewed in terms of the spatial dimension. Figure 2.6 shows a national geographic information system (GIS) bubble map representation of the site specific micro-CHP electrical power $P_e$ and thermal energy $Q_t$ capacity for the locations listed in Figure 2.5. The respective green and red bubble sizes on the Southern African map depict the annual electrical and thermal generation capacity of the TrnSys modelled micro-CHP system at each of the GPS location coordinates. Energy generation at some of the selected sites may be constrained by limited availability of primary energy resources, but these effects are inherently considered in the model outputs since annual Meteonorm weather data is used in the TrnSys model. The size of the bubbles on the map gives reflects the generation capacity of the micro-CHP system at that location, while the numerical value represents the daily amount of $kWh_e$ generated for that region. The amount of thermal energy ($kWh_t$) generated is represented by the size of the red bubbles and is typically around three times that of the electrical energy.

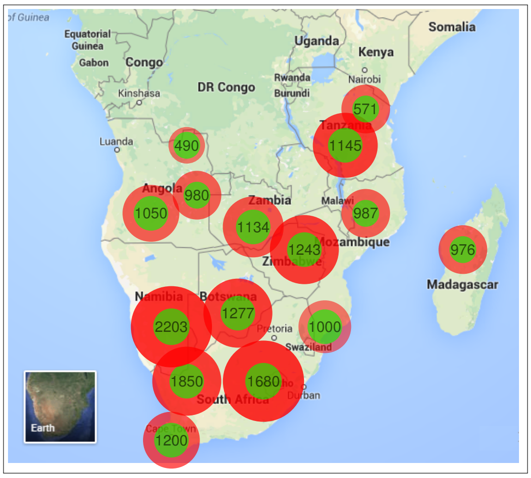



**Figure 2.6:** Potential energy harvesting capacity for a standalone solar micro-CHP at each Southern African location in Figure 2.5 (red = $Q_t$, green = $P_e$, units = $kWh_e$) (map from [252]).

If more energy is required at any site, then the generation capacity may be extended by stacking additional micro-CHP units (with CPV, HCPV, PV, CCHP, CHCP, biogas) in a microgrid energy distribution configuration at the installation site. The above TrnSys model and simulation results are further useful in decision support system and to identify important micro-CHP system improvements within the specific context and application in rural Africa. In general, intermittent solar generation is challenging for any micro-CHP system since the microgrid supports varying loads and will have difficulties in following varying electricity and heat production. Domestic rural village energy usage mostly occurs outside sunlight hours, meaning buffer energy storage components and digital control scheduling optimisation will still be required in Figure 2.1 to overcome mismatches in time-synchronisation between micro-CHP generation supply and village demand cycles as part of cost and environmental optimisation [231].

### 2.3.2. Solar micro-CHP village size serving capacity

To investigate autonomous micro-CHP serving capacity aspects, the electrical energy $P_e$ requirements are used as a basis for capacity calculations in determining the number of households that could be served by a single installed system in a rural African village. This calculation is site-specific and depends on the village location, solar DNI and weather patterns. For this purpose, the study applied the TrnSys model simulation results in terms of electrical power generation capabilities of the micro-CHP, and related these fuel stacking competitive outputs to the household energy load requirements $P_l$ in a typical rural African village context. This research also draws from experience around a scoping exercise and the development of an off-grid rural village load simulator (Matlab Simulink, Homer Energy, EnergyPlus, EnergyPlan formats) in which archetypal load profile reference models were defined.

Table 2.2 presents the load template for the electricity usage load simulation in a hypothetical newly electrified tribal village consisting of a cluster of five households. In this table, it is assumed that a conceptual rural village in Africa (5 households, 7 people per house) is equipped with a combined total of fifteen indoor lights (9 W each), five outdoor security lights (9 W each), five USB battery chargers for cellphone-charging (4 W each), five radios (0.5 W each), five television sets (20 W each) and two shared refrigerators (50 W each). These conceptual appliances and devices are assumed to be highly efficient with low power consumption. The conceptual load $P_l$ includes light emitting diodes (LED's) with a 9 W power consumption rating for in-door and out-door lighting. The television and radio have power ratings of 20 W and 0.5 W respectively, while the refrigerators are rated at 50 W that run as a normal intermittent load.

**Table 2.2:** Synthetically derived electricity load profile for a conceptual newly electrified rural African village consisting of five households.

| | Rural village energy load | | | |
|---|---|---|---|---|
| **Load Type** | **#/Village** | **Home load (W)** | **Hours/day** | **Load/year** |
| Indoor lighting | 15 | 9 | 9 | 443.5 |
| Security lighting | 5 | 9 | 12 | 197.1 |
| Portable radio | 5 | 0.5 | 16 | 14.6 |
| Television | 5 | 20 | 6 | 219.0 |
| Refrigerator | 2 | 50 | 10 | 365.0 |
| Mobile charger | 5 | 4 | 14 | 102.2 |
| Annual Total | | | | 1341.4 $kWh_e$ |

Table 2.2 shows that the estimated annual electricity load for a hypothetical African village of five households amounts to an estimated value of 1341.4 kWh$_e$. This equates to an estimated P$_l$ = 268.3 kWh$_e$ per household (7-persons), or an estimated annual consumption of 38.3 kWh$_e$ per person. The ratings for electrical load demand P$_l$ together with the site specific micro-CHP electrical power production capacity P$_e$ enable us to estimate the theoretical maximum number of rural households that can be serviced by a single micro-CHP system (village size per rural location in Africa). Since village demand is based on load archetypes listed in Table 2.2 and the micro-CHP supply is based on the TrnSys simulation outputs for that specific location, the TrnSys output can be applied to Equation 2.2.3 to compute the average number of rural households per rural village that the micropower system can optimally supply with electricity. In this regard, an analysis can be made of the micro-CHP village service capacity in the rural region surrounding Giyani in the most northern part of South Africa. From Figure 2.5, the simulated TrnSys model solar micro-CHP electrical generation output for Giyani is known to be around 1500 kWh$_e$. From Equation 2.2.3), the number of rural households per village the solar micro-CHP system is able to serve in terms of electrical energy in rural Giyani is theoretically computed to be about five households (1500/268.3$\approx$ 5). The theoretical village size for any other off-grid rural location can likewise be computed through Figure 2.6.

The waste heat energy output in Figure 2.6 (red bubbles) for the listed locations in Southern Africa can also be equated to a volume of available water heated from waste heat. In the next section, the volume of hot water generated from the waste heat obtained from TrnSys is applied to compute the daily/yearly fuelwood equivalent for daily/yearly hot water production.

### 2.3.3. Solar hot water fuelwood replacement potential

Rural and township electrification projects impact positively on communities in terms of saving energy resources for lighting and entertainment. However, fuelwood remains a prominent source of energy to meet thermal energy needs [253], even if there was an increasing scarcity of wood in the environment around the village [254]. In the sun rich areas of Sub-Saharan Africa, such as Southern and Central Africa, solar energy is a good substitute for wood fuel since unsustainable harvesting and the combustion of fuelwood is aggravating climate change. Micro-CHP provide options for switching fuel to solar and can control harvesting while avoiding overexploitation in open-access forests and woodlands. With micro-CHP substituting wood, biomass and fossil fuel in hot water making, it becomes part of the solution and can be viewed as a $CO_2$ abatement intervention.

The TrnSys outputs in the previous experiment can be used to predict the energy transition affects of the micro-CHP system, and will help to determine the amount of environmentally hazardous fuelwood that rural villagers can save and replace with solar thermal energy at any hypothetical location in Africa. In terms of fuelwood currency and use, open-source reports of the International Energy Agency (IEA) states that fuelwood use per capita per day in countries like South Africa, Botswana and Zimbabwe, is between 2 and 3 kg [76]. For the rural areas in these countries, it means that a typical rural household of 7 to 8 people can collect and consume up to 24 kg of fuelwood per day. For a smaller village consisting of 4 to 5 households, it means that between 56 and 120 kg of wood needs to be collected for the village per day. The United Nations Development Program estimates that women in Sub-Saharan Africa spend around 40 billion hours per year to collect water and wood fuel, which is equivalent to the annual labour of the entire work force of France [255].

These statistics highlight the importance of approximating the micro-CHP thermal energy output in terms of fuelwood equivalent at each pilot installation site in Africa. It would further demonstrate that fuel stacking with solar micro-CHP can help to reduce the need for firewood collection, while valuable time and manpower can rather be applied to eduction and enterprise activities. If only half of the amount of fuelwood usage by a rural African village can be replaced/saved in terms of thermal energy for hot water production by the solar micro-CHP system (recovered waste heat from electricity generation), then the system would have a tremendous impact on energy fuel transition and education within the village [256].

As such, there is a special interest in the fuelwood replacement potential of the solar micro-CHP system for those fuels used in thermal heating applications at specific rural African villages. In general, the site specific thermal energy generated by the solar micro-CHP system in Figure 2.5 can be equated to traditional fuels and biomass. In order to relate the fuelwood requirements to micro-CHP hot water production, one needs to calculate the amount/mass of fuelwood that would typically have been used to increase water temperature by the same amount. The volume of hot water generated by the micro-CHP system can be obtained from the TrnSys model by way of integrating the flow rate of the hot water exiting the Stirling engine. For the rural reference site in Giyani, this simulated value for the total annual amount of hot water is computed at $S_m$ = 42519.9 kg of fuelwood replaced.

In order to make the comparison between the amount of wood that would typically be used to bring about the same increase in water temperature, it was first needed to determine the amount of energy required for this increase. In this regard, Equation 2.2.4 computes the energy required to heat the total amount of water output from the TrnSys simulation model $S_m$. Equation 2.2.5 then use this cumulative energy harvest to compute the total mass of fuelwood $W_h$ that would be required to replace the annual volume of hot water generated by the solar micro-CHP (in terms of the TrnSys simulation).

To compute the required energy $E_h$ to heat water to the same levels as the solar micro-CHP (Equation 2.2.4), the specific heat capacity of water ($c_p$) is taken as 4.186 kJ/kg°C. Equation 2.2.4 further requires a setting on the increase in water temperature ($\Delta T$) that occurs as a result of the Stirling waste heat recovery process. The hot water temperature difference is set at $\Delta T = 40°$C, that is assuming that the micro-CHP Stirling heats cooling water from an ambient temperature of $\Delta T = 20°$C to a preset temperature of $\Delta T = 60°$C.

With $E_h$ available from Equation 2.2.4, the mass of fuelwood required/saved to heat water to the same levels as the solar micro-CHP is then computed using Equation 2.2.5. The heat transfer efficiency of an open wood fire in the final term of the equation is set at $\eta_{fire} = 5\ \%$. This efficiency level is taken to be equivalent to that of the so called "three stone stove" [251].

Equation 2.2.5 further requires the energy equivalence or net calorific value (NCV) of the fuelwood. Table 2.3 provides information from the Wood Fuels Handbook [257], which indicates the NCV energy equivalence values for wood at different moisture content levels. The energy equivalence or NCV value for fuelwood in Table 2.3 is essentially a linear function of the percentage of the moisture content $\mu_{wood}$ of the wood. The moisture content is expressed in terms of water present in the wood in relation to the mass of fresh wood. The function starts with the NCV for dry fuelwood ($NCV_0$ = 19 MJ/kg) from where the NCV for fuelwood decreases linearly from $M_0$ = 19 000 kJ/kg by about 2160 kJ/kg i.e. 0.6 kWh/kg for every 10 % increase in timber wood moisture content $\mu_{wood}$.

**Table 2.3:** Energy equivalence for fuelwood logs at different moisture content [257].

| Energy equivalence - fuelwood | | |
|---|---|---|
| **Moisture content (%)** | **NCV (kJ/kg)** | **Energy (kWh/kg)** |
| 15 % | 15 360 | 4.27 |
| 20 % | 14 310 | 3.98 |
| 25 % | 13 270 | 3.69 |
| 30 % | 12 220 | 3.4 |
| 35 % | 11 170 | 3.11 |
| 40 % | 10 120 | 2.81 |

The estimated fuelwood replacement results for the various locations in Africa are shown in a GIS type site specific bubble map display in Figure 2.7. In this figure, the yellow bubbles on the map represents the relative amount of fuelwood that could hypothetically be saved per day ($W_h/365$) for each solar micro-CHP installation at each of the listed rural African sites given in Figure 2.5. These site locations correspond to the listed locations in Figure 2.5.

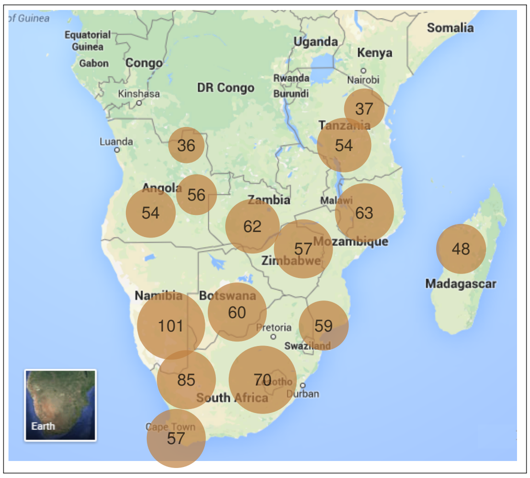



**Figure 2.7:** Daily fuelwood replacement potential for a standalone solar micro-CHP at each Southern African location in Figure 2.5 (brown=fuelwood, units=kg wood) (map from [252]).

Figure 2.7 emphasises the fact that the typical saving of fuelwood $W_h$ per solar micro-CHP unit installation for hot water generation can vary from 36 kg to 100 kg per day in Southern African countries. This equates to the conservation of between 13 and 36 tons of fuelwood per annum for each individual village to make hot water. This is a significant amount of wood considering that it requires hours of strenuous labour by women and children under dangerous and hazardous conditions to cut and collect this source of fuel on a daily/weekly basis (often logging larger tree branches and wooden stumps for charcoal and biochar production in open-fire instead of kilns).

Applying Equation 2.2.5 to our reference rural site at Giyani, the average amount of fuelwood saved for hot water generation amounts to approximately 78 kg per day (28 600 kg per year for each installed solar micro-CHP system). In the drought-stricken regions of Africa where woman and children typically collect wood, the fuel switching potential of a green energy solution like our solar micro-CHP would save a group of 4 women (or girls) about 4 to 5 hours of gathering wood. The solar system can thus be a transformation driving force that helps women avoid the logistics of having to walk or wheelbarrow distances of 2 to 8 km at a time to move wood or carry woody biomass loads of 20 to 25 kg each [253], not to mention the heath damages and degradation due to smog inhalation and acute massive exposure to smoke and greenhouse gas emissions from dirty fuels in open-fires and in-efficient cooking stoves [258].

From a methodological point of view, simulations allow us to determine *cumulative annual* fuelwood replacement potential while Equation 2.2.5 further provides the basis for energy density calculations that approximate the site-specific annual mass of fuelwood saved. From this formula, the numerical values were obtained, shown in the green bubbles of Figure 2.8, which represents the annual cumulative kilogram weight of fuelwood saving $W_y$ for a single micro-CHP to make hot water at each selected location. In this illustrative case, the underlying color map in Figure 2.8 represents the individual African countries in different color shading, each color shading reflecting the percentage of population in that African country that still uses solid fuels (such as fuelwood or charcoal) for cooking and water heating purposes [250].

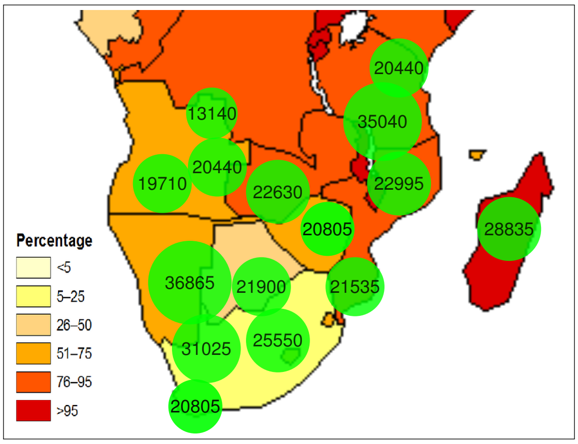



**Figure 2.8:** Annual fuelwood replacement potential (kg) for micro-CHP superimposed on map indicating % of total population still using solid fuels in Southern Africa [250].

Given the importance of fuelwood in rural African villages, the context around the percentage of the population who still make use of solid fuels if Africa gives additional impetus to the results. The numbers are striking and place the spotlight on the fuelwood demand as well as the solar supply in terms of the annual cumulative amount of fuelwood ($W_y$) that can be saved through a single standalone solar micro-CHP installation. This African country map representation together with the annual potential for fuelwood replacement potential, stress the importance of solid fuel and fuelwood replacement with associated $CO_2$ stabilisation at rural areas and forests of African countries such as Zimbabwe, Mozambique, Tanzania and Namibia.

Other examples include Zambia, where a single solar micro-CHP system can annually replace around 22 tons of fuelwood per rural village. Such impact on time allocation and daily routine in village households leaves more time to overcome skill shortages through children and adult education and training. Similarly, a rural village in Madagascar equipped with a solar micro-CHP would theoretically be saved the effort to collect around 28 tons of fuelwood per year. Again a massive amount of fuelwood for rural Madagascar where the WHO map shows that more than 95 % of the country's population have to collect solid fuels (fire wood or dung) to sustain their daily energy requirements [250]. When wood fuel harvesting exceeds wood growing accumulation rates, the effect would be disastrous to these rural populations.

From an environmental point of view, harvesting wood fuel at unsustainable high rates can lead to ecological disasters. Madagascar has for example exhausted approximately 90 % of its original biomass since the extinction of the dodo [259]. By controlling harvesting and limiting biomass extraction for fuel with the help of solar, micro-CHP can help reduce forest and woodland degradation in villages and surrounding plantations. Thus, apart from reducing the burden of wood fuel collection, an appropriate technology such as solar micro-CHP can further have a tremendously positive environmental impact in terms of the prevention of fuelwood depletion and mitigating catastrophic deforestation damage [260]. As an indirect nature conservation solution, solar energy will help to preserve the natural habitat (woody biomass, plants and trees) around rural villages.

### 2.3.4. Business/economic prospects for solar micro-CHP system

From an energy business viability perspective, energy sustainability and energy access in a growing world population is of increasing importance. In this regard, the National Planning Commission of South Africa has developed a National Development Plan for renewable energy [261]. Herein, solar renewable energy has been identified for strategic infrastructure projects and seen as a suitable natural resource to drive local economic development [249]. The local availability of solar resources and the fact that solar micro-CHP can help overcome political energy service delivery challenges faced by rural councils [262, 263] will help this technology to gain momentum as preferred technology choice.

Government subsidies, tax deductions and carbon credit incentives further create special economic, technology transfer and commercialisation opportunities for the solar micro-CHP system. Such opportunities motivated our team to look into the economic manufacturing prospects of the present micro-CHP system. One of our research team members [264] developed a feasibility study and business plan for the manufacturing of the proprietary solar Stirling micro-CHP system, as this system may be selected as one of the first affordable plug-and-play type solar cogeneration kit assembly design to be used as standalone solar powerpack technology for remote off-grid indigenous rural villages. The financial viability of prosumer based power supply units is generally gauged in terms of available government funding and impacts on required energy reforms at rural pilot installation sites [265]. Competitiveness can be enhanced by policy/regulatory frameworks with socio-economic emphasis on reducing energy poverty in developing countries. The TrnSys model will thus be a valuable asset in market appraisal and government foresight exercises where price negotiations/bid-offers require cost-benefit and ecological conservation projections.

In terms of suitable rural operation business models, the International Solar Energy Society (ISES) developed a number of Rural Energy Supply Models as a structured best practice guide to economic sustainability based on alternative sources of energy, life-cycle cost, payback time and demographic information [266]. This will help government partner programs, private investors, philanthropies, utilities, cooperatives, system developers, humanitarian programs and non-profit project developers to utilise solar micro-CHP microgrids as flagship demonstrator and replicable energy solutions in community shared village electrification solutions. Solar micro-CHP also provides opportunities for addressing service delivery challenges and socio-economic development through free basic electricity and hot water to informal settlements in developing and BRICS countries (Brazil, Russia, India, China, South Africa). Solar micro-CHP can also benefit from credit guarantees and loans by cooperatives or micro-finance institutions to work with foundations such as Innovations Against Poverty, Engineering for Change, KiloWatts for Humanity, Power-Hive, Rural-Power and other African technology innovation and development organisations to fund specialised solar systems with community solar microgrids for addressing off-grid settlement challenges [267].

The experimental model based platform for power output analysis of the micro-CHP system in the present study offers a competitive edge towards evaluating the use of Africa's rich natural sunlight resources to deliver on socio-economic objectives and sustainable development goals [268]. The simulation platform will especially be valuable in terms of de-risking investments through the prediction of solar energy outputs and fuel flexibility at communities locations in isolated rural areas not yet included in future national electrification and grid-extension plan reaches [263]. Some isolated rural districts and farmlands have already been identified by the local authorities and district municipalities of South Africa for potential roll-out of renewable energy micro-power plants provided validated techno-economic projections prove viability [269].

## 2.4. Summary and Conclusions

There is a growing realisation that barriers of entry for solar energy in Africa is likely to be overcome through emphasis on the fuel reforms that solar energy can bring about through small-scale distributed CSP cogeneration technologies. In terms of the role of government incentives and subsidies, specific support for small-scale energy systems, at least some level of basic electricity, have great potential. While such programs need to be carefully though through, there should be some incentives and subsidies to support local entrepreneurs who want to become micro utility owners. An accurate system simulation model, serving as a projection tool, can serve as a valuable instrument to encourage funder and public participation in the adoption of renewable energy technology [270]. Recent global initiatives such as the Alliance for Rural Electrification and the Smart Villages Program have called for new thinking in terms of power generation, power distribution and demand side management concepts that would help to ensure sustainable renewable energy access to off-grid communities worldwide [99, 241].

As solar project designers accurate projections for the energy production capability was needed of the solar micro-CHP system. In this paper, the NREL design guide was followed in terms of developing a system model to project micro-CHP performance and predict fuel transitions effects by using the TrnSys simulation platform. This TrnSys simulation model was subsequently used to conduct location-aware analyses by way of simulation experiments to predict the energy output performance of the current solar micro-CHP system at various locations in rural Southern African. The TrnSys time-series outputs were used to predict the cumulative electrical and thermal energy generated annually by the system. In terms of electrical power output, simulation results for the Giyani rural reference site in South Africa shows that the micro-CHP system should be able to generate approximately 1500 kWh$_e$ per year. Simulation experiments were extended to other off-grid rural village regions in Africa that may in future be targeted for rural electrification in government programs. Statistical weather prediction models for those regions were applied to the micro-CHP model to survey the annual electrical and thermal energy generation capacity of the solar micro-CHP system. These results were catalogued and displayed in Figure 2.5, Figure 2.6, and Figure 2.7.

The second part of the TrnSys simulation experiments explored fuel transition effects of the micro-CHP system at the same site locations used in the previous experiment. This investigation was conducted from an indigenous rural African village resource dependence perspective, where the focus was on solar micro-CHP energy transitions away from increasingly scarce fossil fuel and biomass resources [271]. The study applied the developed TrnSys model to analyse the potential for fuelwood replacement in terms of micro-CHP hot water production from recovered waste heat in the combined heat and power process. Since fuelwood is one of the most prominent heat sources in rural residential use in African villages, solar generated thermal energy was converted into fuelwood equivalents for each of the selected rural African village regions. In terms of fuel transitions at the reference site in Giyani, the results show that the micro-CHP system is able to reduce water heating fuelwood use by up to 58 kg per village per day. These simulation experiments were also extended to survey other off-grid rural village regions in Africa, and the results were displayed in Figure 2.8.

The design of our solar micro-CHP unit was motivated by the need to solve challenges faced by rural communities in terms of meeting basic household energy needs through clean renewable energy resources. From this perspective, the former energy reform experiment proved that the solar Stirling micro-CHP system can help limit the harvesting and burning of fuelwood and will thus play a valuable role in GHG mitigation. Such transitions away from biomass and fossil fuels will further help reduce the rate of deforestation, preserve natural habitat and assist with conservation. Significant health advantages include the role micro-CHP energy can play in the reduction of death and diseases caused by smoke inhalation, especially among young children, while access to electricity will help to preserve food and vaccinations. It also reduces the daily burden of fuelwood collection by women and children under increasing scarcity and dangerous conditions, leaving time for empowerment through education and micro-industries. Within this context, the simulation model and experimental results are of significant value to future cost-benefit and market value trial analysis to be performed as part of government feasibility studies for sites in rural Africa. The results help advocate the fact that solar micro-CHP fuel transitions can bring about prosperity and alleviate energy poverty among rural populations. Arguments around subsidised energy in economically sustainable ways may further path the way to lift perception barriers and spark a rush of interest in solar cogeneration to graduate as popular rural energisation technology.

In terms of future research, solar micro-CHP performance can be presented as a spatial distribution and displayed graphically using geographic information systems (GIS) for visualisation and preview by funders or interested parties. The TrnSys model will further be incorporated in model based control, supply/demand synchronisation, demand response, load curtailment, economic sensitivity analysis and microgrid dispatch optimisation. In this follow on research work, consideration will be given on how the energy can be spent in a cost effective manner. The focus will thus shift from a supply side focus on a balanced supply and demand model where energy is both produced and consumed in an energy management enterprise type configuration. From an energy management operations research perspective, this TrnSys model holds significant value as a discrete digital component in an intelligent multi-objective control automation and microgrid storage capacity optimisation solution for this solar powered micro-CHP system [231].

# Chapter 3

# Solar Cogen Smart Grid Centralised Optimisation

**Paper:** Prinsloo, G.J., Mammoli, A.A., Dobson, R.T. 2016. Discrete Cogeneration Optimization with Storage Capacity Decision Support for Dynamic Hybrid Solar Combined Heat and Power Systems in Isolated Rural Villages. *Energy*, 133(1), 1051-1064 [231].

## 3.1. Introduction

This paper is presented as part of Objective 3, and is supported by additional publications as discussed in §1.7. The full introduction to this paper can be found in Prinsloo *et al.* [231]. The focus of this paper is on integrated control and optimisation methods for off-grid residential village supply generation to accomplish load demand balancing within certain cost and communication constraints. §3.2 introduces a custom designed packaged hybrid micro-cogeneration system prototype. The control design model and multivariate optimisation method for the integrated cogeneration and embedded microgrid system is detailed in §3.3 and §3.4. The storage capacity optimisation support procedure is described in §3.5. §3.6 evaluates the control solution in a scenario-based case study simulation, with conclusions in §3.7. Results demonstrate control optimisation and cost outcomes under different microgrid storage capacity scenarios.

## 3.2. Solar Cogeneration Control Application

Governments in developing countries are interested in rural energisation solutions that offer multi-stream energy with high microgrid viability and high replication potential [269]. The technical choice for a community based solar cogeneration system was inspired by parabolic dish micro-cogeneration technology such as the Innova Trinum-Turbocaldo system and the Qnergy Infinia system [272, 273]. These micro-cogeneration power plants, in addition to electricity generation, offer hot water solutions suitable for renewable energy programs meant to support sustainable village housing in isolated rural areas. Micro-cogeneration based village power systems may also help to overcome load congestion in off-grid rural village settlements where PV microgrids suffer blackouts when dealing with heavy loads such as heating water [269].

The prototype for the solar micro-cogeneration system includes a dynamic mechatronic platform and parabolic dish combination, configured as a standalone packaged cogeneration unit (rated capacity 3 $kW_t$, 1 $kW_e$). The system was designed to be installed by unskilled support personnel and acts as a plug-and-play village power and hot water generation system for remote rural areas. The benefits of the technical choice for this particular micro-cogeneration configuration have been demonstrated in computer simulation models for various rural village locations in Africa [240]. An optimal low-complexity control and energy management method is now sought for this hybrid solar micro-cogeneration system, to make it more suitable for the electrification of rural areas in developing countries [248].

In this design, the solar receiver feeds a combined heat and power type Stirling engine manufactured by Migrogen Engine Corporation [274]. This unit can operate in both a solar-operation-mode and a gas-hybrid-mode, which makes it suitable for domestic micro-cogeneration in community solar projects. To accommodate the gas-hybrid-mode, the system includes an external gas-fired generation unit that allows the use of burner flames using liquefied petroleum gas (LPG) as fuel. When used in the gas-hybrid-mode, the unit uses a fixed thermal energy source to generate electricity at 1 kW and thermal energy at 3 kW, at the prevailing gas $ costs [274]. These features make this system especially suitable for small-scale cogeneration applications that require electric power of capacities around 1 kW and thermal energy of around 3 kW (residential hot water supply, 1500 l storage in this case).

## 3.3. Control Solution Design and Modelling

As part of our model based design approach, all of the components of the solar cogeneration system have been modelled on the digital Transient System Simulation (TrnSys) platform. TrnSys and other advanced mathematical modelling and computer simulation techniques are useful in complex control environments, especially with the design of control automation in a multi-carrier community microgrid environment [275]. Detailed descriptions of the TrnSys models and parameter specifications for the solar cogeneration components are given in a separate paper [240].

With the addition of storage components, the system is able to shift energy generated during normal sunlight hours to night-time when most power and hot water is typically required for domestic use. By extending the TrnSys mathematical model to include microgrid system functionality, the overall solar generation plant and microgrid can run in discrete step-wise timeslot simulations. This platform enables us to experiment with intelligent control signals to optimise the performance of the solar cogeneration microgrid system over strategic time horizons [276]. A crucial element in the development of an intelligent solar cogeneration system is a pragmatic digital control automation solution that integrates renewable energy variations, increases energy efficiency, ensures energy stability, and optimises costs for village community microgrid operation. optimisation in these autonomous green-energy controller solutions must give special attention to robustness, remote communication limitations and social economic circumstances of traditional rural African village communities [277].

In this approach, the aim is to create a compact structure that integrates a microgrid energy distribution management system into packaged hybrid solar/gas cogeneration control automation. The overall layout of our proposed integrated cogeneration microgrid system control solution is depicted in the block diagram of Figure 3.1. This diagram shows the main components and energy flows for the solar/gas hybrid cogeneration, solar photovoltaic (PV) emergency backup supply power and hot water residential energy storage components with the extended microgrid control automation elements. In this design, solar cogeneration, gas hybrid cogeneration, solar PV and microgrid dispatch solutions need to work together in order to support the operation of the integrated autonomous packaged community solar village power unit. The focus is thus on the development of a computational algorithm for solving this dynamic optimisation problem for the concentrating solar cogeneration system.

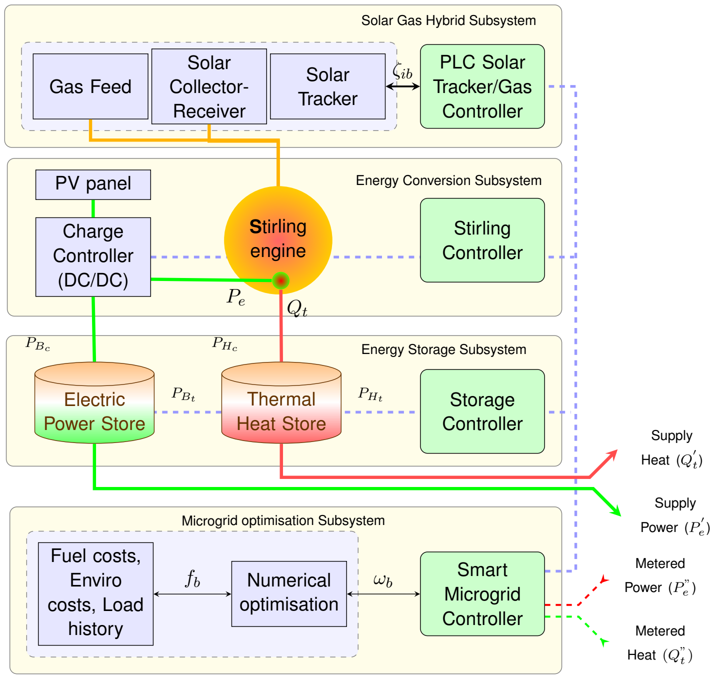



**Figure 3.1:** Block diagram of model based design layout for integrated solar tracking, hybrid solar/gas cogeneration, energy storage and smart microgrid components with controls.

From a control automation perspective, the hierarchical control levels in Figure 3.1 can be described as follows. On the primary control level, cogeneration control comprises of a solar tracking controller and the Stirling controller. The Solar Tracking Controller includes an astronomically based solar tracking automation solution installed at the customer site. The Stirling controller includes an integrated electronic control architecture as part of the sealed linear free piston arrangement [274]. This controller has the function of processing certain sensor signals in order to regulate the operation of the cogeneration unit based on configurable parameters (i.e speed of operation, drooping control, frequency of output electrical signal, alternator temperature, coolant flow rate, water temperature, etc.).

The secondary control level in the control hierarchy is located in the smart microgrid optimisation subsystem, and is also shown in Figure 3.1. It includes the microgrid energy management system (micro-EMS) and energy balancing control strategy. This feeds strategic high-level optimised decision control signals to the solar tracking controller, Stirling controller and the storage controller. The micro-EMS and power flow control solution proposed in this paper offers functionality and intelligence to optimise the balance between the demand side load (i.e. domestic appliances), supply-side generation, and supply-side generation fuel costs. This smart microgrid platform helps to integrate primary energy generation control and secondary microgrid distribution control solutions, ensuring local synchronisation of load demand with energy production cycles of renewable energy resources. The integrated smart microgrid platform also creates opportunities to implement flexible low-computation local control optimisation based on numerical integration of the resource commitment and economic optimisation solutions. In this compact power flow optimisation solution, the smart microgrid controller numerically optimises operational costs and environmental impact through mathematical processes that accommodate the addition of renewable energy and other distributed polytopic generation sources.

The next section describes the strategic energy management optimisation problem from a solar cogeneration, microgrid dispatch, energy management and resource scheduling control perspective. It also describes the way in which the energy supply scheduling and microgrid energy distribution control solution is numerically integrated into a Smart Grid control solution.

## 3.4. Control Scheduling Coordination Method

This section focusses on a proposed multi-objective optimisation approach and characterisation of the microgrid control solution in terms of the system and model components. The hybrid solar cogeneration control problem can essentially be addressed from a resource and supply scheduling optimisation perspective wherein optimal operational plans and operational cost performances are determined numerically. This means that effective distributed generation optimisation is achieved through Strategic Energy Management (SEM), and incremental planning procedure wherein the task scheduler formulates a scheduling policy or operational plan for a set future time horizon [278, 279]. This scheduling policy essentially formulates the optimal generation unit commitment sequence or supply source synchronisation schedule for the responsive generation sets using multi-criteria, discrete-time optimisation dispatch principles.

### 3.4.1. Discrete multi-objective optimisation

A mathematical description of the scheduling optimisation solution for Figure 3.1 would thus have to be defined in terms of one or more objectives to allow a solver the opportunity to minimise (or maximise) an objective function in terms of a set of decision variables, given a set of predefined system constraints. In the power generation and microgrid dispatch control space, complementary objectives (economic, technical and environmental factors) in the smart microgrid control concept must be defined to achieve multi-objective optimal energy generation and dispatch [280]. Once the problem has been defined, a mixed integer linear programming (MILP) solver can be used to solve stochastic multi-objective optimisation (MOO) control problems for grid-connected microgrid systems [281].

Within the MOO framework, MILP numerical optimisation offers the ability to influence control decisions around the optimal dispatch and control of available distributed energy resources (DER) based on economical and environmental measures in hierarchical energy management control structures [282]. The general MOO power generation and microgrid dispatch control space, complementary objectives (economic, technical and environmental factors) in the smart microgrid control concept is defined to achieve multi-objective optimal energy generation and dispatch [280]. Within this framework, MOO offers us the ability to influence control decisions around the optimal dispatch and control of available DER based on economical and environmental measures in hierarchical intelligent energy management control structures [282]. To support any energy usage monitoring and balancing method, the MOO technique offers the ability to influence control decisions around the optimal dispatch and control of available DER based on economical and environmental measures. In smart microgrid optimisation for isolated off-grid energy systems though, the optimisation problem is slightly more complex. This is because the optimiser has to consider the survive-ability of the system whilst ensuring economic optimisation and at the same time ensure microgrid storage operate at optimum levels. At the same time, the microgrid energy management optimiser has to balance the impact of diverse factors such as economic operational costs ($ costs), environmental factors ($CO_2$ footprint, greenhouse gas emissions, fuelwood conservation, etc.). This is difficult to achieve in the primary feedback control loop of a pure electronic control system since the control process requires techno-economic measures.

Dynamic smart microgrid control optimisation in isolated microgrids therefore calls for a MOO solution to handle multiple sets of diverse inputs within the context of a set of optimisation constraints. In general, MOO control problems are based on the optimisation of a multi-dimensional performance criteria (often conflicting) that takes different control specifications into account. Figure 3.2 represents the general MOO power generation and microgrid dispatch control space, wherein complementary objectives (economic, technical and environmental factors) in the smart microgrid control concept is defined to achieve multi-objective optimal energy generation and dispatch [280].

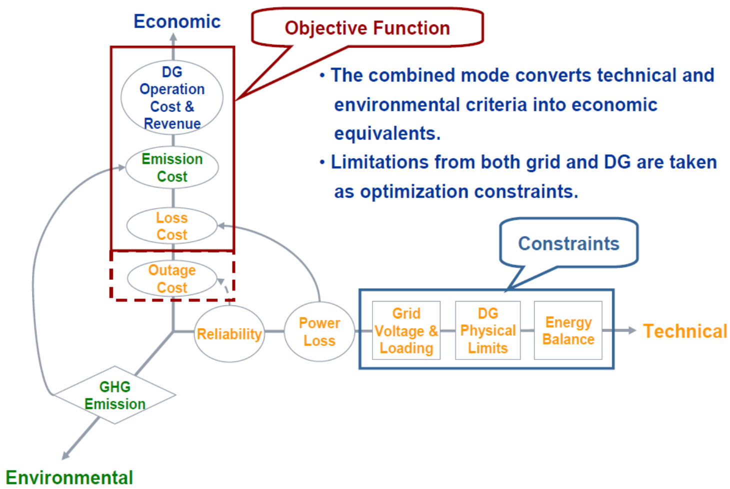



**Figure 3.2:** Centralised multi-objective smart microgrid energy dispatch control optimisation space and objectives [280].

In the MOO control space of Figure 3.2, the smart microgrid control optimisation strategy thus needs to find the perfect balance between reliability, availability, efficiency and cost objectives. The mathematical description of the control problem and optimisation solution thus have to be defined with one or more objectives to allow a solver the opportunity minimise (or maximise) an objective function in terms of a set of decision variables, given a set of predefined system constraints. The numerical optimisation solution would thus aim to select a set of best fit sequence of control signals over time that can be manipulated and optimally tuned by a mathematical solver within a certain given set of available alternatives. MOO problems generally include the components of (i) defining input variables, (ii) defining decision variables, (iii) defining optimisation objectives, and (iv) defining barrier constraints for multi-criteria optimal control. The software flow chart proposed in this research for the implementation of centralised multi-objective smart microgrid optimisation is depicted in Figure 3.3.

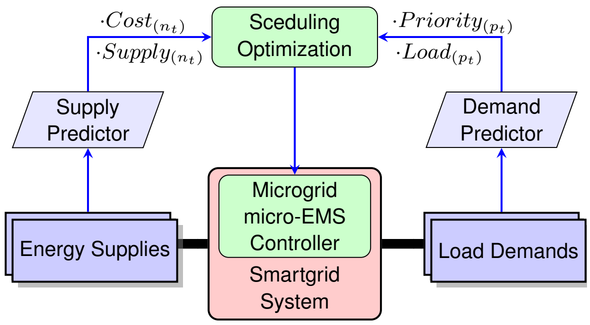



**Figure 3.3:** Software flow chart proposed in this research for the implementation of centralised multi-objective smart microgrid optimisation.

In terms of defining input variables in the smart microgrid digital MOO problem definition, we need to express the supply side generation capacity and demand side load curves by mathematical representations or discrete time-series datasets. In discrete-time control for linear interconnected systems [283], we define the supply source contributions as a collection of discrete-time linear components to enable supply scheduling optimisation based on load predictions and historical load data/cycles within the MILP.

### 3.4.2. Scheduling optimisation variables

The first input variable to the smart microgrid energy management balancing and control solution in Figure 3.1 is the DPGS supply sources. The optimiser operates as a longer term strategic optimum control planner and thus works over a future time horizon that requires day-ahead predicted supply potential data. Thus, assuming the day-head solar DNI and weather data is available, we can use the discrete TrnSys simulation model to determine the day-ahead supply sequence. The supply streams in Figure 3.1 can be discretely represented by the incremental TrnSys event simulation time-series $S_i = f(P_e)$ for the solar and gas cogeneration power supply sources ($n = 2, 3, \ldots, N$). This includes power contributions from the solar rooftop PV and additional DER devices that may be added to the microgrid system over time. The supply datasets can be algebraically expressed in terms of discrete-time energy supply samples $S_{n_t}$ over a time horizon ($t = 1, \ldots, T$), as given in the expression:

$$\begin{aligned} S_{1_t} &= s_{1_1} + s_{1_2} \cdots + s_{1_T} \\ &\ldots \\ S_{N_t} &= s_{N_1} + s_{N_2} \cdots + s_{N_T} \end{aligned} \tag{3.4.1}$$

In defining the optimisation problem for the packaged hybrid cogeneration microgrid system, the microgrid energy storage facilities in Figure 3.1 can serve as both supply source or demand load. The charge controller in Figure 3.1 ensures that battery storage accepts charge at times when spare capacity and residual solar, hybrid gas or solar PV energy is available. The optimiser, by default, treats energy storage as one of the supply sources $S_{n_t}$, meaning the battery energy storage serves as a grid stabilising generator. The release of energy from storage can be controlled by the optimiser in terms of its objective function and cost function optimisation procedures. In terms of the optimiser storage parameter set, we define variables for the battery depth of discharge $P_{B_d}$ level and battery nominal rated capacity $P_{B_c}$.

The second discrete input variable to the smart microgrid energy management balancing and control solution in Figure 3.1 is the microgrid energy consumption devices or demand loads. In terms of optimiser input parameters, we can discretely represent the predicted day-ahead microgrid demand loads as a time-series $L_{m_t}$. This time-series represents the household demand load sequences as discrete elements in each timeslot for a number of elastic loads or households ($m = 1, 2, \ldots, M$) for the remote rural village, over the same time horizon ($t = 1, 2, \ldots, T$). Keep in mind that the optimiser should also entertain storage as a demand load source, meaning we have to make provision for storage as a village power demand load. If the surplus supply energy produced exceeds the storage capacity of the supply, then the excess energy would either be dumped in (dummy load $L_{m_t}$) or directed to an ancillary service such as village water pumping. The time sequence $L_{m_t}$ thus represents the village electricity load (with storage demand and dummy load) as discrete time-series sequence in expression:

$$\begin{aligned} L_{1_t} &= l_{1_1} + l_{1_2} + \cdots + l_{1_T} \\ &\ldots \\ L_{M_t} &= l_{M_1} + l_{M_2} + \cdots + l_{M_T} \end{aligned} \tag{3.4.2}$$

With the incremental discrete-time sequences for the supply $S_{n_t}$ and demand $L_{m_t}$ defined, we want to formulate a digital smart microgrid control solution as an algebraic objective function that will aim to optimise the microgrid cost of operation and proportional energy balance within certain definable constraints over an optimisation day-ahead time horizon ($t = 1, 2, \ldots$,24 hours).

### 3.4.3. Objective and cost functions

In the formulation of an objective function for the microgrid optimisation strategy, we define the linear function in Equation 3.4.3 as the overall supply generation for the entire time schedule horizon in terms of the control decision variables $x_{n_t}$. The objective function then needs to be solved within a number of definable constraints, namely: the optimiser strives to satisfy the load demand at each time instance, the control variable

$x_{n_t}$ $(n = 1, 2, \ldots, N; t = 1, 2, \ldots, T)$ remains within specified control signal level limits, the individual solar $P_{e_s}$ and gas $P_{e_g}$ hybrid supply sources should run as mutually exclusive sources, and the energy storage level $P_{B_t}$ should adhere battery specification constraints (battery discharge level $P_{B_d}$ and battery storage capacity level $P_{B_c}$).

$$f(x) = \sum_{t=1}^{T} \sum_{n=1}^{N} S_{n_t} x_{n_t} \tag{3.4.3}$$

subject to constraints:

$f_t(x) \leq L_t$
$0 \leq x_{n_t} \leq 1$
$P_{B_d} \leq P_{B_t} \leq P_{B_c}$
$P(P_{e_s} \; and \; P_{e_g}) = 0$

With these objectives in mind, we define a discrete MOO objective cost function that aims to minimise the sum of the generation costs and maximise the use of renewable DPGS energy resources. The cost function $C_T$ is defined as cost measure to optimise the linear supply control function in Equation 3.4.3, as per Equation 3.4.4. Future cost functions may further include aspects around device behavioural models and run-time configuration costs (i.e. start/stop costs, state transition, running-time costs, service-interval costs, state transition probabilities). It should be noted in Equation 3.4.3, the value of the relative weight $\omega$ in the cost function $C_T$ balances the relative importance of cost and environmental objectives to achieve optimal economic efficiency.

$$\text{min} \;\; C_T = \sum_{t=1}^{T} \sum_{n=1}^{N} (\omega) c_{n_t} S_{n_t} x_{n_t} + (1 - \omega) k_{n_t} E_{n_t} x_{n_t} \tag{3.4.4}$$

In this multi-objective cost function, the first control objective is to reduce the operating cost of the microgrid energy generation and dispatch. In this regard, the first term in the objective cost function $C_T$ of Equation 3.4.4 makes provision for dynamic pricing, variable tariffs and discrete-time differentiated fuel costs for each of the DPGS energy supply sources (i.e. LPG gas costs in the hybrid mode). Dynamic fuel pricing is included in the general cost of generation, which is represented by the time-of-day differentiated cost of supply coefficients $c_{m_t}$ in the cost function $C_T$. This term in Equation 3.4.4 allows for flexible timeline differentiated fuel consumption prices in the definition of the hourly variable tariff rates (enabling the use of both fixed and variable fuel or spot price rates per timeslot throughout the day). Time differentiated tariff rates are generally not required in government sponsored off-grid village power systems, but the inclusion of this optimisation feature will allow for the flexibility to implement a number of attractive Gridwise transactive control features in later research. For example, dynamic pricing can be used as a means to develop future business models for local community co-operatives around pre-paid token billing, or to dynamically link fossil fuel levels in the village and increase the cost of fossil fuel generation in situations where village fuel levels have the probability of running low.

The second control objective in the multivariate cost function $C_T$ of Equation 3.4.4 is to maximise the use of renewable energy resources by minimizing the greenhouse-gas (GHG) emissions for the overall microgrid system. This part of the cost objective function incorporates the $CO_2$ emissions for each device, represented by the environmental metric term $E_{m_t}$. This term reflects the absolute $CO_2$ emissions for each of the supply sources, for which the $ costs are captured in the time-of-day differentiated cost of emission coefficients $k_{m_t}$ in Equation 3.4.4. These coefficients in the objective function will help ensure that the cost optimisation function gives preference to renewable energy sources as it penalises the selection of energy sources with high $CO_2$ output emissions (e.g. LPG gas, fossil fuels, and biomass).

With the smart microgrid energy management optimisation objective and costs functions defined in the discrete expressions Equations 3.4.3 and 3.4.4, a digital MILP optimisation algorithm can be used to determine the optimal selection and sequence of generation sources that is able to satisfy the load demand at minimal operating cost and environmental impact. We used the SimplexLP algorithm [284] to solve Equation 3.4.4 in order to accomplish day-ahead scheduling optimisation over the T = 24 hour time horizon. A variety of other state-of-the-art linear programming equation solvers (ANOVA, GAMS, etc. [284]) can also be used to solve the cost function in Equation 3.4.4.

### 3.4.4. Integrated Smart Grid control architecture

The overall multi-objective solution described in this section is graphically illustrated in Figure 3.4 and operates as the numerical optimisation block in the Smart Grid optimisation subsystem of Figure 3.1. This solution uses the discrete optimisation objective function in Equation 3.4.3 and the cost function in Equation 3.4.4) to determine if the system is able to meet the load demand within the prescribed minimal operating cost and maximum use of renewable energy criteria. In this discrete-time periodic optimal control approach, the smart microgrid controller continuously monitors essential control points in the microgrid with advanced metering infrastructure to generate optimal supply generation control signals based on the optimal combination of operational cost, environmental impact and availability of solar, storage or gas supply sources.

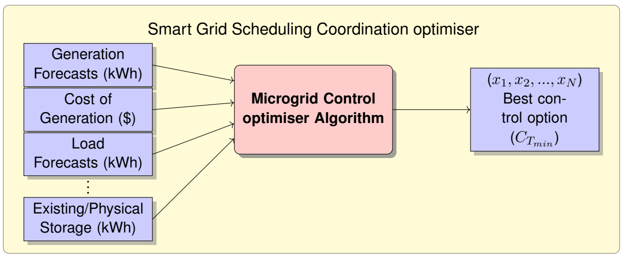



**Figure 3.4:** Block diagram of the proposed integrated packaged cogeneration smart energy management and scheduling solution.

In practice, the day-ahead optimisation objective and cost functions in Equations 3.4.3 and 3.4.4 of the optimisation solution (Figure 3.4) further operates on the basis of a sliding mode control method [285]. In this self-tuning sequential sliding window optimisation principle, sliding data window is used in a rolling horizon scheme wherein the updated supply and load forecasts are obtained at each time instance "$t$", while the control parameters with respect to the next horizon ($T = 24$ hour time periods) are computed and supplied to the smart microgrid controller. Thus, at the end of each hour, the optimiser loads the predictions for the following 24 hours on a sliding window basis and determine the best or optimal supply unit schedule control signals for the next time horizon.

As mentioned previously, the cogeneration system uses concentrated solar power, or LPG, to simultaneously generate electricity and domestic hot water. The water is heated as a result of the cooling process in the Stirling engine meaning that the generation of electricity and hot water are directly related and one cannot happen without the other. The real-time control of this cogeneration system is managed by its own on-board control system containing the necessary procedures to maximise efficiency and maintain safe operating conditions [274].

This energy management system proposed in this paper is concerned with the optimisation of distributed energy resource generation scheduling and the optimisation of storage size within a rural off-grid microgrid. Real-time control is managed by a separate model predictive controller that ensures a close adherence to the optimised day-ahead schedules. The distributed energy resources that function within the microgrid are still dependant on their own on-board controllers during operation, but are instructed by the main energy management system described in this paper to engage or disengage at certain time slots.

## 3.5. Storage Decision-Support Optimisation

In energy management operations research, battery energy storage solutions and storage intelligence features as a means to enhance the efficiency and stability of renewable energy microgrids have generated a lot of interest. Energy storage physically assists with optimising microgrid energy balance and efficiency since it acts as a power store and microgrid stabilisation system that support operational reliability in the islanding mode [286]. It has the ability to store energy generated from intermittent renewable sources, allowing the optimiser to decouple the generation sources supply schedule constraints from the load schedule. Energy storage elements in Figure 3.1 help to optimise the efficiency of energy distribution while smoothing renewable energy inputs to the microgrid within the capacity constraints of the energy storage facilities.

In the context of off-grid packaged cogeneration, the village microgrid cannot afford the constant dumping of excess energy generated from renewable energy sources during the daytime because of insufficient storage capacity. This leads to the realisation that there exists an operational need to develop a microgrid numerical storage optimisation indicator. From a rural village operational perspective, such an intelligent advisory feature is meant to alert and advise the community when consistent signs of village microgrid energy dumping due to storage capacity limitations are detected. Especially if there is a logical opportunity to shift more solar renewable energy into the evenings, it offers the potential to directly reduce the microgrid operating costs (especially in terms of fossil fuel costs). A storage indicator will thus help off-grid isolated rural village communities understand the energy capacity limitations of their microgrid and advise them to accept/defer added storage procurement decisions.

The proposal for a storage decision support system is thus based on an optimisation solution that constantly monitors battery energy storage capacity (resource adequacy) based on technical and financial metrics. It was noted that the proposed discrete optimisation approach of Section 3.4, by default, treats energy storage as one of the supply sources $S_{n_t}$. This implies that battery storage capacity constraints in the optimisation objective of Equation 3.4.3 are essentially a storage bound optimisation solution. It means that the installed storage capacity constraints will limit the optimiser's ability to find more optimal energy efficient solutions that could reduce the daily monetary operational costs and environmental burden on natural resources.

Modelling of the battery energy storage system application have always allowed for a more flexible and detailed performance evaluation of the battery storage response. The microgrid optimisation in Section 3.4 in combination with such storage models can further help to analyse the effects of costly storage upgrades in a desktop computer environment. In order to achieve this, we can extend the optimisation solution of Figure 3.4 as graphically illustrated by the dotted parts in Figure 3.5.

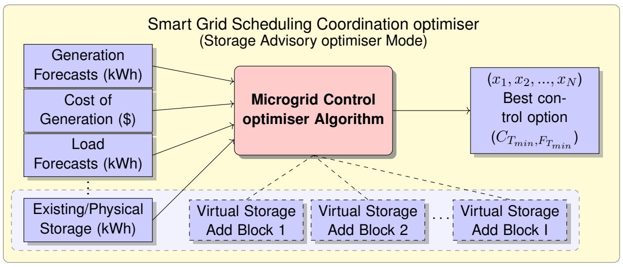



**Figure 3.5:** Integrated cogeneration Smart Grid energy management scheduling solution, with added virtual storage blocks enabling optimiser to operate as storage capacity advisor.

In the storage optimisation solution of Figure 3.5, one or more local energy storage components can be artificially added to the village microgrid optimisation solution such that it can best determine the lowest operational cost scenario given the limitations and constraints of the supply generation sources and demand loads. This optimisation solution thus uses the cost optimiser of Section 3.4 in a second discrete numerical optimisation loop to determine/recommend the ideal long-term average optimum storage capacity for an isolated off-grid village that best suits the specific capacity requirements.

The storage optimisation solution in Figure 3.5 forms the key part of a storage decision-support system that will help the village to monitor their dynamic storage capacity efficiencies over time. It will also enable the community to compare operating costs with investment decisions in terms of adding physical storage capacity that would be required for optimum storage capacity in the village microgrid. This discrete storage optimisation solution allows the storage capacity of the battery bank to be increased in increments of 1.2 kWh in a modular fashion. In this way, the storage optimisation uses computer simulations to implement a stepwise procedure to determine an optimum storage capacity where daily accrued fossil fuel costs $F_T$ are kept at a minimum. We therefore introduce a framework for an incremental simulation-optimisation loop in which the storage capacity constraint in the objective function of Equation 3.4.3 is allowed to grow in discrete battery capacity steps as formulated in Equation 3.5.1.

$$P_{B_d} \leq P_{B_t} \leq P_{B_c} + (i \times 1.2 \text{ kWh}) \tag{3.5.1}$$

Conceptually, adjustable storage is realised virtually by selectively engaging a set of discrete modular storage blocks in the discrete multi-objective optimisation model as illustrated in Figure 3.5. The simulation based optimisation procedure can iteratively optimise and gauge the potential operating costs of the microgrid under a range of artificially extended storage scenarios. Thus, by virtually expanding the modular storage capacity of the village microgrid in a stepwise manner (based on available battery size options), the optimiser determines the minimum microgrid running costs in a procedure that finds the daily cost-optimal energy storage capacity $P_{B_{opt}}$. It then recommends the application of proper battery storage capacity that increases self-consumption of renewable energy during cost-efficient time-of-day periods.

Under normal long-term rural microgrid operating circumstances, the daily cost-optimal energy storage capacity $P_{B_{opt}}$ will fluctuate as a result of short term micro-grid supply and demand dynamics (user behaviour, occupancy, ambient temperature, weather patterns, solar DNI, cloud screening, etc.). Under such fluctuating circumstances, it will be logical to smooth the daily cost optimal energy storage capacity recommendation over a number of days. This can be accomplished by running the outputs of the storage optimiser through a first order autoregressive moving average filter. This filter continuously smooths the daily storage upgrade metric and includes a weight function that separates long-run storage capacity metric from the short-term supply/demand dynamics. For this purpose, we propose to use a low computation discrete time weighted infinite impulse response (IIR) filter for which the feedback transfer function is given in Equation 3.5.2. In this function, the update rate configuration setting $\alpha$ smooths the storage metric over multiple days $d$ to provide the smoothed optimum storage capacity recommendation $Y_d$ as in Equation 3.5.2.

$$Y_d = \alpha Y_{d-1} + P_{B_{opt}} \tag{3.5.2}$$

Future attempts to solve the storage optimisation problem for the whole state and parameter space may include more complex solutions such as multi-parametric programming [287]. Generally mp-MILP and mp-MIQP can ensure concurrent optimisation of generation and storage manipulated variables in a global optimisation strategy. These procedures might be considered in future, although it may complicate the implementation of the decision support system to recommend appropriate storage augmentation through off-line computation in an microprocessor on-board environment.

The proposed intelligent energy and cost-aware control automation solution of control structure in Figure 3.5 within the control structure in Figure 3.1 is now ready to be evaluated within the context of different energy storage scenarios in a rural solar cogeneration microgrid. The linearised objective model for the solar cogeneration and demand side energy consumption scheduling control problem can be solved and fed to the TrnSys cogeneration supply model. Doing so, the control scheduling solution generates control commands by predicting the system behaviour and optimising the system performance at a rural African village location within certain storage capacity scenarios.

## 3.6. Experimental Scenario Simulation and Results

The hybrid solar cogeneration microgrid control optimisation solution will be evaluated in a simulation case study approach based on available remote rural household consumption data repositories. For the purpose of this study, we selected a rural agricultural settlement around Giyani in the Limpopo Province of South Africa as design evaluation site (part of a broad area that has been identified for rural electrification in South Africa). The aim of the experiment is to investigate and benchmark the response of the renewable energy optimisation and control solution at this isolated rural location in Africa where the cogeneration system should generally support a small rural village consisting of around four to five households.

The experiment starts off by quantifying the optimiser input parameters that will be used. This includes user energy demand profiles for electricity and hot water as well as weather and power generation data that is relevant to the scheduling time frame and test site. It also details the technical features of the microgrid such as capacity and limitations of hardware, and economical assumptions such as cost of energy generation for the various technologies involved. The next two sections describe the results obtained with the scheduling en storage capacity optimiser operating in constrained and cost-optimised storage microgrid scenarios, while the final section offer results for domestic hot water usage and the effect of control scheduling on hot water storage levels.

### 3.6.1. Input parameters for optimisation case study

Day-ahead forecasting of the supply side generation and demand side load is required as data inputs to the microdgrid control scheduler shown in Figure 3.4. For the purpose of this paper we will use known generation and consumption data, thus eliminating the effects of uncertainty in predictions. In this regard, we consider the TrnSys computed simulation outputs to be the day-ahead predicted solar cogeneration supply forecast.

In terms of supply side generation prediction data, Figure 3.6 displays the discrete TrnSys simulated solar cogeneration system output graphs for the solar electrical power and secondary heat with the system running in solar mode. The model uses the given mathematical notation for the solar cogeneration electrical power $p_e(t)$ and thermal power $q_t(t)$ outputs determined from weather data $w(t)$ for the Giyani target site on a day with favourable weather conditions [240]. The simulation outputs are computed in time increments of 0.01 hours, or $\Delta t = 36$ seconds. The volume of hot water generated (litres per hour) is also determined from the TrnSys simulation. When there is no sunlight (evenings or rainy days), the Stirling system can be scheduled to switch to the gas hybrid mode where it will use fossil fuel (gas) combustion as heat source. In the gas mode, the TrnSys simulation generates power at the specified gas unit capacity levels of 1 kW of electricity and 3 kW thermal energy (in our case hot water), at the prevailing fuel costs. The vertical red line in Figure 3.6 at 147 hours indicates the starting point of the predictive scheduling control front in the present experiment, meaning data for the 7th day of this week is considered as supply generation forecast.

As a result of the limited availability of rural African village load demand data, we have the option to use either measured load profiles from other villages, load evaluation calculator data, or a discrete-time load event simulator to characterise the rural village load demand. In this paper, we opted to use hourly measured electrical load and hot water draw-off pattern datasets from rural village household repositories [288, 289]. These measured power and hot water demand load data patterns represent a snapshot of the energy dynamics of rural village life and are shown in Figure 3.7. These datasets are used as next-day supply and demand load forecast, which enables us to proceed with investigations around the ability of the microgrid control optimisation solution to

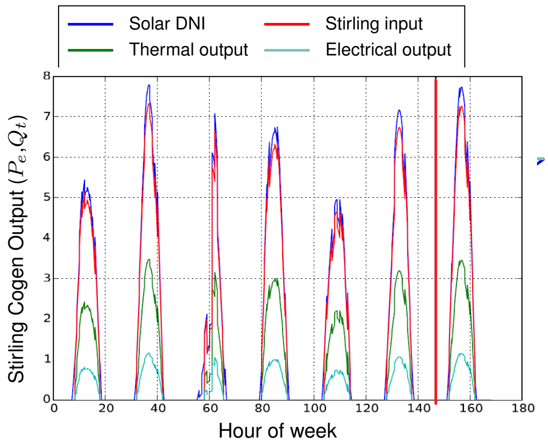



**Figure 3.6:** Predicted electrical (kW) and thermal (hot water) (kW) outputs for the solar micro-cogeneration system. Location: Giyani, South Africa (March).

deal with control challenges under less-optimal and optimal energy storage capacity scenarios.

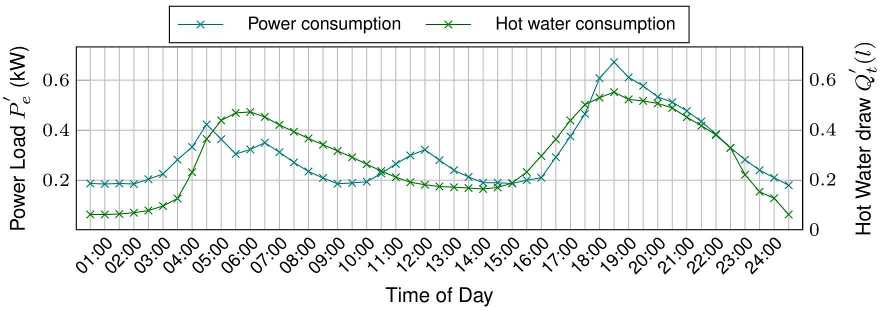



**Figure 3.7:** Discrete rural village household consumption load time-series [288], with per-capita rural village household hot-water consumption load times-series [289].

In terms of the cost function considerations for the discrete microgrid optimisation case study, certain cost and performance assumptions for modelling electric power generation technologies are made. We define the village microgrid configuration in terms of optimiser parameter sets given in Equations 3.4.3 and 3.4.4, while all $ cost terms in the optimiser equations are specified in USD currency. The relative levelised cost of energy (LCOE) for each of the rural village powerplant components are estimated on the basis of first-order cost and performance assumptions for technology characterisation and energy resource modelling studies [290]. Table 3.1 presents a summary of the competitive modelling cost and performance assumptions for electricity power generation and microgrid optimisation in the empirical problem. Note that although the optimiser provides for variable tariff flexibility in Equation 3.4.4, supply costs in the case study experiment will only include flat tariffs (no time-of-day variations).

The packaged cogeneration and microgrid system of Figure 3.1 is fitted with universal 12 Volt 166 amp-hour (C8-rated) sealed deep-cycle lead acid batteries in the battery box to ensure energy on demand. The starting microgrid configuration includes 2 kWh

**Table 3.1:** Summary of case study system optimisation cost and performance assumptions.

| **Device** | Capacity $S_{n_t}$ (kW) | Sply LCOE $c_{n_t}$ (\$/kWh) | Relative $CO_2$ $E_{n_t}$ (kg/kWh) | Env LCOE $k_{n_t}$ (\$/kWh) |
|---|---|---|---|---|
| Cogen | TrnSys | 0.25 | 0.000 | 0.0051 |
| LPG gas | 1.0 | 0.43 | 1.015 | 0.0051 |
| Solar PV | TrnSys | 0.18 | 0.000 | 0.0051 |
| Storage | 2.0 | 0.22 | 0.000 | 0.0051 |
| Modules | 1.2 | 0.22 | 0.000 | 0.0051 |

nominal capacity, while storage capacity can be modularly extended in steps of 1.2 kWh (12 V, 100 Ah at $ 240 per module). For this microgrid battery bank storage, the daily deep-cycle battery depth of discharge $P_{B_d}$ level is specified to be maximum 80 % of the nominal rated capacity $P_{B_c}$ of the battery. Keeping the battery state of charge $P_{B_t}$ within the $P_{B_d}$ safety discharge level will prevent over-discharging of the battery bank and thus limit irreparable long-term damage to the microgrid storage batteries.

In terms of power storage capacity, it is important to note that standalone solar cogeneration microgrid battery storage capacity would normally be designed for around three days of safety margins. This would yield three days of autonomy for microgrid operation when no solar resource is available. In this case study we experiment with storage capacities $P_{B_c}$ with approximately one day of autonomy. This is to demonstrate the optimiser principle of operation and to make the role of the optimiser more apparent.

### 3.6.2. Scheduling experiment: Undersized storage

In this part of the experiment, the abilities of the smart microgrid control scheduling solution to deal with higher level intelligence challenges under non-optimal or undersized storage capacity conditions will be under investigation. This part of the experiment is conducted in a limited storage capacity condition scenario in order to observe the operational plans proposed by the optimiser. The optimised operational plan will further be used to perform an economic cost analysis to determine the operational dollar costs for the optimised system under certain limited storage capacity conditions. For this purpose we define a battery storage capacity of $P_{B_c}$ = 2 kWh and a hot water storage tank of 1500 litre capacity. The cogeneration supply data in Figure 3.6 and load consumption data in Figure 3.7 will be used as anticipated day-ahead supply generation and demand loads respectively. The battery capacity constraint in the objective function of Equation 3.4.3 is thus set to a limit of 2.0 kWh battery capacity with a depth-of-discharge $P_{B_d}$ at 80 % as depicted in Equation 3.6.1, and a 50 % initial state of charge .

$$P_{B_d} = 0.2 \times P_{B_c} \leq P_{B_t} \leq P_{B_c} = 2.0 \text{ kWh} \tag{3.6.1}$$

By engaging the supply devices in the sequence determined by the multi-objective optimisation algorithm in Section 3.4 (objective weights $\omega = 0.5$), we are able to determine the supply schedule contribution from each of the supply sources. In the present optimised storage scenario case, the microgrid Control optimiser Algorithm in Figure 3.5 determined the optimal day-ahead supply and generation unit commitment schedule. The optimal set of next-day microgrid control signal were determined with objective weight $\omega = 0.5$ and the control logic signal results are shown in Figure 3.8. These control signals reflect the mathematically optimised microgrid strategic energy management control signal time-table that represents the microgrid strategic day-ahead resource commitment schedule.

Keep in mind that the control signal schedule as multi-level logic essentially describes the strategic control commands for the microgrid secondary hierarchical control level layer, a strategically optimised sequence of control signals required to guide the solar cogeneration, solar PV, LPG gas and energy storage controls in each time period throughout the following day to ensure optimal operational economic efficiency. During operation, the microgrid controller will use these signals to ensure that supply devices adhere to the microgrid scheduling on an hourly time-frame clock-signal basis.

By engaging the supply devices in the sequence, the microgrid energy management system is able to determine the supply contributions from each of the supply sources. The graph in Figure 3.8 reflects the resulting optimised resource coordination for the generation schedule sequence (for solar cogeneration, solar PV, energy storage, and gas supply generation sources) that will achieve optimal economic and environmental operation. It shows the relative load serving contribution, in terms of power generated from each of these resources.

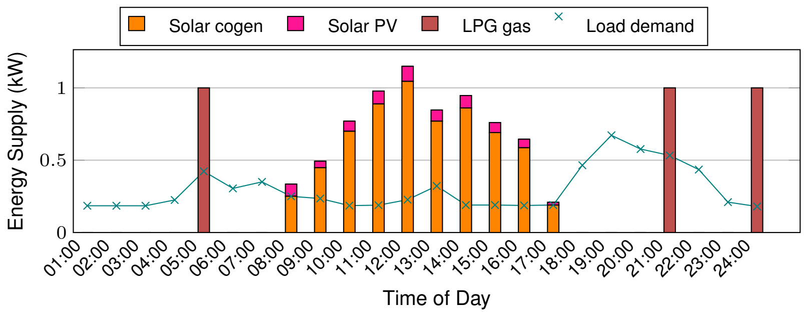



**Figure 3.8:** Optimum hourly supply sequence determined by optimiser, showing energy contributions from solar cogen, solar PV, storage, and gas sources (demand overlaying supply).

Figure 3.9 shows the relative contributions from the solar cogeneration, solar PV, energy storage and gas resource unit in relation to the Stirling supply ratings (3 kW$_t$, 1 kW$_e$) and rural customer consumption load demand (Figure 3.6 & 3.7). Keep in mind that the optimiser has to operate within the constraints of the given storage capacity limitations and is thus forced to dump excessive power when the battery storage is fully charged. Note that, although the supply and consumption levels may seem low when compared to urban household consumption levels, in an isolated rural village household context these numbers are realistic values based on a scoping exercise around physical measurements in rural areas (Figure 3.7) [230, 288, 289].

The optimiser further computes the cumulative daily fossil fuel operational cost and power dump associated with this optimised generation schedule and is shown in Figure 3.10. Here we can see that the most significant portion of the power dump occurs during peak sunlight hours of the day when the output of the solar cogeneration system far exceeds the user demand. The current battery storage was not able to store all of the excess energy and it ends up being dumped. Related to this is the cost of generation using fossil fuel, which occurs in the evening when no sunlight is available

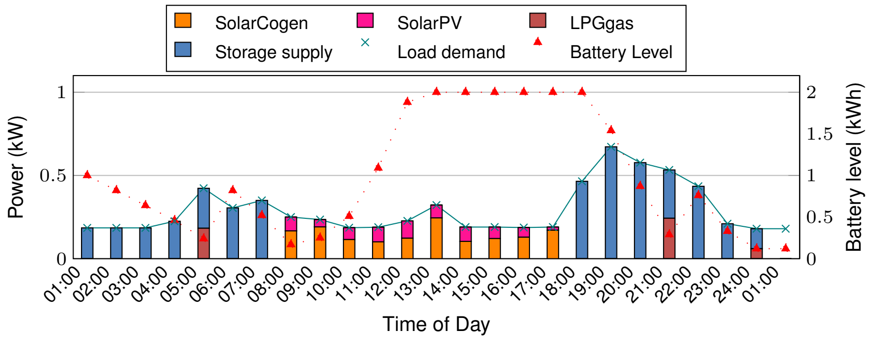



**Figure 3.9:** Microgrid proportional load servicing contributions with optimal supply sequencing schedules from solar cogeneration, solar PV, storage and gas supply resources.

and when the battery storage has been depleted. The cost optimised schedule for this scenario shows that the LPG contribution is made for a total of three hours of the day (05:00, 21:00, 24:00). The proportional cost of gas (fuel cost plus transport cost for the reference site) is estimated to be around \$ 0.18 per kWh. This means that the 24 hour accumulated LPG costs for the optimised generation schedule is \$ 0.54, which adds up to a very rough estimated annual cost of \$ 200. The estimated operating costs are significant for a rural African village, given the low income levels along with time and effort spent in transportation of these non-renewable fuels.

The current battery storage was not able to store all of the excess energy and it ends up being dumped. Related to this is the cost of generation using fossil fuel, which occurs in the evening when no sunlight is available and when the battery storage has been depleted. Thus, reading the cumulative operational dollar costs together with the total amount of energy dumped as a result of storage shortage, it is clear that storage capacity should be optimised to save operational costs under the existing community micogrid village storage scenario.

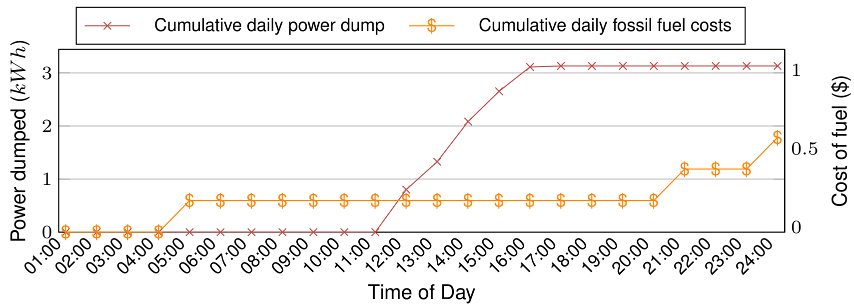



**Figure 3.10:** Cumulative power dump (scale left) and daily fossil fuel costs (scale right), showing high levels of solar energy dumping and fossil fuel costs due to insufficient storage capacity.

An isolated microgrid already operates within a constrained renewable energy power budget, meaning that daytime energy dumped to a dummy load (potentially as a result of limited battery storage capacity) may be crucial later on during the night-time where it would be able to sustain mission critical loads when solar energy is not available and LPG gas generation would be expensive. This has a direct bearing on the rising levels of daily cumulative $ cost of the fossil fuel consumed which means that there is potential for reducing operational costs by investing in additional storage.

### 3.6.3. Scheduling experiment: Cost-optimal storage

In this section, the storage optimisation discussed in Section 3.5 is used to determine the most economical storage size for this system. As discussed previously, the optimiser will virtually expand the modular storage capacity of the village microgrid in a stepwise manner based on available battery size options in Table 3.1 (1.2 kWh increments). As the optimiser artificially engages additional storage capacity, it is able to determine the daily cost-optimal energy storage capacity $P_{B_{opt}}$ by minimizing the microgrid running costs in a simulation procedure. In this case, it was determined that the microgrid electrical storage capacity should ideally increase from the present undersized nominal capacity of $P_{B_c}$ = 2 kWh to a more cost-optimal $P_{B_c}$ = 4.4 kWh nominal capacity.

In the following simulation we use the optimised battery bank capacity of $P_{B_c}$ = 4.4 kWh (adjusting constraints in Equation 3.6.2) to investigate the ability of the smart microgrid control scheduling to deal with renewable energy management challenges under the adjusted storage conditions. Other inputs, constraints and starting conditions remain the same as in the previous simulation where the storage was undersized.

In this part of the experiment, we ran the optimiser in a storage simulation-optimisation mode as detailed in Section 3.5. In this way the optimiser will virtually expand the modular storage capacity of the village microgrid in a stepwise manner based on available battery size option in Table 3.1. As the optimiser artificially engages additional storage capacity, it is able to determine the daily cost-optimal energy storage capacity $P_{B_{opt}}$ by minimizing the microgrid running costs in a simulation procedure. It was thus determined that microgrid electrical storage capacity should ideally increase from the present undersized nominal capacity of $P_{B_c}$ = 2 kWh to a more cost-optimal $P_{B_c}$ = 4.4 kWh nominal capacity. The battery capacity constraint in the objective function of Equation 3.4.3 is set to a discrete limit of 4.4 kWh battery capacity with a depth-of-discharge $P_{B_d}$ again at 80 % as in Equation 3.6.2.

$$P_{B_d} = 0.2 \times P_{B_c} \leq P_{B_t} \leq P_{B_c} = 4.4 \text{ kWh} \tag{3.6.2}$$

Using these newly determined constraints, the optimiser once-again generates a day-ahead control schedule to determine the associated strategically optimised supply powerplant control signals to ensure least-cost day-ahead microgrid energy supply management. In the present undersized storage scenario case, the Control optimiser Algorithm in Figure 3.5 determined the optimal day-ahead supply and generation unit commitment schedule (objective weight again $\omega = 0.5$) graphically reflected in Figure 3.11. This mathematically optimised control signal and time-table clock describes the microgrid control signals for the to-be-determined day-ahead resource commitment schedule in terms of strategic (secondary hierarchical microgrid control level) control commands required to guide the solar cogeneration, solar PV, LPG gas and energy storage controls throughout the next day.

By using these newly determined constraints, the optimiser was thus able to calculate a new day-ahead control schedule with relative microgrid supply source contributions as in Figure 3.11. When comparing this to the contributions in Figure 3.8, it is clear that there has been a reduction in power generated using LPG. This is due to the increased battery capacity which has allowed the system store more of the excess solar electricity generated during the day-time. As mentioned previously, the contributions made by LPG based generation has the highest cost associated with it and reducing this can be very advantageous.

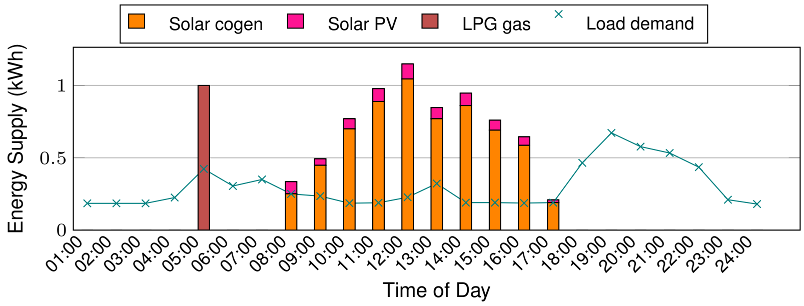



**Figure 3.11:** Optimum hourly supply sequence determined for energy contributions from solar cogeneration, solar PV, storage, and gas sources (load demand overlaying supply).

Figure 3.12 shows the optimal direct-to-load supply contributions from the solar cogeneration, solar PV, energy storage, and gas resources. The simulation starts out with the same amount of energy stored in the battery as in the previous case (for the sake of comparison) which naturally leads to a lack of power in the early morning hours. However, being able to store more of the electricity generated during the day allows the microgrid to meet night-time demand without having to engage LPG to power the cogeneration system. This will have a significant impact on the system operating cost and control schedule complexity.

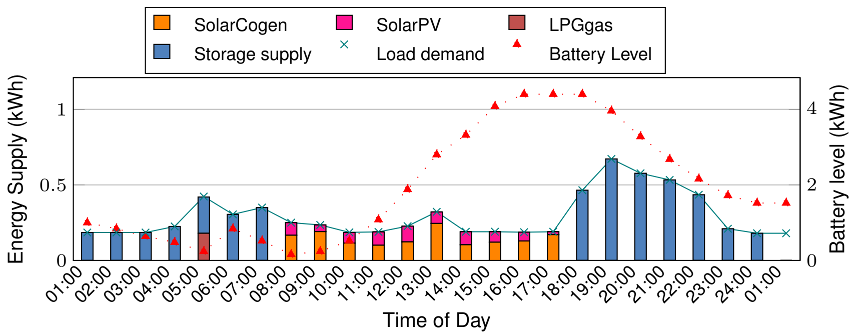



**Figure 3.12:** Storage optimised microgrid proportional load servicing contributions with optimal supply sequencing schedules from solar cogeneration, solar PV, storage and gas supply resources (relative to daily microgrid load demand variation sequence).

We calculate the cumulative daily LPG cost associated with the optimised generation schedule given in Figure 3.12. This fuel cost along with the daily power dump is shown in Figure 3.13. The customer bill comparison (Figures 3.10 and 3.13) highlights the positive impact of added storage on the customer bill, reducing the annual LPG expense from around $ 200 to $ 66. Only looking at the cost of LPG saved, results show a return on investment of about three and a half years. This will be reduced even further when the LCOE of the reduced daily energy dump is taken into account. The reduction in daily power dump after storage optimisation was around 2.4 kWh. The indirect cost for the electricity dumped during day-time generation is taken at $ 0.25 which roughly adds up to $ 219 per year resulting in a final return on investment of only one and a half years. Even disregarding the short return on investment period, a reduction in electricity bill of $ 350 is a significant amount for a predominantly low-income community.

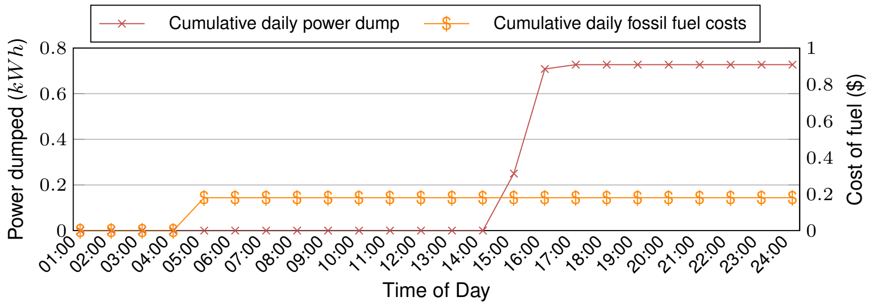



**Figure 3.13:** Cumulative power dump (scale left) and cumulative daily fossil fuel costs (scale right) under an optimised storage capacity, showing reduction in microgrid operating costs.

The hourly electric power dump graph in Figure 3.13 further highlights the cumulative energy dumped to the dummy load in relation to the cumulative $ cost of the fossil fuel consumed to supply the village under the new storage capacity and fossil fuel consumption scenario. Compared to the power dump in the non-optimised storage scenario in Figure 3.10, the storage optimised scenario reflects a situation where much less solar renewable energy is dumped during the sunlight hours of the day. The experiment illustrates how increased power storage capacity enabled the microgrid energy management optimiser to shift more solar generated energy into the morning and evening peak loads, dumping less energy due to a cost optimised microgrid storage capacity recommendation according to the procedures described in Section 3.5. The cost-aware and cost-optimised energy storage scenario thus enhances the economy of this hybrid renewable energy solution.

### 3.6.4. Microgrid hot water draw and storage

The generation of domestic hot water is the result of the cooling process during electrical power generation in cogeneration engine. Since the generation and storage aspect of available hot water is inherently related to electricity generation, it can be impacted by adjustments made to storage size on the electrical front. In the case of this village (Figure 3.7), the average daily hot water consumption is well below the volume generated by the system. However, while the available water storage of 1500 l will take some time to fill up, a more closely matched availability to consumption profile can greatly reduce system losses. The optimiser supply schedule, determined in Section 3.6.3, is used to determine the hourly hot water draw versus hot water supply from the TrnSys model (TrnSys hot water set-point temperature at 60°C, ambient temperature taken as 20°C, thus $\Delta$T = 40°C).

Figure 3.14 shows the hot water load/storage graph for the simulation before the electrical storage was optimised (same schedule as Figure 3.9). We can observe a rise in the hot water storage levels for the hours between 21:00 and 24:00 when solar micro-cogeneration system scheduled the cogeneration system to run on LPG. As mentioned earlier, it is clear that the average and peak hot water consumption is well within the hot water generation capacity of the hybrid solar/gas cogeneration system.

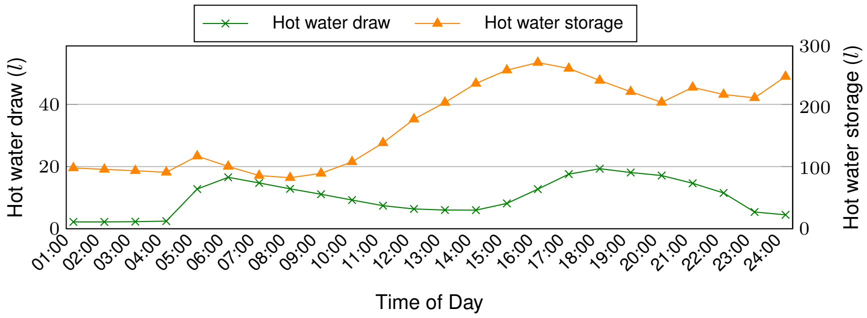



**Figure 3.14:** Hourly hot water draw (scale left) and storage (scale right) patterns to show storage reserves for cooling of Stirling engine for sub-optimal battery storage scenario.

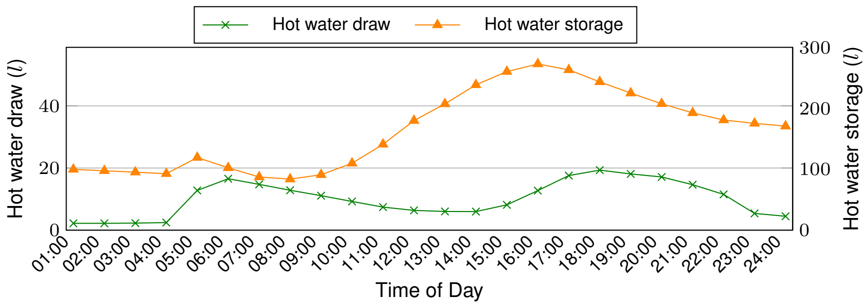



**Figure 3.15:** Hourly hot water draw (scale left) and hot water storage (scale right) patterns showing storage reserves for cooling of Stirling engine in cost-optimal storage scenario.

The optimised electrical storage parameters are now added to the simulation in order to determine its impact on hot water storage. From Figure 3.15 we can see that the consumption curve is more closely matching the availability profile of hot water in storage (using the same schedule as Figure 3.12). The previous peaks in hot water generation (around 21:00 - 24:00) have been eliminated and over consumption has been reduced. This is due to the ability of the system to now support the microgrid (electrical components) deeper into the night without having to engage LPG, thus avoiding over generation of hot water.

## 3.7. Summary and Conclusions

This paper discussed the integration of a renewable micro-cogeneration system with a rural village microgrid system, as well as associated control and operational issues. It deals with the problem of cost-aware control automation and optimisation in smart microgrids and presents an intelligent cost aware optimisation algorithm for case studies in African rural villages. The proposed isolated rural village energy management system includes a localised smart microgrid control solution to address on-site energy management and supply/demand balancing challenges in isolated rural community microgrids. This econometric optimisation further accounts for mitigation of environmental pollutants in energy conversion operational planning schedules. It is customised around the needs of small off-grid village settlements and remote townships in isolated locations and simulation results are used to demonstrate the proposed multi-objective optimisation algorithm aimed at finding balances between the performance and cost objectives.

The proposed storage optimisation solution was evaluated within the context of an energy storage scenario in a rural solar cogeneration microgrid. The results for the limited storage scenario (Figure 3.8) showed how economic, environmental and energy efficiency optimisation ensures intelligent unit commitment control for a hybrid solar renewable cogeneration microgrid. The optimisation procedure makes use of predicted generation and consumption load profiles for the relevant microgrid (in this case a village in rural parts of South Africa). Using this information, in conjunction with physical, economical and environmental constraints, the optimiser is able to generate a day-ahead control schedule using mixed integer linear programming. The optimal coordination of microgrid supply sources is further highlighted in Figure 3.9, where the discrete rural village hourly electrical demand is overlaid onto the supply contributions. This highlights the misalignment between solar supply and peak load demand, which is a very typical occurrence in the field of renewable energy. While it is possible to do a second scheduling optimisation from the consumption point of view to further improve system efficiency, it is not always possible to shift loads to periods where excess energy is generated. In this case we were determined to avoid load shifting as much as possible in order not to disrupt the typical daily schedule for the villagers. Optimisation of the generation schedule allows the microgrid controller to achieve this goal at minimal impact on the consumer budget or whatever other goals might be added to the objective function.

Finally, the effects of limited storage on the operational conditions of the self-generation and self-consumption microgrid is highlighted in Figure 3.10. It shows that significant amounts of electricity generated through solar is dumped for most of the peak sunlight hours (12:00-15:00), mainly as a result of limited microgrid storage capacity. The impact of this limited storage capacity is illustrated in Figure 3.10, which shows that loss of solar energy is made up through expensive gas generation in the evening (21:00 & 23:00). While the advantages of optimising the size of the electrical storage is clear, further analysis shows that it can also improve the hot water energy management efficiency.

A proposed storage optimisation decision support expert system was subsequently developed to help overcome the above added costs to the user bill. This optimiser operates by constantly weighing up operating costs (Figure 3.10) against storage extension capital costs. This is used to alert the user of potential billing cost/operating cost savings that could be achieved by increasing the battery energy storage capacity of the microgrid system. The storage cost optimiser for single(or multiple)-day-of-autonomy battery storage scenarios enable us to conduct revised customer billing/cost analyses. This is based on optimum recommended storage capacity and new operational plans for energy delivery proposed by the optimiser to improve dollar operational costs under improved cost-efficient storage capacity conditions.

The simulation-optimisation method described in Section 3.5 was subsequently used to determine the cost-optimal storage capacity for the previous scenario in Figure 3.9. The recommended storage capacity for this microgrid amounted to 4.4 kWh (existing microgrid storage configuration plus two additional 1.2 kW battery modules). Figure 3.12 shows how more of the daytime solar energy can be available in the evening by engaging the recommended storage capacity, thus mitigating the requirement to engage more expensive gas generation in the evening. Figure 3.13 further highlights the fact that midday renewable energy power dump reduces from around 3 kWh to around 0.8 kWh. If the goal of storage optimisation was to avoid energy dumps, it would have suggested additional storage to absorb this 0.8 kWh also. Instead the algorithm takes the day-ahead user demand into consideration and thus determines that storing the remaining 0.8 kWh would be wasteful in the present day-ahead cycle since the electricity would not be utilised by the consumer in that day. An additional 2.4 kWh storage recommendation is thus based on economic or operational cost optimisation measures and not only on energy metrics. The storage optimiser finds the present day operational cost savings that can be moved into storage capacity investment, thus advising on cost-optimal energy storage capacity $P_{B_{opt}}$ recommendation based on merits of daily savings.

From Figure 3.13 we conclude that an investment in additional storage capacity of two battery module units (2 x 1.2 kWh at cost estimate $ 480 in total) is required to overcome non-optimal storage deficiencies in our microgrid configuration. The addition of two additional storage units would account for a reduction in daily operational costs of around $ 0.36 per day (down 66 % from $ 0.54 to $ 0.18). This relates to an estimated annual savings of $ 135, which roughly means a payback period of around three and half years ($ 480/$ 135). Taking into account the cost of electricity being dumped on a daily basis due to insufficient storage further reduces the return on investment period to one and a half years.

Overall, the experimental results show that incremental optimisation of the storage capacity ensures improved energy management efficiency and reduced operational and customer billing costs. Increased power storage capacity enabled the microgrid energy management optimiser to shift more solar generated energy into the morning and evening peak loads. The proposed decision support system procedures were able to ensure that less energy is dumped as a result of automated microgrid storage capacity recommendations. The case study experiment showed that storage cost optimisation in favourable solar day conditions led to around 66 % reduction in daily microgrid LPG operational costs. An even bigger financial gain rooting from the storage optimisation was the reduction in dumped electricity that amounted to an average annual cost of around $ 200. These cost savings could be applied to investments into larger village microgrid storage capacity or generation resources. The automated storage decision support system recommendation further ensured increased sustainability and heat storage efficiencies with bigger thermal safety margins for Stirling engine cooling.

Based on the optimisation algorithm's knowledge of the microgrid (i.e. the microgrid parameters set during configuration) this strategic control algorithm provides certain "recommended" control set-points which are to be followed as closely as possible. If the system parameters are not accurately defined, or if the parameters change dynamically (e.g. more generation or storage added by villagers) without the energy management system being updated, then the operating schedules determined by the algorithm will no longer be optimal. This means that the controller needs to closely monitor these systems, and even more problematic is that the system needs a serious amount of customisation (re-configuration) to accommodate new installation and system changes.

The proposed optimiser will be extended to incorporate load splitting, using disaggregated multi-bus load priorities on distribution-board-level. Such multi-tiered ranking factors in microgrid-wide demand response will protect critical loads categories, while ensuring demand reduction during periods of load congestion or load imbalances. If replacement reserves are expensive, energy balancing and outage management can be accomplished through peak shaving, load shedding, load levelling, load curtailment, or load scheduling of low level priority direct controllable loads (i.e. through bluetooth and wireless/wifi addressable lighting, DC fridge, entertainment, TV, radio devices). Plug-in hybrid electric vehicles, weather patterns and ambient temperatures will have a direct bearing on demand requirements. Deep-learning artificial neural network load forecasting algorithms are presently under development to account for weather pattern variations through predictive self-learning and machine learning capabilities.

# Chapter 4

# Case for Smart Village Transactive Energy

**Paper:** Prinsloo, G.J., Dobson, R.T., Mammoli, A.A. 2017. Customer domain supply and load coordination: A case for smart villages and transactive control in rural off-grid microgrids. *Energy*, 135(1), pp 430-441 [291].

## 4.1. Introduction

While it is clear that microgrids powered by renewable energy technology can be a great solution for powering off-grid rural villages, it is important to factor the role of energy management systems (EMSs) for such microgrids. Empowering remote off-grid communities depends on the energy management system (EMS) to ensure effective integration of generation and distribution planning. This paper is presented as part of Objective 3, and is supported by additional publications as discussed in §1.7. The full introduction to this paper can be found in Prinsloo *et al.* [291].

The focus of this paper is on the energy management aspect of rural microgrid operations. It starts with an introduction to typical microgrid control architecture and the role of the EMS, followed by a comparison of energy management approaches that are typically encountered and how they apply to off-grid microgrids in rural settings. This is followed by a focus on modern EMSs and the role of scheduling optimisation and communication protocols, and a case is made for transactive energy management in rural off-grid microgrids

## 4.2. Microgrid Control and Energy Management Approach

Designing a suitable off-grid microgrid requires a good understanding of the term *microgrid*, and to know what pragmatic energy management in a shared rural community microgrid entails. According to the US Department of Energy there are three distinct features that characterise a microgrid: it must have clearly defined electrical boundaries, a master controller must be present to control and operate the distributed energy resources and loads, and it must be able to operate in island mode while still being able to supply critical loads [292, 293].

The microgrid controller is mentioned as a distinct qualifying feature, and it is this very feature that is at the center of many research and development projects [294]. Microgrids for rural electrification projects mostly operate in isolation without the option of

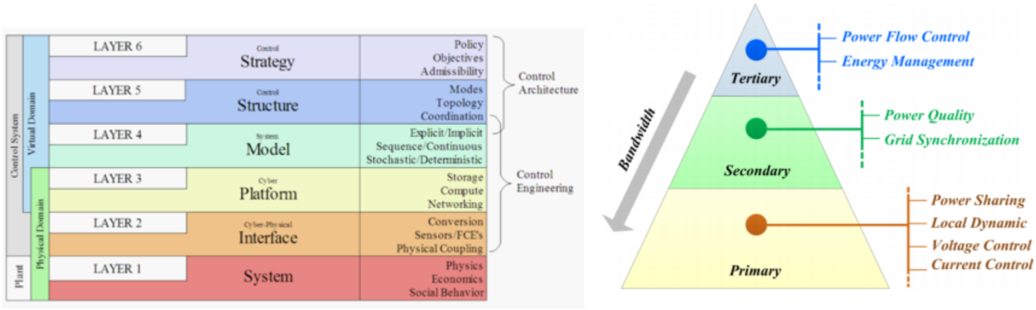



**Figure 4.1:** Control abstraction layers in cascaded hierarchical microgrid control [23, 124].

connecting or disconnecting to a national grid. The control automation architecture in microgrids are layered in functionality, and control duties are usually categorised into a primary, secondary or tertiary layer [124]. These cascaded control layers associated with the enterprise-type Purdue industrial automation, which in turn relates to the Smart Grid SGAM hierarchical control model [41, 295]. These layers, and the functions associated with each of them, are shown in Figure 4.1. The tertiary layer, shown in the top section of Figure 4.1, is responsible for *strategic energy management and resource planning* to ensure optimal microgrid economic and efficiency operation. This typically involves planning for future events based on information from forecasting models, customer preferences, and other market information to ensure that the system can balance supply and demand [296]. This layer is also commonly referred to as the EMS hosting layer and will be the focus of this study in order to make meaningful recommendations for rural microgrids.

### 4.2.1. Energy management approaches at distribution level

Distribution level EMS approaches can generally be divided into four categories (Figure 4.2) based on their communication capabilities, and decision-making strategies. Starting in the bottom left corner of Figure 4.2, *top-down switching* represents a basic demand response approach where a control signal is broadcasted to switch target device groups [297]. The decision-making process takes place at a central location where the optimal power flow is planned based on available information about optimum energy management, optimum scheduling of distributed generation (DG) and responsive load demand (RLD) [298]. Similarly, *price reaction* systems make use of single direction communication, but instead of sending a switching signal the price of electricity is communicated to consuming devices [297]. In this case it is up to the consumer devices to decide if they are willing to purchase electricity at the communicated price. This allows for decision-making to be distributed to consumers, but does not allow for significant feedback. Since both of these approaches make use of one way communication it is not always possible to make accurate predictions on load demand or system reaction, meaning that the control system has to react in real time without much anticipation or foresight.

On the right hand side of Figure 4.2, it is clear that both *centralised optimisation* and *transactive control* rely on two-way communication. The increased information flow allows for a better understanding of the system, leading to more accurate forecasting

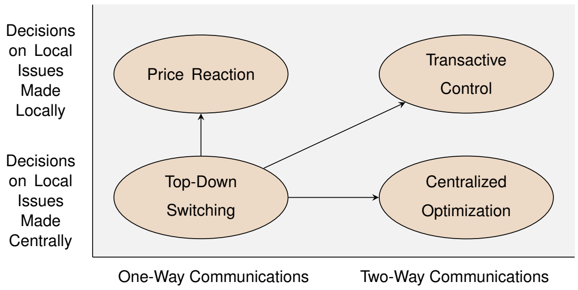



**Figure 4.2:** Classification of distribution level energy management approaches [297].

and thus a better anticipation of system reaction. This is beneficial since it allows the system to prepare for anticipated conditions and react in a near optimal way. In the case of central optimisation, the EMS has access to detailed system information, but needs to process it in time in order to generate optimal schedules. This can become problematic as systems grow in size and thus generate large amounts of data resulting in increasingly complex optimisation. While centralised optimisation makes full use of the available information gathered from two way communication, it has a clear weakness in terms of scalability and adaptability [297, 299]. Similar to the price reaction approach, transactive control envisaged by the Gridwise Architecture Council (GWAC) allows the decision-making to be distributed among devices in the microgrid [300]. With the added ability of two way communication this approach becomes very powerful as systems start to increase in size.

### 4.2.2. EMS functionality in rural microgrid contexts

Section 4.2.1 gave a brief overview of operational characteristics and basic operating principles of the various distribution level energy management approaches. This section considers these approaches in a rural off-grid context.

Decision-making intervals for EMSs (secondary and tertiary control layer) are usually in the order of minutes, while the functional primary layer of control act in millisecond time steps [60]. The rest of the control mechanisms rely on the foresight and the optimisation capabilities of the EMS to produce optimal control schedules for both consumption and generation. The optimisation problem faced by a microgrid EMS will typically have multiple goals such as minimizing operating cost, maximizing generation distribution and consumption efficiency, grid resiliency, customer satisfaction etc.

Figure 4.3 shows some of the advantages and disadvantages that are associated with each of these four energy management approaches and will be used as a basis for the following discussion on their application in village microgrids. The first approach (bottom left) makes use of very simple communication mechanisms while demand side management decisions are made at a central location. This allows fairly simple design and operation, but the one way communication greatly limits autonomy and information about system reaction. Response potential is also very low since there is no real ability for decision-making at device level. In a rural off-grid microgrid, such an EMS approach will often have difficulty in adapting to rapidly changing operating conditions that typically occur at these installations [80].

| | One-Way Communications | Two-Way Communications |
|---|---|---|
| Decisions on Local Issues Made Locally | **Price Reaction**<br>(+) Full Use Response Potential<br>(–) Uncertain System Reaction<br>(–) Market Inefficiency<br>(+) No Privacy Issues | **Transactive Control**<br>(+) Full Use Response Potential<br>(+) Certain System Reaction<br>(+) Efficiency Market<br>(+) No Privacy Issues |
| Decisions on Local Issues Made Centrally | **Top-Down Switching**<br>(–) Partial Response Potential<br>(–) Uncertain System Reaction<br>(–) Autonomy Issues<br>. | **Centralized Optimization**<br>(+) Full Use Response Potential<br>(+) Certain System Reaction<br>(–) Privacy & Autonomy Issues<br>(–) Low Scalability |

**Figure 4.3:** Advantages and disadvantages of various energy management approaches [297].

The second approach (top left) still has limited communication, but has the ability to distribute some of the decision-making to devices. While this allows for an increased response potential, the way in which the system might react is unclear since the EMS has limited or no feedback on participation intentions of devices. In a rural microgrid, such an approach would allow the users much more control over their electricity consumption and spending, but the limited feedback systems cause inefficient operation and difficulty in control scheduling and optimisation.

Centralised optimisation (bottom right) is able to communicate in both directions and is able to use the more detailed feedback information in optimisation and scheduling processes [301]. Unlike top-down switching, where a control signal is used to switch certain devices, this approach is aware of pre-established device and user preferences which are taken into consideration during optimisation. This allows for an increased response potential and high levels of certainty when it comes to how the system will react. It relies heavily on optimisation algorithms to solve power flow and energy management problems. These algorithms are often complex and optimal solutions come at a high computational cost. In a rural microgrid, this approach allows for a good working relationship between the users and the EMS and can achieve high levels of efficiency and user satisfaction. These systems do however experience limitations when it comes to scaling the number of participating users and devices in the system. As with both the previous approaches, the EMS might also find it difficult to adapt to changing operational conditions (from an optimisation point of view) that often occur in rural microgrids [297, 296].

A transactive EMS (top right) brings together many of the advantageous features from the other approaches while eliminating many of the disadvantages. Indeed it calls for advanced decision-making capabilities down to device level, but such smart devices are becoming increasingly available at lower cost. These levels of communication and decision-making allow the system to do self optimisation, based on market principals, and ultimately achieve high levels of efficiency and user satisfaction over the project life time. Transactive control further overcomes the most prominent issues of scalability, privacy and autonomy experienced in the centralised optimisation approach.

The following section will further evaluate the transactive energy management approach in a rural off-grid village setting.

## 4.3. Case for Participative Transactive Control in Microgrids

The increased intelligence of modern day devices, along with the ability to communicate across platforms, have allowed energy management strategies to evolve and achieve higher levels of interaction [297]. As a result, it has become possible for the microgrid control mechanisms to optimise and manage operations with increased efficiency and ultimately reach new levels of operational success.

Most modern day microgrids make use of two way communication which leaves the system designer with the option of whether decision-making will be handled centrally, or whether it will be distributed (centralised optimisation vs. distributed decision-making). The main factors to consider when selecting an EMS approach are listed and compared in Figure 4.4, serving as an introduction to the discussion that follows in this section.

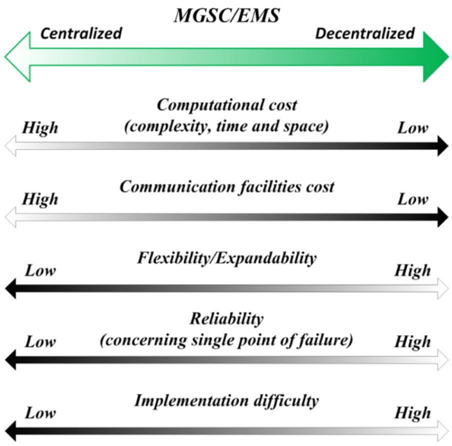



**Figure 4.4:** Centralised versus Decentralised microgrid energy management [60].

In such multi-tier real-time command and control of microgrid dynamic behaviour, the control for each sub-system takes place on the primary control layer. The higher control lever tiers then operate on the process control level commanded where different control time horizons are used by secondary and tertiary control mechanisms in intelligent control policy strategies.

### 4.3.1. Centralised optimisation operating principles

The centralised optimisation approach is concerned with solving the so-called unit commitment problem, which is aimed at finding the optimal schedule for engaging generation resources as well as managing permitted loads in order to optimise operations based on given objectives [302]. This problem can be described mathematically and is typically formulated as a cost minimisation function that can be solved using standard optimisation algorithms [302].

The basic operation of such an EMS is shown in Figure 4.5. The EMS collects information from the microgrid during normal operation which is then used to forecast short term supply capabilities and user demand [303]. This information, along with other system status information, is fed to the model resulting in an optimised unit commitment schedule [302]. One example of such an EMS, that is currently in operation, is the Distributed Energy Resources Customer Adoption Model (DER-CAM), developed at Lawrence Berkeley Labs [304].

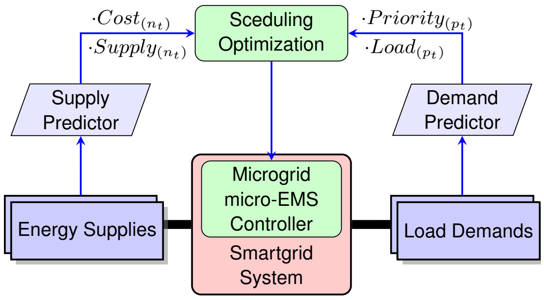



**Figure 4.5:** Process flow-diagram for conventional centralised microgrid EMS control optimisation [231].

In the case of DER-CAM, the forward-looking objective function is focussed on project economics and the customer energy bill and will therefore focus on minimizing operational costs. The objective function could alternatively be focussed on other targets such as minimizing down-time, maximizing efficiency, environmental goals, or it can attempt to find a balance between these by doing multi-objective optimisation [299].

### 4.3.2. Transactive control operating principles

In contrast with centralised optimisation, the transactive control approach does not rely on complex optimisation techniques to solve the unit commitment problem. Instead, it attempts to find optimal operational solutions by enabling all consumer devices to engage in a local energy auction bidding process. The transactive mechanism accommodate energy dealing between load devices and power producers in the local microgrid marketplace. The auction for energy economic environmental axes optimisation involves the use of price-performance relations bid/offer definitions similar to how market forces rely on supply and demand to determine market equilibrium in economics [305, 306].

Figure 4.6 shows the topology and process flow-diagram for our proposed simplified transactive control scheme for strategic microgrid resource coordination. In this strategic (secondary control layer) microgrid control scheme, energy consuming devices want to buy electricity. Based on their current operating state and the user-defined priority configuration, devices are willing to pay a certain price for the energy product (this drives the demand load bids). On the other hand, the polytropic distributed generation resources in the microgrid generate power and are willing to sell this energy at a certain price (supply cost offers) [307]. A mechanism is needed to ensure that microgrid supply and demand (producers and consumers) is balanced such that both supply and demand device agents are satisfied with the transaction and market equilibrium is achieved in a digital service oriented architecture [308, 309]. At the core of the transactive energy management approach in Figure 4.6 are local granular economic market place principles, wherein supply and demand regulates quantity and value of traded goods in a local retail energy trading platform [310]. While the success of a transactive EMS relies

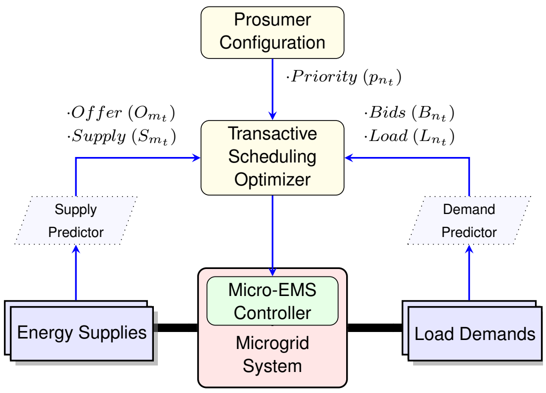



**Figure 4.6:** Process flow-diagram for proposed transactive control topology.

on the willingness of both producer and consumer to interact and work together, it is the market based approach that achieves optimal power flow and energy management on programmable economics principles [311]. From an isolated rural microgrid perspective, this significantly reduces the optimisation complexity normally encountered in other EMSs that are based on a centralised optimisation approach [60, 297].

### 4.3.3. Proposed transactive architecture for rural smart villages

Successfully applying off-grid technologies and pragmatic digital software-based control strategies to the task of energy independence in sustainable de-regulated rural electrification is challenging without standardisation [63]. The IEEE engaged in developing the P2030.10 standard as a means of standardizing DC microgrids in sustainable energy systems aimed at serving remote rural communities [77]. This standard extends into independent microgrids on the grid-edge which enables full decoupling from the AC electric power system with provision for microgrid interconnections through DC links. The purpose of this IEEE standard is to address the need for compatibility and interoperability in rural electrification projects in order to provide safe, reliable and affordable access to electricity in rural areas of developing countries (especially where centralised energy generation and distribution infrastructure may not exist) [312].

The microgrid layout used to study the performance of the proposed rural microgrid EMS transactive control system, is shown in the schematic diagram of Figure 4.7. It comprises of multiple supply generation sources on the left-hand side of the diagram. This includes a hybrid combined heat and power (CHP) Stirling engine (powered by solar or biogas/natural gas), an array of solar photovoltaic panels, and battery energy storage. The system further makes provision for interconnect linkage with microgrids from adjacent villages. The operation of all the local microgrid supply generation sources are coordinated by switching order management (SOM sequence) controlled by the microgrid EMS. The EMS coordinate resource engagement are commanded by priority action plans or resource scheduling plans determined in accordance with the supply and demand balancing transactive energy management process depicted in the control topology flow-diagram of Figure 4.6.

In terms of demand response coordination, each household distribution panel (DC distribution board) enclosure houses software controllable switchgear coupled with an

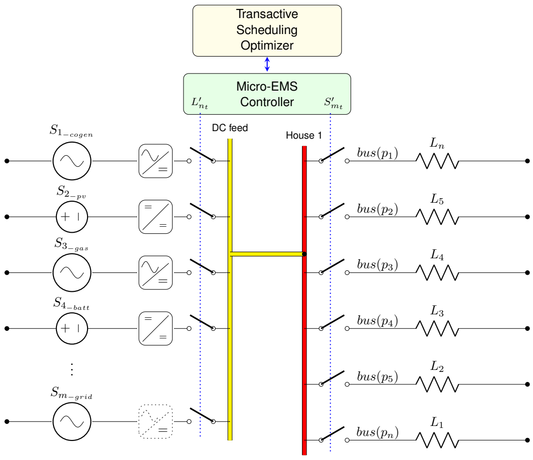



**Figure 4.7:** Diagram for a proposed multi-source ($S_m = S_{1_{cogen}}..\ S_{M_{grid}}$), load differentiated ($L_n = L_1..L_N$), multi-bus and multi-bid priority ($p_n = p_1..p_N$) rural village DC microgrid for transactive EMS experiments (priority/load associations are user configurable).

array of six priority earmarked din-rail DC bus-bars. These bus-bars are shown on the right-hand side of Figure 4.7 and they are each selectively powered from the household feed to manage the status of those load groups wired to it. Low-voltage wiring from each household's switchboard and distribution panel to the respective outlet sockets and DC power outlet receptacles (USB) use 2-core small-gauge copper wires. Individual bus selection switching in this multi-bus configuration for each household is driven by the *Transactive Scheduling Optimiser* block through the *Micro-EMS Controller* block highlighted in the transactive microgrid topology of Figure 4.6. With networked full-duplex communication, the microgrid control devices govern power feed to the array of DC buses that power the multi-priority load groups (based on bid-cleared transactive control signals). This integrated priority bus architecture offers a simple "personal home area network" solution for cost-effective energy management and customer demand response in a remote rural village context.

In the model of Figure 4.7, smart microgrid load groups are managed using switchgear and control signals that operate based on economic value principles. The load priority settings are adjustable by home owners to meet rural village energy budget constraints. The approach is novel in that it offers a low complexity "value driven" demand response mechanism and coordination framework for strategic management of priority grouped devices. It is based on prioritised load groups as a means of differentiating between un-intelligent off-the-shelf devices used in rural microgrids. This is different from the normal intelligent "prices-to-devices" Power-Matcher type transactive energy management implementations proposed for the modern Smart Grid and urban residential smart microgrids [19].

The standardised IEEE configurations are designed around the needs of communities in small rural areas, based on available hardware that include protection to users in accordance with existing safety limits and standards. It describes the configuration for a single household structure fed through a low-voltage DC bus of 2.0 to 48.0 volt direct current (VDC), thus covering USB-C level, cellphone-charging, battery charging voltage levels, etc. Based on the IEEE P2030.10 Standard, and the availability of the required hardware [313], a low voltage DC microgrid configuration was chosen to represent a rural off-grid microgrid on which to implement the transactive EMS. The proposed transactive EMS simulation is able to control the engagement of a range of microgrid supply generation sources as well as an array of heterogeneous devices (radios, cellphone chargers, televisions, DC refrigerators, etc) through multi-bus solid state switches. Studies on DC microgrid configurations [314] and their technical/economic benefits [315] offer convincing arguments to use scalable DC microgrids for rural electrification in emerging regions (wiring simplicity, customer safety, cost-savings, cut inverter cost, no frequency re-synchronisation, higher efficiency) [316].

### 4.3.4. Microgrid devices as energy trading agents

Similar to how an auctioning system functions, there are several individual agents involved in a transactive energy market and as such they are often referred to as multi-agent systems [317]. Some agents are supplying the energy that will be sold while others fall into the category of consuming agents who are interested in purchasing the product on offer. The auctioneer acts as a middle man and receives price bids from the other agents to determine the final market price. These are the agents involved in determining the transaction outcomes during each market period by engaging in a bidding process or price negotiation. The general flow of information involved in the bidding process is show in Figure 4.8. Note that there is two way communication and that each individual device, distributed energy resource (DER), and consuming device is communicating with the auctioneer on the bid aggregator level.

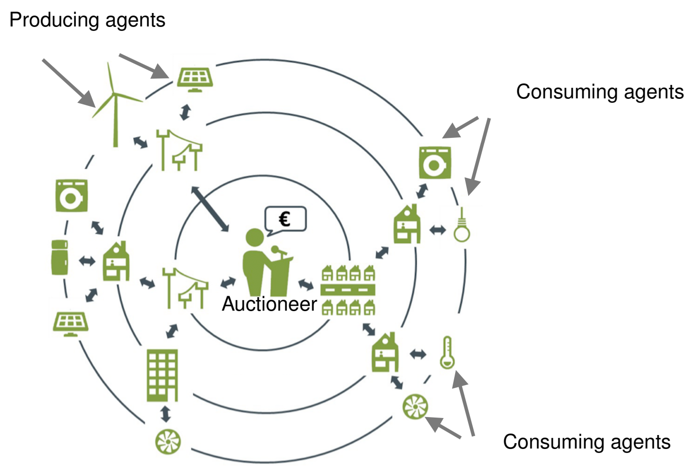



**Figure 4.8:** Transactive energy management platform operating illustration [297].

In the case of a rural microgrid, the *producing agents* are responsible for selling electricity generated by DER's such as a wind generator, PV array, or a diesel generator etc. Each of these agents enter into the auctioning process to sell the energy they are capable of generating. The *consuming agents* include all devices that are energy consumers such as televisions, refrigerators, cellphone chargers, etc. These device agents also enter into the auction market individually by bidding on energy to be purchased. The *auctioneer agent* is responsible for bid aggregation and determining the final market price. It takes a similar role as that of a centralised optimisation EMS, but has a much simpler task since it only has to balance the available supply and demand instead of solving complex optimisation problems. Instead the optimised schedule is found by distributing the decision-making to each individual producing and consuming agent, allowing them to influence the final outcome by participating in the bidding process.

## 4.4. Transactive Platform Algorithm for Rural Microgrids

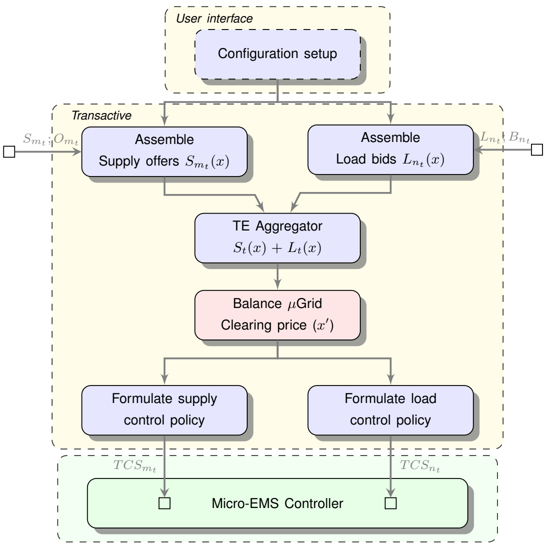
Thus far this paper has been concerned with describing various microgrid energy management approaches and it makes the case that transactive energy management is an ideal solution for rural off-grid microgrids. To show that this EMS can be applied to these type of microgrids, a hardware configuration solution with sufficient communication and data collection capabilities needs to be selected to be used in a simulation. The general transactive energy management control layout advocated in this paper is depicted in the topology of Figure 4.6. This topological flow-diagram for the software implementation of a transactive energy and cost optimisation demand response technique will be tested in a DC microgrid hardware architecture described in this section.

Integrating intelligent distributed resources into transactive energy agents creates a scheduling coordination control platform that operates on the secondary and tertiary control layers. This platform is characterised by cascaded layers of electrical and communication interfaces to provide a flexible digital electronic EMS with uniform command and control protocols to regulate energy product trading and logistics within the smart microgrid energy dispatch system. This section provides a more detailed description of the proposed transactive energy management system for rural microgrids. Section 4.4.1 presents a flow-diagram and accompanying description of the data flow and decision-making of the transactive controller. Section 4.4.2 builds on Section 4.4.1 by focussing, in further detail, on the steps involved in determining the market price as is the function of the *Balance $\mu$Grid Clearing price* block. The mathematical implementation of the energy and price balancing aspects of this transactive control block is detailed in Section 4.4.3 and is followed by Section 4.4.4 where a sample bidding process is discussed.

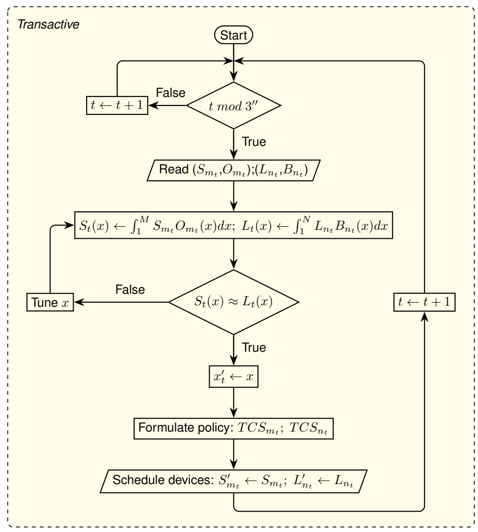
### 4.4.1. Transactive EMS control flow-diagram

For the dynamic market model control topology in Figure 4.6, the parameters are defined as discrete-time variables to deal with multiple trading periods. On the supply side, the Smart Grid micro-generation sources $S_{m_t}$ are defined by associated generation costs $C_{m_t}$ as bid offers $O_{m_t}$ in each control time interval. In a rural village microgrid, the levelised cost of electricity (LCOE) can be used as guideline supply cost parameters $C_{m_t}$ [231]. On the demand side, the loads $L_{n_t}$ are associated with one or more load priority classes $p_{n_t}$, which in turn are associated with load priority group bid offers $B_{n_t}$ for each control time interval.

Configurable supply and load devices participate as responsive energy trading agents in the local transactive energy market according to the diagrams in Figure 4.9. The device agents are configured to submit supply and demand offers as price-quantity pair parameter sets. The price component includes a value function indicating the price(s) at which a given device is willing to sell power $O_{m_t}$, in case of a supply resource, or the price(s) at which a device is willing to buy power $B_{n_t}$, in case of a load. The quantity component includes a value function indicating the amount of power available for sale $S_{m_t}$, in the case of a supply resource, or the amount of power required $L_{n_t}$, in the case of a load device. In more advanced applications, an operational state diagram value may also indicate the willingness of a supply or load device to change between discrete operating states during that period of trading. These parameters serve as inputs to the rural village energy management control scheme depicted in Figure 4.9(a) and Figure 4.9(b). In these diagrams, the section labeled *Transactive* details the workings of the *Transactive Scheduling Optimiser* block from Figure 4.6 and Figure 4.7. The *User interface* section enables customer engagement in terms of defining the bid and offer values ($B_{n_t}$ and $O_{m_t}$) and the switch-gear configurations for load cluster priority $(bus(p_n))$.




(a)




(b)

**Figure 4.9:** Proposed transactive control scheme showing (a) flow-diagram of sequential interactions between control kernels, and (b) software flow-diagram showing transactive computations detailed in Section 4.4.2 and Section 4.4.3.

At the heart of the transactive system is the microgrid balancing and auction bid clearing price mechanism, *Balance $\mu$Grid Clearing price* (seen in Figure 4.9(a)), which receives the aggregated supply and demand bids from the transactive energy aggregator (*TE Aggregator* block). With the bid clearing price determined by the *Balance $\mu$Grid Clearing price* block at the start of each trading interval, the *Formulate supply control policy* and *Formulate load control policy* blocks use the equilibrium price $x'$ to determine the scheduling coordination for the supply and loads respectively. These schedules are coded as transactive control signals TCS$_m$ (supply) and TCS$_n$ (load) and passed on to the *micro-EMS controller*. The *micro-EMS controller* processes the TCS$_m$ and TCS$_n$ signals to control the supply and load coordination logic circuits. It enforces the negotiated energy transactions to enable energy supply and consumption as optimised supply and load coordination profiles $S'_{mt}$ and $L'_{nt}$ respectively. The *micro-EMS controller* thus ensures that the agreed-upon quantity of transacted energy is supplied by the generating resources for each trading interval. At the same time, it ensures that transacted energy delivered to the load device groups via the microgrid distribution system backbone is in compliance with the trading policies. The mathematical implementation for these operations are discussed in Section 4.4.3.

### 4.4.2. Steps of energy and market-price balancing

The microgrid supply and demand balancing function in the *Balance $\mu$Grid Clearing price* block in Figure 4.9(a) is the key component of this energy management approach. The operation of this energy balancing mechanism is illustrated in Figure 4.10 and is active during every market trading interval. It operates on economic principles of supply and demand, where $S$ represents the supply source offers, and $L$ represents the demand load bids in a particular energy market trading interval. From the supply point of view, an increase in price encourages producers to increase energy generation. From a demand point of view, an increase in price will drive down the energy demanded by consumer loads. The market reaches equilibrium when the supply and demand curves intersect at price $P_{x'}$, at which point the consumers can make optimal purchases and producers make optimal sales [309].

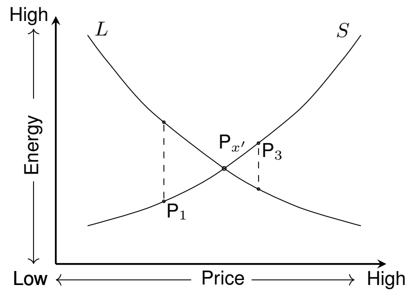



**Figure 4.10:** Price supply and demand curve for proposed Smart Grid transactive energy optimisation in a rural village smart microgrid EMS solution.

At point $P_1$ in Figure 4.10, the price of energy is below optimum and the producers (supply curve $S$) are not willing to sell much of their capacity. This low price means that consumers (demand curve $L$) want to buy more than usual, which leaves trading in the local energy market with an imbalance. This means that the amount of power required cannot be met by the producers, and will result in an energy deficit in the microgrid. At this point neither of the parties involved are operating in their ideal state. This deficit could be narrowed by increasing market price for electricity, prompting producers to sell more while decreasing willingness of consuming devices to purchase. This can drive the operating point closer to the point of intersection, $P_{x'}$, which is where the market would be in equilibrium.

In some cases the market over-compensates with the price adjustment resulting in a move to point $P_3$ where the market price is too high, thus driving the willingness to purchase down. This is also a non-ideal situation where more power will be produced than the consumers are willing to buy, resulting in a surplus. At point $P_{x'}$, the market has reached equilibrium and transactions are optimal for both consuming and producing agents. This simply means that the price and the quantity of energy being sold is ideal for all parties involved.

### 4.4.3. Mathematical implementation of the control solution

This section describes the mathematical implementation of the energy and price balancing aspects of the *Balance $\mu$Grid Clearing price* block detailed in Figure 4.9, which is further implemented on the hardware control architecture of Figure 4.7. Algebraically the supply contributions $S_{m_t}$ for each source ($m = 1, 2, 3, \ldots, M$) during each trading interval ($t = 1, 2, \ldots, T$) are expressed as discrete-time energy supply samples in Equation 4.4.1. At the same time, the demand load sequence $L_{n_t}$ represents the village load as a discrete time-series sequence in the expression of Equation 4.4.2. In price-quantity pairing, the associated supply $O_{m_t}$ and demand $B_{n_t}$ bidding functions are generally formulated in Equations 4.4.3 and 4.4.4 respectively. Variables $a, b, c_m, d, e, g_n$ in Equations 4.4.3 and 4.4.4 are based on selections made by the user in the configuration setup, as well as, the LCOE measures for supply sources, and are used to calculate supply and demand agent bids.

$$S_t{=}S_{1_t} + S_{2_t} + \cdots + S_{M_t} \tag{4.4.1}$$

$$L_t{=}L_{1_t} + L_{2_t} + \cdots + L_{N_t} \tag{4.4.2}$$

$$O_{m_t}(x) = \begin{cases} 0 & x \leq a \\ \frac{c_m(a-x)}{b-a} & a \leq x \leq b \\ -c_m & b \leq x \end{cases} \tag{4.4.3}$$

$$B_{n_t}(x) = \begin{cases} g_n & x \leq d \\ \frac{g_n(x-d)}{e-d} & c \leq x \leq d \\ 0 & e \leq x \end{cases} \tag{4.4.4}$$

For each trading interval, the price-pair functions are integrated for the supply sequence $S_{m_t}(x) = S_{m_t} O_{m_t}(x)$ and load demand sequence $L_{n_t}(x) = L_{n_t} B_{n_t}(x)$ to balance microgrid supply and demand. A numerical search algorithm is used in the objective function in Equation 4.4.5 to optimise the price decision variable $x$, thus determining the market equilibrium price point at which the supply/demand balances within defined constraint margins. It essentially determines the bid clearing price ($x'$ in Figure 4.9) by minimizing the microgrid energy balancing cost function $\mathbb{C}_x$ in Equation 4.4.6).

$$S_t(x) + L_t(x) = \int_1^M S_{m_t} O_{m_t}(x)\, dx + \int_1^N L_{n_t} B_{n_t}(x)\, dx \tag{4.4.5}$$

$$\min_x \quad \mathbb{C}_x = \int_{n=1}^{N} L_{n_t} B_{n_t}(x)\, dx \tag{4.4.6}$$

subject to constraint: $L_t(x) \leq S_t(x)$

While the procedures in Equations 4.4.5 and 4.4.6 are used to determine the bid clearing price $x'$, this price serves as determinant for formulating the supply and load device control scheduling policy in Figure 4.9. These policies subsequently determine the supply and load transactive control signals, TCS$_m$ and TCS$_n$, which in turn drives the micro-EMS control logic to deliver transacted energy sell $S'_{m_t}$ and purchase $L'_{n_t}$ orders. The underlying mathematical computations performed by the *Balance $\mu$Grid Clearing price* block in Figure 4.9 are simplified to allow implementation on a low cost systems suitable for remote rural villages with limited resources.

The proposed microgrid EMS and energy balancing mechanism (Equations 4.4.5 and 4.4.6) operate as a secondary control intervention. It is thus an indirect control method to strategically coordinate and control the supply and load device operating environment in the microgrid ecosystem. It is cascaded with primary control, which still controls real-time current and voltage behaviour of individual devices. Primary control has functional primacy over the EMS and it is directed at the external environment which involves millisecond control measures to change the instantaneous behaviour of individual assets to fit device operational conditions.

### 4.4.4. Energy transaction balancing algorithm operation

Each consuming and producing device agent has its own bidding strategy which allows it to bid for energy purchases in every market time step. In practice, the bidding strategy of each device may include a range of different prices that agents are willing to sell and buy energy for. These are described as functions in Equations 4.4.3 and 4.4.4 that each depict willingness to buy or sell a certain amount of energy. It is based on the current price of that energy, as well as, the current state of that device. Figure 4.11 shows a simplified version of the process with an example of a single power producer, a single consuming device, and the auctioneer platform.

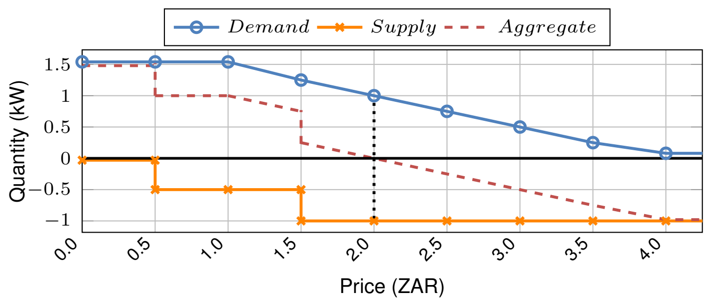



**Figure 4.11:** Illustration of microgrid aggregated supply/demand balancing and procedure of determining the market clearing price in a sample trading interval according to Equations 4.4.5 and 4.4.6.

The *Demand* line in Figure 4.11 represents the bidding function of the consuming device (this could be a TV, refrigerator, fan etc.), and is interpreted in the same way as demand $(L)$ in Figure 4.10. In its current state, this device is willing to consume 1.5 kW of power if the cost of electricity remains under 1.0 ZAR (currency - South African Rand) while the willingness will gradually diminish as the price increases. At 4.0 ZAR, this device will no longer be interested in purchasing any electricity.

The *Supply* line in Figure 4.11 represents a power producing device (diesel generator, PV panel, wind turbine etc.), which is interpreted in the same way as supply $(S)$

in Figure 4.10. In its current state, this device is unwilling to produce and sell power for prices under 0.5 ZAR. The bidding curve of this device is represented by a step function and its willingness to produce will increase in a stepwise manner at specific price thresholds. During the energy auction process, the bid aggregator bid clearing function weigh and balance the aggregated load bids and supply offers as a function of price $x$. The goal of the aggregator is to determine the clearing price $x'$ where the aggregated supply $S_t(x')$ is equal to the combined loads $L_t(x')$.

The auctioneer receives bids from each individual device agent (generation and consumption agents) in the microgrid and aggregates these bids in order to find the market equilibrium or clearing price $x'$. The *Aggregate* line in Figure 4.11 represents the sum of all the bidding curves submitted by generation and consumption agents in the microgrid (in this case there was only one of each) [318]. Note that the bidding curve of the generation resource is on the negative portion of the graph, which means that the aggregate can by found by simply finding the sum of the generation and consumption functions. The point at which the aggregated bid curve intersects the x-axis (at y = 0.0) represents the market bid equilibrium price discussed earlier (point $P_{x'}$ in Figure 4.10) [318].

In this case (Figure 4.11), the aggregate curve intersects the x-axis at x = 2.0 which means that the market price is cleared at 2.0 ZAR until the next bidding period (typically only a couple of minutes). For this specific price, the generating device was willing to supply 1.0 kW of power while the consumption device was willing to consume 1.0 kW. By aggregating the bids, the auctioneer has found a way to satisfy both agents from a financial point of view while maintaining an energy balance on the grid (1.0 kW produced and 1.0 kW consumed).

The same process is followed by the transactive auctioneering aggregator when there are a large number of devices, each submitting their own bidding curve. As with the other energy management approaches discussed in this paper, the results from these bidding periods are passed down to the other control layers discussed in Section 4.2 so that they can be applied by the real-time controller.

## 4.5. Simulation Results

The local supply network configuration discussed above can now be used to simulate transactive resource scheduling when applied to an off-grid microgrid using load profiles for a rural African household. The model aims to demonstrate the simulated operation of the proposed transactive energy management demand response coordination framework described in this paper.

In order to show that the proposed solution provides a pragmatic and feasible approach for energy management in rural off-grid microgrids, it is necessary to use load and power generation data that is applicable to this context and environment. Therefore, the load agents used in this simulation are from disaggregated rural household load profile archetypes generated during previous research and include several rational appliance load groups, such as lights, refrigerators, televisions, radios, cellphone chargers, etc. [229]. To ensure that the generation profiles for the DER's are realistic and representative of a rural village microgrid, these data profiles were generated using

Meteonorm climate data and applied to a TrnSys model representing a village microgrid in rural South Africa.

### 4.5.1. Simulating transactive EMS in a rural microgrid

The simulation starts off with the systematic classification of heterogeneous devices into six homogeneous load priority groups. The priority differentiated buses offer the ability for switchable control over six load category priority levels ($p = 1, 2, .., 6$). The load categories and associated price bid levels can be dynamically modified by the individual home owner for different time slots. In this simulation example the priority levels set on the in-home display (IhD) configuration interface are generally set as follow: Radio ($L_1; p_6$), Fridge ($L_2; p_5$), Security lights ($L_3; p_4$), TV ($L_4; p_3$), Lights ($L_5; p_2$), Cellphone ($L_6; p_1$).

The demand response results for the 24 hour load profile is shown in Figure 4.12. This profile is representative of a single household within the village and is used in isolation to demonstrate the operations of the transactive EMS. The red line in this graph represents the original unconstrained load profile ($L_t$) for the village household devices, while the blue line represents the load profile after transactive demand response control scheduling ($L'_t$) had been applied. It also shows the generation capacity for the solar CHP system, scaled to represent availability for a single household. Operating under budget and energy availability constraints, it is clear that load curtailment mostly takes place during peak consumption times in the morning and evening. Unlike a centralised optimisation approach where these constraints would be used to solve a unit commitment problem, the resulting load profile in this simulation is based on energy transactions cleared during the bidding process.

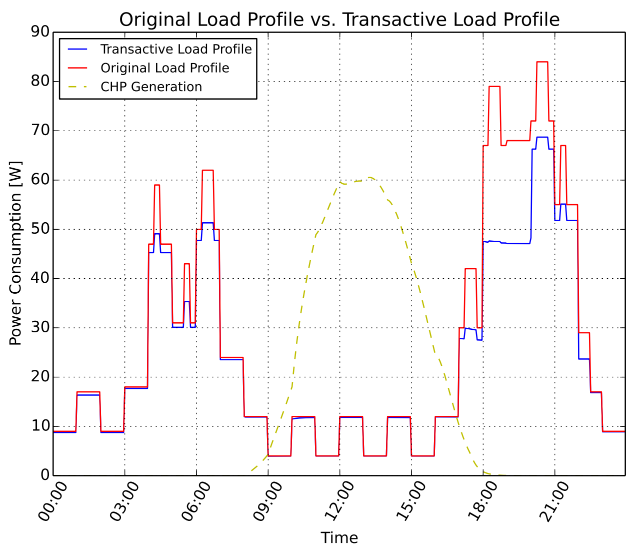



**Figure 4.12:** Device aggregated demand profile $L_t$ (red) versus actual energy purchases for load transactions $L'_t$ (blue) cleared throughout the day.

Essentially the transactive load profile (blue line) represents microgrid energy purchases for load priority group transactions cleared by the bid aggregator throughout the day. It highlights the fact that some load groups do not purchase energy during certain bidding time periods because the bid clearing price was too high. This can be observed more clearly for each load group in Figure 4.13, where the effect of the transactive EMS on each load is shown individually. The individual device consumption profiles (Figure 4.13) show that very little curtailment takes place in the early morning between 00:00 and 04:00, or in the evening between 23:00 and 00:00. This is due to the village load demand being lower during these hours, while the power rating and usage of appliances that require energy during these times (security lights and refrigerator) have been set to a higher priority (willing to pay higher price for energy). Devices also experience lower levels of curtailment between the hours of 07:00 and 17:00 because of an influx of less expensive solar CHP power, which means that appliances with low priority settings can easily afford transactive participation.

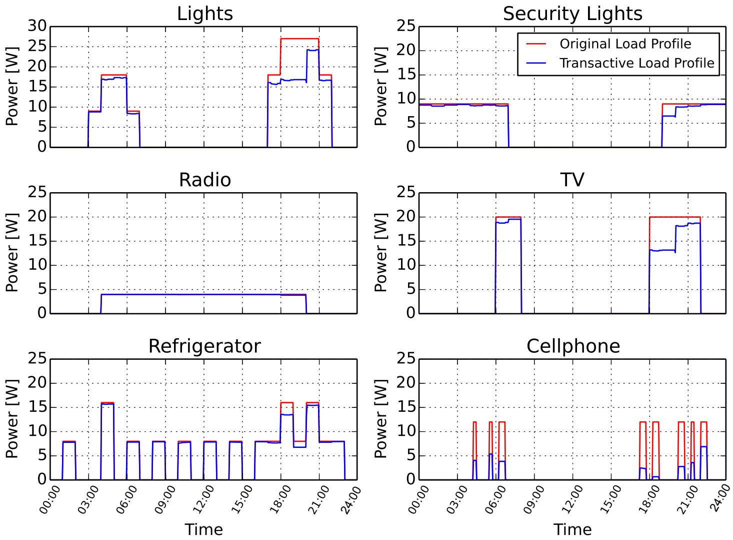



**Figure 4.13:** Device disaggregated energy demand $L_{n_t}$ (red) versus the transactive device bid energy purchases $L'_{n_t}$ (blue) cleared throughout the day.

Figure 4.13 further shows that low priority device groups, like lights and cellphone chargers, experience frequent curtailment during the morning and evening peaks. Televisions also experience a certain amount of curtailment, although at a lower rate, during these times. During these bidding time intervals, the lower cost solar energy system has gone offline while several other loads with higher priority bid settings have started to compete for power. The absence of low cost energy in the presence of the higher priority loads have driven the market price up during these times. Depending on the user energy budget, individual village household users could increase the priority of certain device groups during selected time periods (e.g. increasing priority for TV during news hours). This will allow these curtailed devices to make more aggressive bids and have a better chance to be successful in the bidding process. This would not only drive up the user energy bill, but it will also raise the market price of energy in the microgrid during this time. It means that the users would not only increase spending because more power is purchased, they would also be spending more because each unit of electricity has become more expensive (driven up by demand).

This enables users to easily make adjustments to the load group priorities, allowing them to remain within their daily energy budget while not causing power shortages in critical loads. The ability to interact with the microgrid EMS on such a basic and practical level is intuitive to users and aims to avoid the frustration and disappointment usually experienced by new power users in rural village electrification projects.

### 4.5.2. Advantages of transactive EMS in a rural microgrid

Transactive energy management has already shown great success in modern Smart Grid and microgrid simulation models and field experiments in Europe and the US [297]. This energy management approach builds on previous EMS techniques while adding familiar principals of marketplace supply and demand. This approach has to our knowledge not yet been applied to rural village microgrid projects, in theory or in practice.

To support our case for market-based control in a local rural village energy market, the bulleted list below highlights several advantages of transactive energy that are relevant to rural off-grid microgrid platforms:

- ⇒ High level of self optimisation which is ideal for the rapidly changing operating conditions in isolated rural microgrids [221, 319].
- ⇒ The transactive concept of market based price determination is based on concepts familiar and intuitive to rural village users.
- ⇒ Allows for high levels of user interaction, but can function effectively without user inputs with system changes.
- ⇒ The model scales very well, allowing for growth and interconnection between these off-grid microgrids without requiring additional computational power to solve increasingly complex optimisation problems. This adds to microgrid resiliency.
- ⇒ Field experiments have shown peak load reduction of up to 50 % and wind generation imbalance reduction of up to 80 % [297].
- ⇒ Reduced need for microgrid operational analytics and projections in transactive decision-making.
- ⇒ Centralised EMS relies heavily on accurate forecasting models to generate optimal control schedules. While the forecasting data still has an important role in transactive energy management, it can function effectively without it.

It is clear that while this EMS approach had been successfully employed in several Smart Grid projects in varying environments, the positive outcomes are always overlapping as discussed here. It is believed that the same positive outcomes can be achieved by applying this approach to rural microgrid installations since it can directly address many of the problems faced in when creating a participative low-cost EMS for off-grid microgrids. The following section address the microgrid hardware and network configuration requirements for such a transaction based EMS.

## 4.6. Summary and Conclusion

Many of the difficulties faced in rural electrification projects around the world are often brought about by ineffective system energy management [80, 221]. In many of these cases the lack of understanding from the system designers with regards to energy usage and the rapid increase of energy usage cause major problems during operation [221]. Microgrids with two way communication and effective central EMS can potentially overcome many of these challenges. However, it is only able to do so if operating conditions were accurately defined in the optimisation parameters and remain so for the duration of the project. There are also several other restrictions with this method which prompts the investigation to find an improved approach for rural microgrids.

In order to resolve challenges faced in isolated rural energy applications, designers often borrow from rapidly growing grid environment approaches. The transactive energy management concept offers potential solutions that can help to overcome rural energy management challenges in isolated microgrids [320]. Transactive energy management generally aims to move away from central energy management optimisation towards a multi-agent based system with distributed optimisation, making it ideal for remote isolated off-grid (similar to island power systems) applications. It offers attractive modern Smart Grid attributes that may guide the development of new frameworks, such as blockchain, while promoting exciting opportunities for localised user participation in energy management decisions [321]. In rural microgrid applications, it further ensures advantages such as better scalability, increased reliability, major reductions with regards to computational power required, more control over energy spending through high levels of user interaction, and has the ability to self optimise in a rapidly changing environment [319].

The transactive features described in this paper makes the emerging approach a strong technology contender for orchestrating the coordinated operation of supply and load devices in a local rural smart energy grid environment. It involves forward-looking transactive pricing schemes to facilitate user participation based scheduling coordination in a market-based resource allocation system. This micro-economic enterprise type model provides potential benefits from harnessing the flexibility in the planning and operation of DER's and would thus help to meet an evolving set of requirements for an efficient, safe, reliable and resilient energy systems. The concept embraces the complex system of systems nature to present practical, scalable ways to integrate the assets of many self-directed participants working toward a mixed set of individual and shared objectives. The features discussed here make a strong case for applying a multi-agent transactive energy management approach in rural off-grid microgrids to improve the user satisfaction, productive lifetime and overall performance of these installations. Apart from the hardware requirements, semiconductor switchgear and user load priority configuration boards ,the proposed microgrid EMS system is software based. Since these transactive energy systems are software based, they are inherently scalable and replicable and can be included in new microgrid projects without the addition of more development cost.

The paper proposes a platform for a transactive pricing scheme implementation to be used in rural off-grid microgrid systems. Since EMS generally operate on the secondary and tertiary control layers of microgrid system control, it gives the opportunity to use higher level digital control intelligence with pricing and control logic (such as transactive energy principles) to command local energy resources and load devices. The transactive EMS solution enables customer engagement by allowing them to continuously adjust hierarchical load priority levels in order to meet the village power budget, energy expenditure, and fuel availability needs. The proposed smart microgrid energy management model not only considers the management of energy sources for generation, but also includes demand side management load coordination through flexible timing of energy consumption by controllable and uncontrollable loads. There is also great potential for developing countries to engage transactive energy trading models based on barter and blockchain payment models, especially with a need for the electrification of rural communities through microgrids since the regulation is less restrictive [322].

The proposed transactive EMS system and method aims at rural homestead deployment as enabler for localised rural village energy-related markets. Instead of rural village home owners having to buy expensive new intelligent appliance devices typically enabled for automated internet energy trading in a local (urban) district energy system, the rural village solution proposed herein is greatly simplified to accommodate the control existing conventional appliances. It works by enabling an array of multi-priority DC bus-bars in household distribution panels to operate as collective energy “agents" in a multi-agent system, acting upon owner instructions to bid, buy and provide energy on behalf of categorised groups of conventional un-intelligent appliance devices linked to the respective prioritised DC buses. The transactive EMS auctioneering bid aggregator for the rural village microgrid employs custom formulated and simplified transactive control decision principles to determine the bid-clearing price through multivariate mathematical formulations described in with simulation examples in a follow-on paper.

The simulation results for the proposed off-grid village microgrid EMS broadly illustrates how a transactive based approach operates. Figure 4.12 specifically demonstrates how the microgrid EMS was able to manage the energy transaction schedules in terms of supply source trading dispatch commands resulting from the trading (buying and selling) of energy in the local village energy market platform. With the addition of low-cost devices, the system is able to record energy consumption patterns and create energy transaction reports for financial tracking. This data will be important to support future inter-rural village energy trading platforms for remote rural areas. These smart microgrids allow for easy integration with blockchain platforms and can be based on modern crypto-currency (Bitcoin or OpenCoin) trading to enable peer-to-peer local inter-village trading.

# Chapter 5

# Synthesis of Smart Village Multi-Agent EMS

**Paper:** Prinsloo, G.J., Dobson, R.T., Mammoli, A.A. 2017. Synthesis of an Intelligent Rural Village Microgrid Control Strategy Based on Smart Grid Multi-Agent Modelling and Transactive Energy Management Principles. *Submitted to Elsevier Energy*, [323].

## 5.1. Introduction

Energy liberty in rural communities needs an alternative to the extension of operator-based centralised grids, which has proven to be slow and overly expensive in reaching the people who need it the most [5, 67, 70]. This idea of a new alternative vision is promoted by the IEEE Smart Village movement, which is supported by the IEEE Foundation, to impact 50 million people by the year 2025 through decentralised village projects [120].

Microgrids, powered by renewable energy resources, are considered to be an ideal technological solution to supply energy to remote rural sites [5, 67, 80, 285]. One of the main challenges facing distributed energy microgrid (DEM) designers is the intermittent nature and characteristic unpredictability of renewable sources [324]. This problem is exacerbated by demand variability, especially variances in domestic energy consumption patterns (daily, weekly and seasonal) which creates challenges in balancing local supply and demand [325]. Therefore, the energy management system (EMS), which is responsible for optimising the balancing of supply and demand in the microgrid, is a critical design element [326, 327]. The EMS engages computational intelligence to ensure that fluctuating generation patterns of distributed renewable resources match the energy consumption patterns. In addition to the challenges of optimising the scheduling of supply and demand, most rural energy consumers have a very volatile day-to-day energy budget [5, 80]. This requires careful consideration during the project planning to ensure that the energy consumers have the ability to stay within their daily budget (flexibility in payment) [80, 220].

There are several different approaches to microgrid energy management, but generally, it can be narrowed down to centralised or decentralised decision-making [19, 327]. One the one hand, the centralised EMS approach operates on the principle of collecting data relating to generation and consumption from the microgrid components and then using predictive analytics to forecast future conditions. With the availability of this information, the centralised EMS will employ optimisational techniques, often aimed at meeting multiple objectives, to generate a schedule of control set-points. On the other hand, the decentralised EMS is based on a network of autonomously distributed controllers with embedded decision-making capabilities, each controller acting on behalf of a device in the microgrid. In this case, instead of relying on a single unit for decision-making and scheduling, operational optimisation is achieved by communication and coordination among the controllers in the system. Since the microgrid, in this case, consists of multiple controlling agents that act on behalf of associated devices, these systems are often referred to as multi-agent EMSs. Because of the microgrid control being distributed among several devices, the system has prominent resilience and robustness characteristics, and it will continue to function even when some of the controllers fail [327]. Also, the omission of a centralised controller that collects detailed user information solves many of the privacy concerns often associated with the Smart Grid and smart devices [297].

New opportunities in the era of cyber-physical convergence and ambient intelligence will arise for pervasive computing in intelligent actuation platforms as virtually everything will be enabled to source information and respond to appropriate stimuli [162, 328]. Since end-user devices have access to energy consumption and pricing data (pre-paid meters, digital energy meters, smart meters or an advanced metering infrastructure), dynamic demand response programs can be incorporated. In the context of this user-interactive application development platform, the integration of the microgrid EMS with cascaded multi-agent control and an open automated demand response facility makes microgrid systems smarter and thus more reliable, flexible, and adaptable [31, 329]. Price-responsive demand- and supply procedures focused on function-bidding are able to reach a price equilibrium in facilitating consensus based on prospective trading exchanges in energy (cooperative gaming participation) [297, 330]. Dynamic microgrid inter-connections and cross-trading requirements at the grid edge of smart distributional networks have further inspired the conception of a multi-agent systems approach to transactive energy (TE) [331]. This is based on modern Smart Grid EMS approaches which incorporates computational intelligence with Purdue-type industrial automation principles to ensure that the generation patterns of the distributed renewable resources match dynamically varying energy consumption patterns [122, 332].

From a decision sciences perspective, Kok *et al.* [333] proposed a multi-agent transactive energy management approach for application in a modern Smart City-type microgrid system. Kok's team engaged in two large-scale pilot demonstration projects, EcoGrid and PowerMatching City, where the technology was successfully implemented to improve the efficiency and effectiveness of integrating renewable energy into the grid and microgrids [19]. Key outcomes were the demonstration of technology scalability, the ability to reduce peak loads, and self-optimisation capabilities in the context of the Smart City [19]. Both the EcoGrid and PowerMatcher projects received international sustainability awards for their innovative implementation and overall performance [19]. The Pacific Northwest Smart Grid Demonstration project, run by Pacific Northwest National Laboratories, also featured the application of a transactive energy management approach based on negotiations amongst device agents [310]. The project extended over numerous states and relied on the participation of eleven utility companies and several co-operative electricity providers [297, 310]. Similar to the results of Kok [19], the project outcomes included improved reliability, energy conservation, energy efficiency, and responsiveness, with the sheer size of the implementation impressing in terms of scalability [297]. Karavas *et al.* [327] investigated the application of multi-agent decentralised energy management for the autonomous control of polygenerational microgrids and found overall improvements in performance as opposed to those in centralised energy management, with resiliency being the dominant aspect that stood out in thus respect [327]. Coelho *et al.* [334] found that since a multi-agent energy management approach engages the microgrid users in the decision-making process, it is able to ensure cost reduction as it allows for the additional optimisation functionality, while also preparing the way for future blockchain integration [335]).

With the IEEE Smart Village vision in mind, this paper proposes an intelligent, value-based control as a transactive energy management system (TEMS) for a rural off-grid village microgrid. It engages computer modelling, simulation, and analytical techniques to experiment with the multi-agent reasoning in a Smart Village transactive EMS. In the face of the rural communications infrastructure challenges, such as latency and the costs of cellular airtime [336], the optimisation design for the off-grid Smart Village DEM should be less reliant on web intelligence or centralised controllers. The objective of this paper is to show that a multi-agent TEMS can be used to optimise the balancing of resources in a rural microgrid while simultaneously addressing the volatile day-to-day energy budgets of rural families by allowing for the effective control of user day-ahead energy spending. The proposed EMS is incorporated in a rural village microgrid model with a system architecture that provides for multi-agent transactive control (detailed in a previous study) [291]. Since the EMS is transactive by nature, it relies on value-based control principles to maintain a balance between generation and consumption. This means that every decision made by any of the agents in the microgrid will have an impact on the price of energy as a commodity stream [337]. Furthermore, machine-learning techniques are employed to make day-ahead forecasts of the household energy expenditure which can then be optimised to strike a balance between household needs and the family budget.

The modelling approach for the smart rural village microgrid is presented in §5.2. §5.3 gives an overview of contextual challenges inherent in microgrids powered by renewable DERs, and details a proposed transactive solution and illustrative schematic to integrate the retail energy pricing operation and demand response on a Purdue enterprise automation hierarchy. §5.4 details the market-based control approach, the logical automation architecture of the intelligent energy management system, and the modified digital trading platform. §5.5 employs case-based computer modelling, simulation, and analytical framework as a challenge scenario narrative (developed in our previous research [226, 229, 230, 240]) in the potential use of the proposed transactive approach as a Smart Village distributed energy management and cost control mechanism. §5.6 provides a summary, conclusion, and recommendations for future research.

## 5.2. Model-Based Design Approach to Village Microgrid

Intelligent microgrids should lead the way to 100 % renewable energy in smart microgrids through new smart energy management technologies [324]. To this end, renewable distributed energy resources (DERs), energy storage, and demand response enabling technologies should be intelligently integrated and managed to ensure an efficient and modernised smart energy microgrid. The diversity of highly distributed small-scale generation resources in DEM can satisfy basic socio-economic needs in rural

Smart Village microgrids (LED lighting, portable radios, satellite TVs, cellphone charging, refrigeration) [312]. A Smart Energy Systems (SES) approach, focuses on energy management from a holistic point of view that allows the seamless integration of multiple energy streams, not just electricity [338]. In a prosumer-based SES context, the integration of distributed energy resources (DER), through appropriate distribution management control offers attractive opportunities for software solutions to address multiple economic, technical and environmental challenges, the latter posed by the proliferation of customer-owned distributed resources, into an integrated DER ecosystem.

Various initiatives support accelerated growth in off-grid energy markets for developing countries by underlining the need for transformation that presents opportunities and catalytic empowerment in off-grid energy systems. The IEEE Smart Village (ISV) program supports rural microgrids to simplify operations for distributing local power with improved reliability and efficiency while the USAID has formulated the "Scaling Off-Grid Energy Grand Challenge for Development" (SOGE) program to promote and accelerate energy self-sustainability [78]. Both are campaigning for new solutions, new components, network configurations, operational methods in design, and new business models. This is to address issues around energy access, efficiency, security, and the structure of community energy systems for developing regions where the focus is on the penetration of renewable energy elements. Many of these qualities can be found in modern Smart Grid approaches, especially since they have experienced increased interest in microgrid technology, making them more relevant to the rural energy landscape.

The US DOE Electricity Advisory Committee (EAC) put forward a plan to re-align the Smart Grid as an enabler of the new energy economy [339]. This program aims to transform the grid into a more market-based, interactive, and user-centric network that is more intelligent, resilient, reliable, adaptive, and autonomous [58]. In the utility grid, the next generation network is aligned towards the unbundling of the Smart Grid into microgrid coalitions that allow for enhanced consumer choice, economic opportunities, energy security, environmental stewardship, and operational efficiency [53, 102]. In such a smart energy eco-system, the focus is to meet collective energy goals through creative collaborations for improved energy system operations [42].

To this end, the strategic management of Smart Village microgrid energy in a granular architectural (cellular meshed) microgrid network is approached as a rural Smart Village distributed market-based control automation solution. The focus is on information systems and decision sciences to support computational thinking requirements (smart electric power system data collection, data processing, and action). From a cyber-physical technological point of view, the aim is to simplify smart microgrid economics to engage DEM prosumers in determining dynamic load priorities according to the varying needs of rural village end-users. As a cyber-physical system, a DEM is given expanded scope and variety as an energy manufacturing and management system with added flexibility of control through the integration of dynamic pricing signals, economic attributes and environmental signal components as feedback [163, 340].

Promising features, suited for rural village microgrids, of the distributed multi-agent market-based control approach was presented by Prinsloo *et al.* [291], which prompted further development of this transactive concept as a possible Smart Village microgrid platform. To this end, the present paper aims to model the off-grid rural village microgrid as a multi-agent nodal system and therefore to formulate distributed market-based transactive control as a discrete-time system. This is done according to the proposed methodology depicted in Figure 5.1. A similar approach to those of modern Smart Grid frameworks (SGAM [43, 42]) is used as part of the design conceptualisation (Figure 5.1), which led to the recommendation of market-based control. In this context, the hierarchical Purdue enterprise automation platform provides a wealth of new computationally-intelligent behavioural dynamics, as well as a logical network of control, that enriches the cyber-physical eco-system [44, 341]. The production automation aspects of Purdue models cover the domains (dimension of SGAM) in the energy conversion chain over the hierarchical levels of control in power system production management. It ultimately prepares the microgrid control design for future market integration (including commercial blockchain) as part of a Smart Village economy.

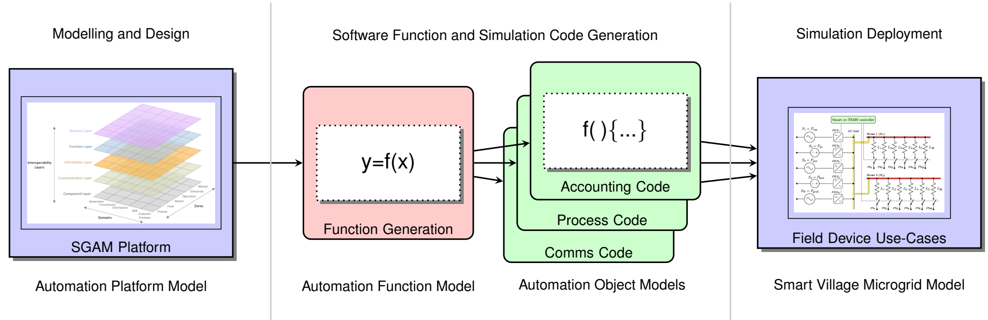



**Figure 5.1:** Conceptual view of Smart Village microgrid simulation engineering methodology in a virtual platform deployment environment.

Digital algorithmic conceptions were realised in discrete-time mathematical formulations in the following stage of Figure 5.1, while software objects were allowed to operate as device-representative agents. Figure 5.1 aims to ensure a conceptualised digital-network-oriented Smart Village distribution system platform that allows for prosumer devices to be intermittently added and removed without compromising the optimisation capabilities of the system. The new digitalised version is further able to accommodate software objects as future participating service agents in the microgrid network (similar to mobile apps in cellular platforms), thus allowing for options towards a more service-oriented architecture for the future. These agents can represent all microgrid network devices, including non-smart conventional DERs and non-smart appliance devices.

## 5.3. Conceptual Participative Transactive EMS Solution

This section contains a brief discussion of the structure of the proposed microgrid EMS platform, shown in Figure 5.2, to facilitate an understanding of its operations. The fundamental principle in the proposed microgrid platform is that a user-configurable transactive energy management system (TEMS) operates as a distributed, value-based, dynamic control automation solution for peripheral energy devices.

A unique approach was needed to design a Smart Village microgrid that could operate on the proposed transactive EMS principles without exclusively using smart appliances. The proposed power routing architecture, shown in Figure 5.2, inherently allows for the necessary communication and decision-making capabilities needed for legacy devices as proposed in previously published work [291]. The TEMS resource coordinator is hosted by the smart energy system's on-premise processor and the is characterised by cascaded layers of power and communication interfaces to provide a flexible platform and uniform protocol for regulating energy product traffic and logistics within the microgrid. The system includes various software layers for the registration, accreditation, and management of configurable add-in components (DER, storage devices, load devices) in governing the local energy auction market.

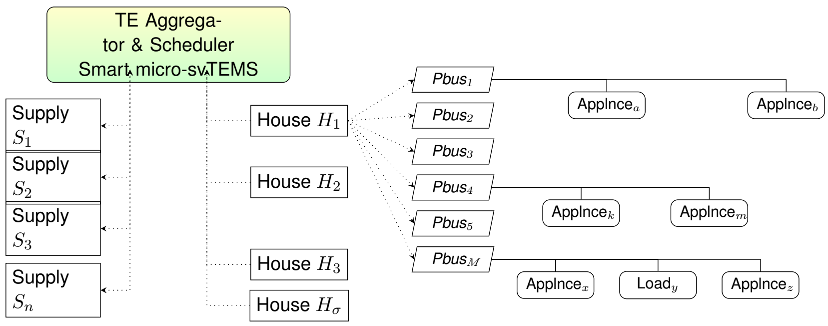



**Figure 5.2:** Proposed transactive sv-TEMS with telemetric interactions between the microgrid network node devices as dealing agent elements.

The conceptual schematic diagram in Figure 5.2 offers a bare-bones layout to assimilate the proposed TEMS solution. A multiplicity of microgrid node device components ($S_{1..n}$, $Applnce_{a...z}$) function as resource supply/demand capacity in the microgrid (consumer supply capacity, supply curtailment, load curtailment etc.). Registered device units in the microgrid system are dynamically configurable and act as distributed agent entities which allow for participation in local market deals in energy. In the case of inflexible/non-smart devices ("dumb" appliance devices), device groups can be cluster licensed and chartered as active representative grid element (group feeder) electronic agents ($Pbus_1..Pbus_M$). Registered agents are dynamically configured as prosumers, and are licensed as such, while each user is assigned a unique identifier (IP address), object attributes (economic/performance) and method of behaviour. Agent agendas include routine points such as: giving an indication of interest in energy sales and/or purchases through tender filing; reaching agreement on transaction; ensuring the delivery of energy packets; and reporting on the deliveries and/or consumption of energy. The Smart Village transactive energy management system (sv-TEMS) coordinator issues router messaging instructions to certified agents over a secure communications network, using digital messaging protocols to coordinate cohesive device operations. The dashboard-configurated interfaces at each node ($S_{1..n}$, $H_1..H_\sigma$) enables consumers and operators to dynamically administer economy/performance settings for registered microgrid client device agents (includes both generation and load devices).

The conceptual architectural solution in Figure 5.2 can now facilitate formulated programming and economic models to ensure optimal supply/demand logistics in the microgrid ecosystems. The aim is to facilitate the development of an argumentative knowledge platform that can interact with the user in a social system (a microgrid systems in which people and collective decision-making play a principal role). Device agents on both the supply and demand side participate in the distribution arrangement as shows in Figure 5.2. On the supply side, $S_{1..n}$ comprise a combination of distributed generation resources (i.e. micro-cogeneration, solar PV, biogas, wind). On the demand side, heterogeneous devices (load assortment $Applnce_{1..z}$: lights, refrigerators, television, portable radios, cellphones, battery chargers, consumer electronics, etc.) are connected to prioritised in-house supply lines ($Pbus_{1..M}$). Supply buses ($Pbus_{1..M}$) cluster inflexible load in homogeneous groups as an array of power wall-sockets with differentiated load service ratings. Each supply line (consortium of loads) acts as a registered *Broker Agent* in energy dealing for its associated array of wall-sockets (a proxy for "intelligent sockets"). Programmable load device models in Figure 5.2 thus operate as certified load coalition brokers/traders in the DEM transactive registry. Licensed registry certification and accreditation allow for the device broker/agent entities to legally participate in contractual transactive offer/bid activities (DEM energy orders and sales). This also allows the device logistics to be regulated/managed by the sv-TEMS supply/load task-scheduling controller in terms of the rules and policies of the energy auction.

## 5.4. Smart Village micro-TEMS Control Architecture

This section offers an enabling disclosure of the user programmable transactive automation solution in. The smart microgrid architecture for rural customer participation is established in a programmable economic environment. This architecture primarily incorporates a conceptual multi-priority transactive control management solution, based on user concensus. Its operational model offers embedded operational intelligence for the deployment of resources in local energy markets. This is used to investigate the application of an integrated retail pricing and operational strategy with end-user demand response in the integrated smart rural village energy system. The proposed transactive control model is used to devise a dynamic pricing scheme that considers the cost of generation in tandem with demand response to iteratively deliver optimal dispatch plans that facilitate the integration of renewables while exploiting retail energy principles on the same Smart Village energy platform.

### 5.4.1. Microgrid TEMS automation platform

The transactive energy control approach in Figure 5.3 is at the heart of the Smart Village microgrid platform. As previously stated in §5.3, it realises the functional model and data flow processes for responsive micro-generation and responsive load device participation during DEM market trading intervals. The design supports modern trends where local intelligence is shifted towards devices, while pushing computation and load control towards the grid-edge [297], the purpose being for control software objects and command execution kernels to run on an embedded micro-processor. It enables the agents to perform the required operational sequences through on-board operations towards the goal of the synchronised steering of microgrid supply/load device models (or prioritised device cluster models).

The operational model in Figure 5.3 deals with market orders and the execution of trade, thus solving microgrid control coordination problems. The transactive operational

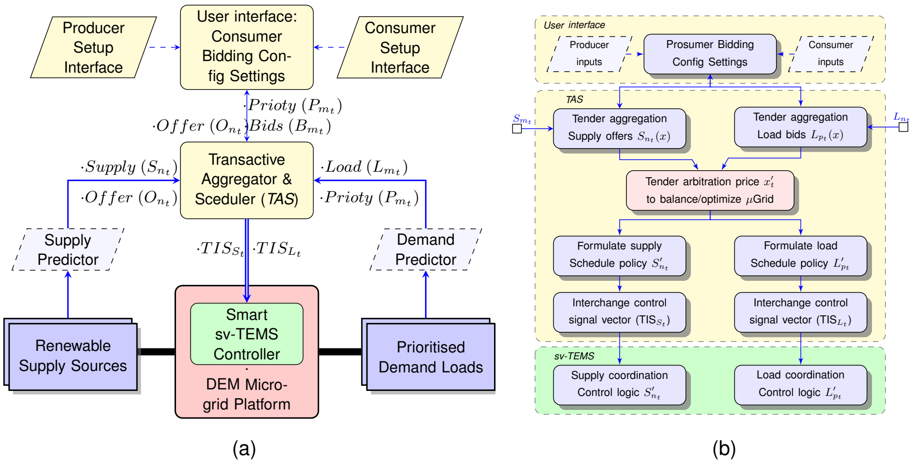



**Figure 5.3:** Proposed transactive sv-TEMS software control approach, showing (a) operational model for control automation architecture, and (b) expanded activity flow-chart for the transactive aggregator, ranking algorithm, and scheduler (TAS) control block.

model and energy delivery system of Figure 5.3(a) manages the flow and exchange of energy between flexible loads and dispatchable supplies. This microgrid EMS platform orchestrates the operation of participating heterogeneous load devices according to the procedure detailed in Figure 5.3(b). The *User interface* enables customer engagement to define the bid/offer values ($O_{nt}/B_{mt}$), cluster priorities ($L_{p_{m_t}}$) and switch-gear/relay settings ($Pb(L_p)$) in [291]. The *Transactive Aggregator & Scheduler (TAS)* software embedded block, resident in Figure 5.3(b), engages mixed-signal transactive tendering values $S_{n_t}$, $L_{m_t}$, $O_n$ and $B_m$ in the auctioning platform, to perform finite capacity scheduling between DEM consumers and power providers. The TAS block serves as the operating and logistics planner for exchanging information about energy transactions and operating schedules in the topology of Figure 5.3.

The inner operations of the TAS auction administrator of Figure 5.3(a) is depicted in the client-server transactive flow-chart layout of Figure 5.3(b). This auction bargaining mechanism functions as a tender aggregator, power balancer, policy compiler and co-ordinating policy governor. The process control layout contains appropriate resource scanning, data flow and processing steps for the dynamic balancing of $\mu$Grid supply/demand through procedures described in §5.4.2 to §5.4.4. The *Tender arbitration price* block in Figure 5.3(b) is at the heart of the TAS. At the start of each trading period, it retrieves and appraises published microgrid resource data to match contesting supply-offers to demand-bid reagent tenders in a win-win situation. The potential of the supplies (energy sale offers) in the current trading buffer is thus lined up to receive load requirements (energy purchase orders) for the mediation of a concessionary middle-ground checkpoint fixed price-agreement. At this mutual concession checkout price $x'_t$, resources are proportionally willing to surrender supplies to reconcile demand orders. *Formulate load/supply schedule policy* blocks subsequently construct scheduling regulatory policies from the compensatory price decided in the settlement to warrant supply/load device balancing as a function of equilibrium price metric $x'_t$ (§5.4.5). TAS *Interchange control* block then submit authorised trading implementation instructions to the *Smart sv-TEMS Controller*, which enforces the scheduling coordination policy $S'_t$ on price-matching devices. As active run-time master controller, its power logic commissions the proverbial shepherding of prospective resources as pipeline devices (device behaviour encoded in electrical signalling).

The component level schematic layout in Figure 5.4 shows the proposed hardware topology to enable the TEMS. With the radial network for heterogeneous appliances wired to prioritise differentiated din-rail bus-bar feeds, groups of clustered legacy devices can be intelligently managed on PES-controlled parallel prioritised buses. From a TEMS perspective, the din-rail bus-bar solid-state electronic control units operate as collective *trading agents* to act upon owner instructions in bidding, buying and providing energy on behalf of appliance sets (the batch processing construct, wired as prioritised or categorised load groups). The society of smart bus-bars in each rural household thus act as multi-agent load energy buying traders, to intelligently regulate prioritised chartered transactions. Load devices can be connected based on multi-tier priorities, as part of customer-setup configurations, as pre-programmed to engage/disengage appliance power outlets as per the distribution panel-based load-controlling governing interfaces.

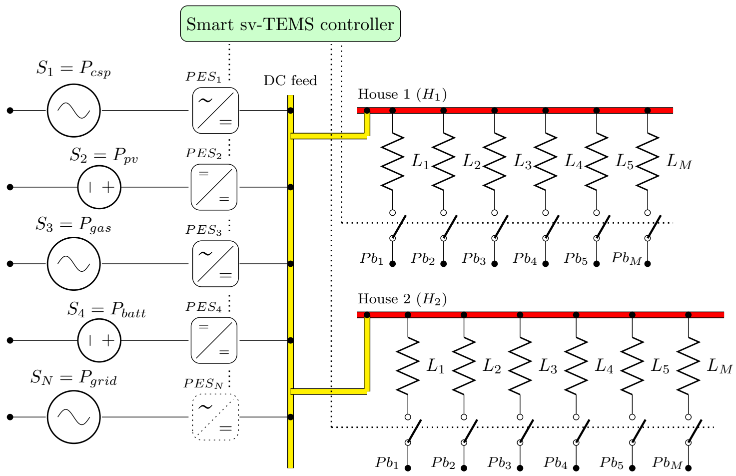



**Figure 5.4:** Smart Village microgrid diagram with multi-source ($S_n = S_{1_{cogen}} .. S_{N_{grid}}$), load differentiated ($L_n = L_1..L_M$), multi-bus ($Pb_n = Pb_1..Pb_M$) and multi-bid priority ($p_m = p_1..p_M$) regime for automated transactive demand response (user configurable priority/load associations ($L_1; p_6$)).

There may be several agent groups involved in the transactive energy management process, agents representing consumer loads, agents representing generation resources, and a balancing agent to receive and balance all the bids. §5.4.2 is concerned with the bidding strategies of the load devices, while §5.4.3 focuses on the generation of resource bidding functions. §5.4.4 engages in a discussion on the operations of the bid aggregation agent and the procedures involved in determining the allocation of resources and the cost of energy. It is immediately followed by a section on scheduling and control. The final part of this section discusses the billing and regulatory framework relevant to this approach to energy management.

### 5.4.2. Multi-priority load bidding functions and parameterisation

Household load devices, as energy trading agents, representing appliance groups on buses $Pb_{1..M}$, are demand-offer-price configured to submit price-quantity pairs $(L_{m_t}; B_{m_t})$ during the bidding process. The load priority bidding function variable $B_{m_t}$ is a key part of the bid price-quantity pair $(L_{m_t}; B_{m_t})$. This determines active participation in transactive energy trading activities to ensure appliance commitment for household load scheduling. This moderation differentiates between expenditure limits for appliance groups (indoor lighting, outdoor lighting, refrigeration, entertainment, as consumption classes). The customer priority configuration determines how household load coalition are prioritised in the priority layers labelled as "$p$". Doing so, the user can earmark flexible loads by assigning them to lower priority groups, which results in lower bids being placed by these devices. Critical loads are given a higher priority during the configuration process, which allows the bidders the freedom to place higher bids and experience less curtailment. This section will focus solely on the bidding functions of the load agents.

The operational status of devices determines their distinct behavioural modalities, adjustable to suit changing microgrid energy-pricing profiles for each load category in each energy trading interval. It is a function of the demand side, priority-differentiated, load- tender- filing functions $(B_{m_t})$, shown in Figure 5.5. In this configurable system, load consortium tender functions are based on a simplistic, fuzzy logical-type of load category (boolean on/off) or a suggestion of a tariff rate that drives the operations of the automated auction for transactive devices. The cut-off price levels for the user bidding membership functions $(B_{p_t}(x))$ in Figure 5.5, It relates to the price offers of the individual buses (energy buying agents) on the multi-bus distribution panel in each home. Differentiating energy buses, managed by the microgrid controller block in Figure 5.2, selectively supply priority addressable appliance/load groups based on the selected service quality/priority pricing of the energy devices.

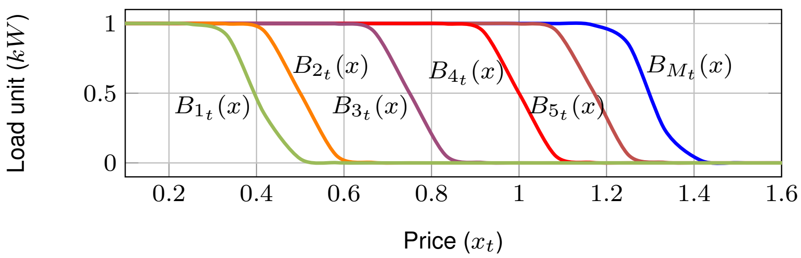



**Figure 5.5:** Sample consumer defined load bid pricing functions $L''_{p_t}(x)$ for multi-layered village load priority transactive auction categories.

Varying pricing bid tender functions $B_{p_t}$ can be programmed/defined by the village microgrid consumer customers for each of multiple village households $(House_{1..\sigma})$. It requires dynamically weighs the importance or service quality for load groups on each priority bus. Participatory decision-making settings can be modified by customers on a time-of-day/day-of-week basis, through a human-machine interface (HMI) configuration setup (toggle-switches, smart consoles, tablets, smart cellphones). The functions representing various load categories, Figure 5.5 which are programmable by the user, can be interpolated between one minute to one hour. For each bidding period iteration, the functions for the load categories interact with the control block of the transactive auction platform control (Figure 5.3) and work with the matching of pricing signals to electronically match energy bid offers to supply trade offers. The bid clearing platform and load controlling entity interpret the community's bidding data. The responsive load-bidding functions $B_{p_t}$ for each load priority category $L_{p_t}$ $(p = 1, 2, ..., M)$ in each offer/bid trading time period is described through the response function expression $f_{L_t}(x, y_p, p)$. A programmable controller is defined as an exponential function to express the pseudo-binary bid response functions for power demand and load priority levels $(p)$ for a particular time slot (Figure 5.5) through the vector set formula of Equation 5.4.1.

$$L''_{p_t}(x) \;=\; f_{L_t}(x, y_p, p) = \frac{L_{p_t}}{(1 + \exp\left[y_p(x - B_{p_t})\right])} \tag{5.4.1}$$

where:

$L''_{p_t}(x)$ is explicit demand load bid for priority $p$ at time $t$
$L_{p_t}$ is load demand quantity response for priority $p$ at time $t$
$B_{p_t}$ is load group priority $p$ bidding price for timeslot $t$
$y_p$ cut-off characteristics for priority $p$ sigmoid demand functions
$x$ the dynamic price variable parameter in present timeslot

Self-service capabilities offer a smart configuration console that allows the village energy prosumer to dynamically adjust device operation priorities as time-dependent functions (example settings displayed in Figure 5.6). This means that the user can shift load priorities to different time periods through dynamic settings on the household distribution panel.

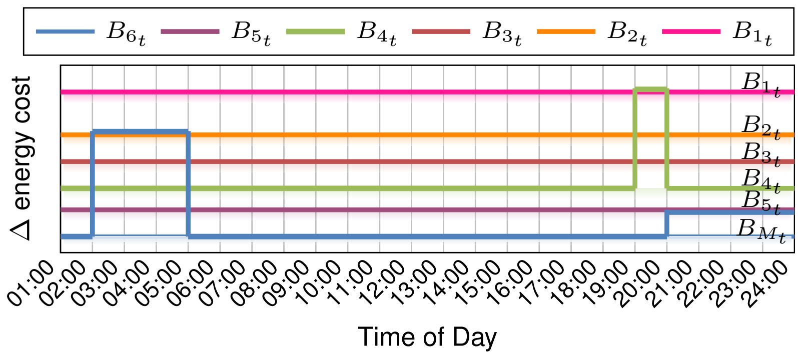



**Figure 5.6:** Example of user selected device settings displayed over a one day period.

The normalised load demand functions in expression $L''_{p_t}(x)$ can thus be adjusted through the energy switchboard settings in Figure 5.6, thus describing the interactive user-defined appliance category orders for each bid category on a tender bid price scale $B_{1_t}$ to $B_{6_t}$ (Figure 5.5). It feeds into the TAS aggregator (Figure 5.3) to determine the market clearing price $x'$ during each local market trading interval $t$. The bid ranking factor $B_{p_t}$ thus represents non-smart devices clusters connected to priority-differentiated buses. These buses make provision for the automated curtailment of non-priority and lower-priority loads in the transactive control scheme. Although six priority membership functions in Figure 5.5 illustrate quasi-binary sigmoid bidding functions, any number of load category functions for any mathematical expression (any linear or non-linear bidding functions) can be formulated by the system designer. The next section details the supply-offer parameters and supply source offers (bids) as mathematical functions, similar to the demand load bids defined in this section.

### 5.4.3. Multi-priority supply offer functions and parameters

Supply-source trading device agents/objects (i.e. agents representing supply resources) for micro-generator management can be configured in terms of supply-offer-prices to dynamically participate in transactive energy trading where a price-quantity pair $(S_n; O_n)$ is offered. This represents the supply generation offer functions and quantity/monetary bid value parameters for gensets, explaining how the TEMS input parameter sets are engineered through mathematical functions that determine the responsive execution of resource sales and participation in the transactions. The supply offers $O_n$ part of the price-quantity pair is defined through LCOE parameters programmable by operators and prosumers. It allows for the supply resources to interact with the physical grid network, in Figure 5.2, as transactive computational components in the software architecture of Figure 5.3.

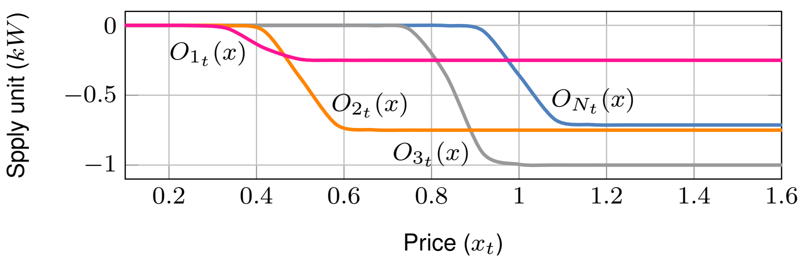



**Figure 5.7:** Normalised supply offer functions $S''_{n_t}$ associated with the village supply sources.

The supply offer functions $O_{n_t}$ in Figure 5.2 are processed to determine supply pipeline scheduling optimisation. For each of the supply sources $n$, energy auction offer functions can be described regarding their respective operational cost of supply information $C_{n_t}$ for each trading time-period (refer §5.4). With the incorporation of levelised cost of electricity (LCOE) parameters into the data-driven transactive control structure, the microgrid energy generation sources $S_{n_t}$ can put out real supply price offers $O_{n_t}$ computed from generation costs $C_{n_t}$ to the auction platform of the sv-TEMS control function block. The supply offer functions for the set of generation resources in Figure 5.7 can once again be expressed numerically for use in transactive bid clearing within the software architecture of Figure 5.3. Similar to the definitions of demand side functions, the supply side offer functions $O_{n_t}$ for each pipeline supply resource $S_{n_t}$ $(n = 1, 2, ..., N)$ in each offer/bid trading time period can be described using a mathematical expression $f_{S_t}(x, y, n)$. A feeder-type price control-line supply formula, Equation 5.4.2, is defined for each of the supply sources as shown in Figure 5.2.

$$S''_{n_t}(x) \;=\; f_{S_t}(x, z_p, n) = S_{n_t} - \frac{S_{n_t}}{(1 + \text{exp}\,[z_p(x - O_{n_t})])} \qquad (5.4.2)$$

where:

$S''_{n_t}(x)$ is supply offer for supply source $n$ at time $t$
$S_{n_t}$ is supply capacity quantity for source $n$ at time $t$
$O_{n_t}$ is supply offer price for source $n$ at timeslot $t$
$z_p$ cut-off characteristics for priority $p$ sigmoid supply functions
$x$ the dynamic price variable parameter in present timeslot

The normalised supply offer functions in expression $S''_{n_t}(x)$ can similarly to the load priorities also be adjusted through an energy switchboard settings. $S''_{n_t}(x)$ thus represents the energy product placement as a set of normalised supply offer functions associated with solar cogeneration, PV, battery storage, and gas cogeneration components (Figure 5.7). Foregoing functions in Equations 5.4.2 and 5.4.1 allow the transactive solution to optimise production scheduling and inventories in the supply chain, simply by balancing load bids in Figure 5.5 and supply offers in Figure 5.7 in the transactive control platform of Figure 5.3. The next section shows how supply/demand offers this power engineering method are weighed or balanced to determine a supply/demand offer or bid clearing price.

### 5.4.4. Transactive bid aggregator and price clearing operations

Based on the preceding transactive supply/demand functions, the TAS decentralised energy exchange operation is modelled to run as a rural microgrid software optimisation program. The mathematical simplification of the transactive optimisation solution is formulated as a programmable price/quantity balancing algorithm to implement the transactive control coordination solution as software object embedded code in the sv-TEMS. This programmable algorithm essentially executes the computational components of the TAS in the software architecture of Figure 5.3, to run the TEMS remedy solution in the physical price-gated design of Figure 5.2.

Micro-generation and the participation of flexible load devices is a function of local market auction mechanics for transactive software control, as shown in Figure 5.3(b) for each microgrid market-trading interval. The given supply offers and demand bids for each device or device priority group (Figures 5.5 and 5.7) feed into the *Transactive Aggregator*. At the start of each energy auction trading operation, the aggregator collates the supply offers $O_{n_t}$ from each of the microgrid supply sources $S_{n_t}$. Upon receiving bids $B_{p_t}$ from each of the device controllers $L_{p_t}$, and processing it regarding user priority settings, it determines the bid breakeven point from the bid aggregator/clearing operation functions. The software TEM aggregator in Figure 5.3 uses programmable intelligence to balance the supply/demand quantities and costs.

To this end, the tender-gathering functions are expressed using Equations 5.4.1 and 5.4.2. These tender-collecting functions accommodate numerical and electronic negotiation calculations to determine bid clearing price values $x'_t$ for local market trading intervals. Tender arbitration proceedings for transactive bid clearing in this local programmable energy economy can be mathematically expressed by price sensitive fitness functions in aggregated load bids/supply offers. The aggregated supply offer function $S_{s_t}(x)$ is expressed in Equation 5.4.3, and aggregated demand bid function

$L_{d_t}(x)$ in Equation 5.4.4.

$$S_t''(x) = \sum_{n=1}^{N} S_{n_t} - \frac{S_{n_t}}{(1 + \text{exp}\,[y_p(x - O_{n_t})])} \tag{5.4.3}$$

$$L_t''(x) = \sum_{p=1}^{M} \frac{L_{p_t}}{(1 + \text{exp}\,[z_p(x - B_{p_t})])} \tag{5.4.4}$$

In this reciprocal negotiating process, the TAS in Figure 5.3(a) incorporates Equations 5.4.3 and 5.4.4 to weigh, balance and arbitrate load-offer/supply-bid quantities as a function of price $x$. The automated negotiation goal is to determine the clearing price $x_t'$ where the aggregated supply offers $S_{s_t}''(x)$ matches the combined loads demand $L_{d_t}''(x)$. As tender referee/umpire, the TAS block adjudicates this quid-pro-quo price reconciliation in a give-and-take supply/demand matching process to pass judgement on a price resolution that does not compromise the stability/security of grid energy. A discrete objective function is defined using low computational requirements as reliability custodian to arbitrate the offered fine-tuning clearing price $x_t'$. Discrete-time objective function $f(S_t, L_t, x)$ defined in Equation 5.4.5, with cost function $\mathbb{C}_x$ in Equation 5.4.6, enables a simple mathematical solver to determine the equilibrium price verdict of a presiding process. A heuristic digital search algorithm tunes the price control variable $x$ within the defined constraint margins, to digitally negotiate prices using a numerical mechanism to facilitate the balancing of energy supply/demand flow. The mathematical solver adjusts the decision-making variable ($x$) to ensure the balancing of supply/demand convergence within the defined constraint margins and function coefficients of Equations 5.4.5 and 5.4.6 respectively.

$$f(S_t, L_t, x) = S_t''(x) + L_t''(x) \tag{5.4.5}$$

$$\min_{x\,\in\,ZAR} \quad \mathbb{C}_{x_t} = \sum_{p=1}^{M} L_{p_t}''(x) \tag{5.4.6}$$

subject to constraints: $L_t''(x) \leq S_t''(x)$ and $P_{R_d} \leq P_{R_t} \leq P_{R_c}$

The optimisation of bid-clearing and the price-discovery process maximise agent welfare (allocation efficiency) by searching amongst aggregated supply cost-and-demand-response functions to find the double auction balancing economic bid value per time slot by optimising Equation 5.4.5. The transactive microgrid network has dynamic hosting capacity (DHC) as it can accommodate any number of devices in the network. Apart from supply-demand profiling and matching constraints, the root-finding algorithm ensures that residential energy storage levels ($P_{R_t}$) should adhere to co-housing battery discharge ($P_{R_d}$) and battery capacity level ($P_{R_c}$) (charge controller) activity rule constraints. The bid clearing optimisation process maps the set of supply offer and demand bids as illustrated in the arbitrary sets of functions of Figure 5.8. For each trading time slot, the bidding aggregator searches for the balancing bid- and offer values to determine the optimal market clearing or bid equilibrium price $x'$ with the help of dynamic programming or an optimisation solver. In the current point analysis of the microgrid techno-economic equilibrium, the discrete cost optimisation strategy for tuning decision-making variable ($x$) in each bidding time interval ($t$) includes computational algebra in a factoring calculator to find the roots of polynomial Equation 5.4.5. The transparent protocol determines the optimal market clearing or bid equilibrium price point metric ($x_t'$) and order book price takers through dynamic programming or mixed integer linear programming optimisation solver. The micro-controller based solver thus operates as a modular reciprocal trading engine to solve the empirical problem within a set of definable network constraints in an offline scenario.

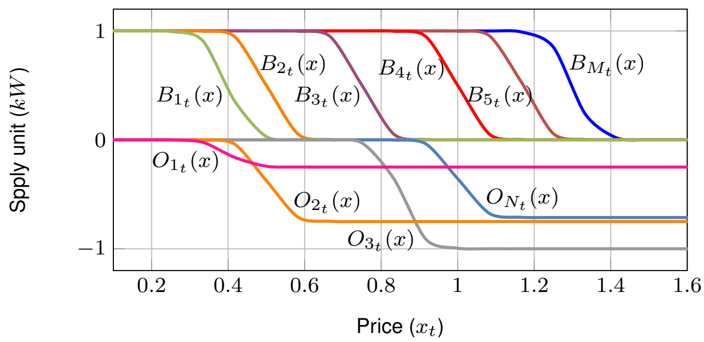



**Figure 5.8:** Compilation of exemplary supply $S_{s_t}(x)$ and demand $L_{d_t}(x)$ curves to be engaged in mapping optimisation, as displayed on a relative price of energy scale.

In the algorithm conceptions of the digital objects mentioned above, the solution is based on a discrete-time mathematical formulation for software agents and objects (hardware/software) to make transactive energy suitable for the coordination of decentralised economic and physical resources in an off-grid rural environment. It conceptualises a networked Smart Village distribution platform that allows for digital and software components (devices, storage, applications) to be dynamically added and removed without compromising the optimisation capabilities of the system [19]. Since the interests of all the individual actors (generation and load resources) are balanced against each other at the local level, the system adheres to the principles of a Pareto optimal solution [19]. To optimally maintain the integrity of the system during the dynamic balancing of supply/demand, generation and load resource agents adjust their performance for each bidding period through the coordination and optimisation procedures of Equations 5.4.5 and 5.4.6. With the relevant constraint conditions for balancing supply/demand met, the next section uses the auction cleared price ($x_t'$) to determine the operating statuses of appliance loads and supply sources.

### 5.4.5. Smart Grid load and supply source scheduling coordination

The proportional allocation mechanism is a crucial enabler of the transactive energy paradigm. It enforces the auction trading schedule policies through service invocation procedures between device components based on the local microgrid market equilibrium prices $x_t'$. Smart-meters or price-responsive smart devices/buses determine how controllable load class device colonies are obligated to deliver on tenders for power in the local microgrid market. For a competitive solution to an economic Smart Grid simulation problem, demand side management $f_{L_t}(x'_t, p)$ for a given bid clearing price control variable $x'_t$ and controllable load priority layer $p$ can be expressed as $L'_{p_t}$ in Equation 5.4.7. For each trading interval, the TAS block in Figure 5.2 broadcasts the cleared price $x'_t$ to device controllers in the microgrid network as TIS load regulation signals for device pelotons to track this signal. During each market period, load priority levels with a bid price value below the winning bid value quantity of $f_{L_t}(x'_t, p)$ are engaged by the sv-TEMS.

$$L'_{p_t} \;=\; f_{L_t}(x'_t, p) = \frac{L_{p_t}}{(1 + \text{exp}\,[y_p(x'_t - B_p)])} \tag{5.4.7}$$

The price-based direct load control scheme engages the demand response function(s) in Equation 5.4.7 as automated load sensor intelligence. As a mathematical mapping function, this type of fuzzy logic control governs the actions of participating loads. It thus empirically manages load device coordination as a function of market pricing ($x'_t$). Corresponding mechatronic device controllers thus interpret regulation signals $\text{TIS}_t$ to invoke energy service for a prioritised bus supply-line $p$ to receive $L'_{p_t}$ energy quantity for interval $t$. To overcome technical challenges in moving power over the appropriate circuits, a multi-signal micro-controller circuit guides devices as precision timed machines through load context switches. It uses multi-level logic registers, power electronics (integrated circuit diodes, TTLs, transistors, SCRs, Triacs or Thyristors), or solenoid-electro-mechanical relay boards to ensure that priority pricing accomplishes the desired functionality. These energy channel mixers or multiplex switches are guided by a control-oriented software interrupt handlers. It guides energy flows in multi-route energy fanouts and facilitates cross-over power switching through multi-line switches. Furthermore, is uses open-source assembly language- and machine- codes for microchip processors (Hanadu, PIC, CompactRIO, Arduino, Raspberry-Pi, Controllino or PLC). The sv-TEMS thus coordinates the operational status of the respective load devices for priority-differentiated pico-grid (clustered heterogeneous devices) through the associated bid functions to meet the aggregate behaviour objectives of bid cleared performance contracting. The TC2 regulation signal, TIS, thus essentially administers the actuation of semiconductor switch-gear or programmable control circuitry selectively to govern their compliance to offer/bid-cleared loading devices. The same procedure holds for enforcing regulation obligations of microgrid generation devices. Market liability instructions may also be communicated as event notification sequences to agent objects to effect the precision clocked synchronisation of supply/demand through coordinated scheduling of devices. Note that in this local time-period continuum for this energy service market, the transactive memory over the discrete trading period(s) are limited to one market trading interval period.

Regarding the coordination of supply-side scheduling, the device controllers for supply resources in this transactive control framework use a similar decision-making algorithm for the regulation and utilisation of the supply resource through TFS/TIS signals. The micro-generation supply coordinator essentially implements a time-synchronised resource throttling control policy, based on the commitment schedule of the optimal supply units computed by the transactive scheduler (TIS for $x'_t$). In this automated process, the respective controllers of the power supply units receive/interpret the transactive regulation signal to orchestrate the engagement of targeted supply-side resources during the cleared energy trading period for the local microgrid. In regulating the orchestration of one or more supply sources in the microgrid system, the same TIS signal is engaged. The sv-EMS and supply device controller determines the winning power modulation devices and their respective energy supply magnitudes $f_{S_t}(x'_t, n)$ through the response membership function $S'_{n_t}$ in Equation 5.4.8 for market clearing price $x'_t$.

$$S'_{n_t} = f_{S_t}(x'_t, p) = \frac{S_{n_t}}{(1 + \exp\left[z_p(x'_t - O_{s_t})\right])} \tag{5.4.8}$$

The supply source control functions $S'_{n_t}$, expresses the Smart Village microgrid hybrid solar/gas cogeneration, solar PV cells, and energy storage dispatch schedules. $S'_{n_t}$ optimally adjust their performances to deliver energy stock and to maintain energy balance within the integrated village microgrid. Remember that the transactive optimisation process uses a repetitive sliding time-window approach to conduct the execution of the discrete-event auctions. Sequential iterative optimisation over consecutive time interval, thus governs optimised microgrid resource dispatch over a given time-horizon. In this way, the transactive control scheme provides a method for managing the coordination of energy supply side measures by way of digital instructions that commands the energy supplies in proportion to the cleared-offer bid-price $x'_t$. This process essentially implements integrated supply-side measures and demand control auction as regulatory enforcement to uncover contractual obligations of energy supply/load devices in the transactive registry about their respective supply/demand contract obligations (Figures 5.5 and 5.7). Such innovative Smart Grid technological control determines the operational mode of the respective devices for one or more supply objects and notifies these supply components to modulate their operations at the appropriate time intervals.

### 5.4.6. Distributed microgrid billing regulatory framework context

CES technologies for sustainable consumption/production must offer affordable, reliable and modernized energy access under the UN's sustainable development goals [7]. In this context, the welfare impact of rural electrification on citizens in countryside dwellings at the base of the pyramid (BOP) must form part of pricing optimisation procedures described above. Sustainable development and the alleviation of humanitarian poverty call for non-monopolistic methods to address the socio-cultural and socio-economic needs of the vulnerable, resource-constrained end-using communities in developing countries. The methodology should make provision for full/partially subsidised operational models such as lifeline energy awards, pre-payment metering solutions or credit based tariff collection schedules [342].

South Africa's national utility provider uses an inclined-block-tariff (IBT) electricity-billing approach to charge energy customers for power at consumption-based demand charges (kWh-kVA) [223]. It further embeds low-income household tariff and pricing considerations to cater for a social agenda and novel post-apartheid energy provision regulating policies. IBT essential offers subsidised electricity to developing communities under the government's statutory free basic electricity (FBE) program [269]. This initiative allocates 50 kWh of FBE per month to qualifying households. In pre-payment systems, this regulatory policy is enforced at the point-of-sale and must be compliant with the ward-branch regulations of the municipal tariffs. Other small power users in domestic/residential spaces pay consumption-based electricity tariffs (South African Rand (ZAR) 1.50/kWh to low-income citizens for Cape Town peri-urban township inhabitants).

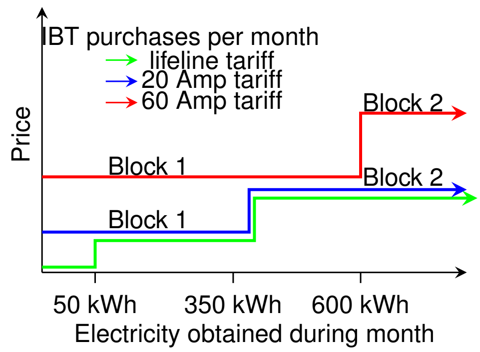



**Figure 5.9:** Diagram of a typical inclined block tariff billing structure, with the green trace indicating provision for FBE at lifeline tariffs [223].

From the perspective of a business management and evaluation procedure, the green trace in the IBT billing structure of Figure 5.9 reflects the lifeline FBE provision scale offered to disadvantaged domestic households (15 Amp tariff) [223]. This energy rebate or subsidy is one of the regulatory policy goals aiming to provide open access to essential energy resources and to enhance the well being of poverty-stricken citizens [343]. FBE is that amount of monthly energy considered to be sufficient to provide essential energy services. The rebate is deemed adequate to fulfil the basic energy needs of domestic households, such as running a small fridge, powering a small television set, and powering a radio. To include the monthly FBE monetary value as a regulatory constraint in sv-TEMS, an additional constraint in the cost objective function based on the clearing price metrics $x'_t$ may be introduced.

$$\min_{x} \ \mathbb{C}_x = \sum_{t=0}^{31\text{days}} L'_t(x') \ \leq \ \text{FBE} \tag{5.4.9}$$

From the perspective of a microgrid regulatory policy framework, the sv-TEMS system in Figure 5.3 should keep track of their aggregated daily as well as monthly cumulative energy consumption levels. This is to effect compliance to the IBT regulatory framework to ensure that rural communities are made aware of their purchases of energy in terms of the IBT scales of Figure 5.9. The sv-TEMS is thus able to guide and alert the customers should the monthly FBE limit be exceeded at the current rate of consumption, given the local weather patterns and renewable energy supply sources. As regards the above-mentioned factors, the sv-TEMS system must deal with pay-as-you-go energy tariffs (rate plans), which offer a variety of discount rates applied against pre-payment rates for the proportional usage recorded on the prepaid meter. While working against ruralisation, these rural-residential electricity tariffs are complex because of the upward sliding scale of fees based on average monthly consumption, while concomitantly the IBT system makes it difficult for rural customers to understand how much they will pay each month. Using a simple user interface, the sv-TEMS can guide customers through the iterative bidding processes to avoid overspending in terms of their household FBE or village energy budget.

This is where the predictive analytical component of the sv-TEMS can play an important role. The microgrid architecture and operational procedures discussed in this section are to be employed on a practical level and it is clear that the user can toggle appliances between different priority buses to effect the household energy expenditure. However, owing to the complexity of the energy market platform, it is difficult to estimate the exact outcome of such changes. The effect of moving a device with a high power rating from a low priority to a higher priority will most likely increase the energy cost for that user. That is due to the fact that the price of electricity in the sv-TEMS is based on the quantity of supply and the demand, as well as willingness to pay a certain price. Furthermore, the action of increasing the bid priority means that the device is willing to place a higher bid for power than usual. However, the market price is not only determined by a single device; each priority bus in the microgrid places a bid for the time period in question. As this is an automated process, there are millions of bidding data points and possible combinations, each resulting in a different market price. Clearly, predicting the day-ahead energy cost for one household is complex and it would be unlikely for the user to make meaningful adjustments to the configuration of the load priority in order to meet certain budgetary constraints. In order to assist low-income households to optimise their load configuration settings, whether to meet the constraints of a daily energy budget or to remain within the FBE threshold, more sophisticated tools need to be introduced. A Gaussian Process (GP) predictive analytics tool is employed to assist the user with configurational optimisations for the forecasting of energy expenses and device agent bidding settings. These results are also discussed in the simulation result section.

§5.5 discusses the simulation results of a sv-TEMS when applied to a rural village microgrid scenario. The effectiveness of the multi-priority TEMS is demonstrated through monitoring its performance in the village microgrid simulation, given solar energy and appliance load profile data.

## 5.5. Simulation Results

This section presents results for Smart Village scenario narratives, case-based simulations that used to challenge the transactive, agent-based energy system dispatch. It demonstrates the performance for the software implementation of the sv-TEMS in a distributed energy microgrid environment. In this theoretical performance assessment, engineering models reproduce the characteristic behaviour of the multi-fuelled rural village microgrid in order to observe the operation of the various device agents under these conditions. The chosen location for the simulated village is in the Eastern Cape region of South Africa, near Lusikisiki, where many rural communities are currently not part, and will not be part, of the national grid expansion plans for at least the next ten years [12].

These microgrid supply generation resources include a hybrid solar/LPG cogeneration system, solar PV, and battery storage. The supply output capacity $S_{n_t}$ of these supplies is weather dependent, meaning microgrid installation site-specific conditions must be pinpointed in this model-based simulation model. The weather inputs for this model are generated using Meteonorm, a global climatological database, which is often used to carry out viability and resource modelling studies in respect of solar energy systems [344]. The simulated supply offer price $O_{n_t}$ use the approximate levelised cost of energy $C_{n_t}$ for available generation sources which, in this model, is the lowest for solar

PV, followed by solar cogeneration, then battery storage; LPG gas-powered cogeneration on the other hand has proved itself to be the most expensive [231]. In terms of the properties associated with distribution load flow, and from the perspective of its intermittent renewables, it can be safely said that the microgrid storage model can adequately meet the village energy disbursement schedule and requirements when charged to capacity.

Authentic user load profiles serve as input to the Smart Village microgrid simulation model. These load models are derived from archetypal load profile models for rural African villages, and are based on energy consumption patterns determined in previous research [229]. In addition to this energy consumption data, the load contribution from each of the household devices has been attributed according to a probability factor to more closely resemble a typical daily profile. This village consist of a cluster of five households in an agricultural community and all share similar load profile characteristics. In the initial state, discrete event simulation of production planning starts with a federated load classification process. It systematically pools heterogeneous sets of appliance devices into homogeneous appliance load groups $L_{d_t}$, through cluster segregation of appliance data into a set of load device group priorities (6 appliance groups per household, p = 1,2,..,6). Table 5.1 reflects the DEM demand-purchase orders in prioritised load groups, based on customer willingness to curtail, discard or forfeit load groups during specific time periods. The prioritisation of user-configured load priority clusters is physically realised by the soft-multiplex switching of load buses (Figure 5.2). By dynamically associating these electronic agents or intelligent buses with each load group $L_{p_t}$, the buses submits TE bids $B_{p_t}$ (based on encoded user-configured priority bid cost, ZAR, levels) to state their intention of energy purchases during each trading period. Higher priority load clusters make higher bids and thus have a better chance of those bids being cleared to make purchases. Energy valuations through the post-processing and archiving processes accrue daily for each household, and for each device group. This fosters complete transparency as to the cost contribution of each appliance.

The sv-TEMS simulation demonstrates the operation of the user-interactive transactive control approach in a multi-priority load curtailment operation for experimental energy trading. The transactive control method maps the automated set of device manoeuvres for multiple energy trading session intervals "$t$" over a time horizon sequence ($t = 1, 2, .., T$), 48 hours in this case. The user configurable power purchase settings Table 5.1, defined through a bidding user interface trigger progressive and increasing comfort levels as energy-on-demand ("energy when I want, at the cost I want"). The bidding strategies of §5.4 apply the daily load quantities $L_{p_t}$ accompanied by its ZAR bidding value settings $B_{p_t}$, together with the supply generator quantities $S_{n_t}$ plus its ZAR offer value $O_{n_t}$, to the microgrid sv-TEMS model Figure 5.3. The bidding process uses a step-by-step sliding trade window to determine energy price and amounts transacted throughout the day. These bidding iteration time-intervals are set to three minutes in these simulations, but can be as short as one minute. Based on the cascaded village load set and priorities, the sv-TEMS algorithm determines the transactive bid cleared trading prices $x'_t$ for energy auction trading intervals.

Based on these model parameters, Figure 5.10 shows the resultant operating schedule determined by the microgrid sv-TEMS over a two-day simulation period. The resultant local village auction trading prices, or market clearing price metrics $x'_t$ shown in Figure 5.12, are determinants for relieving market tensions in marrying supply and load engagements. Fluctuation in the market price is driven by supply disturbances, the supply/demand quantities of resources, as well as supply/demand trade willingness (Figure 5.12). Whereas the market price is high in the mornings and evenings (high demand, with only the more expensive battery resources available). The price of energy is lower at midday, when the demand is lower, while an influx of solar power is flooding the market with less expensive power.

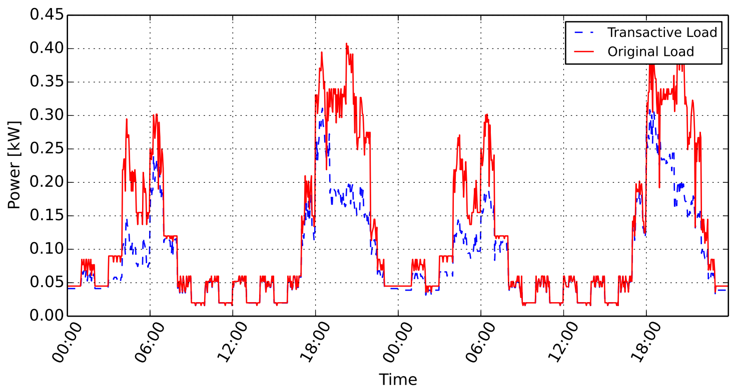



**Figure 5.10:** Two-day load profile for the village microgrid showing potential load profile without TEMS (original load) versus curtailed profile resulting from energy trading (transactive load).

While the available solar power and the expected load profile ("Original Load" as shown in Figure 5.10) for the village from the first to the second day of the simulation vary slightly, there is a notable difference in the amount of transacting power in the morning and evening hours. This variation is attributed to the configuration adjustments made by the village households transitioning between day one and two, as shown in Table 5.1. Household 1, for example, has decided to move the lights to a higher-priority setting, the radio remains on the same priority bus, and all the other appliances have moved to lower-priority buses (possibly because of budgetary constraints). Household 4 has taken a very aggressive power-purchase approach which allows its device agents to enter near maximum bids almost across the board.

**Table 5.1:** Distributed microgrid demand-purchase orders in prioritised load groups, based on customer willingness to curtail, discard, or forfeit load groups.

| Day1 / Day2 | House 1 | House 2 | House 3 | House 4 | House 5 |
|---|---|---|---|---|---|
| Lights | 5 / 3 | 5 / 2 | 5 / 4 | 5 / 2 | 5 / 5 |
| Secrty Lghts | 2 / 3 | 2 / 2 | 2 / 4 | 2 / 2 | 2 / 2 |
| Radio | 4 / 4 | 4 / 3 | 4 / 4 | 4 / 2 | 4 / 1 |
| Television | 1 / 3 | 1 / 1 | 1 / 4 | 1 / 1 | 1 / 1 |
| Refrigerator | 3 / 4 | 3 / 3 | 3 / 4 | 3 / 2 | 3 / 3 |
| Cellphone | 1 / 3 | 1 / 1 | 1 / 5 | 1 / 1 | 1 / 1 |

The effects of these adjustments can also be observed in Figure 5.11. Since all of the village households employ a similar bid priority configuration for the first day

(00:00 in Figure 5.11), all the energy expense profiles are practically identical and cluster around ZAR 2.30. While the bidding strategies of Household 1 and Household 3 saw a reduced approach on Day 2, Household 2 and Household 4 were willing to spend more on energy in Day 2.

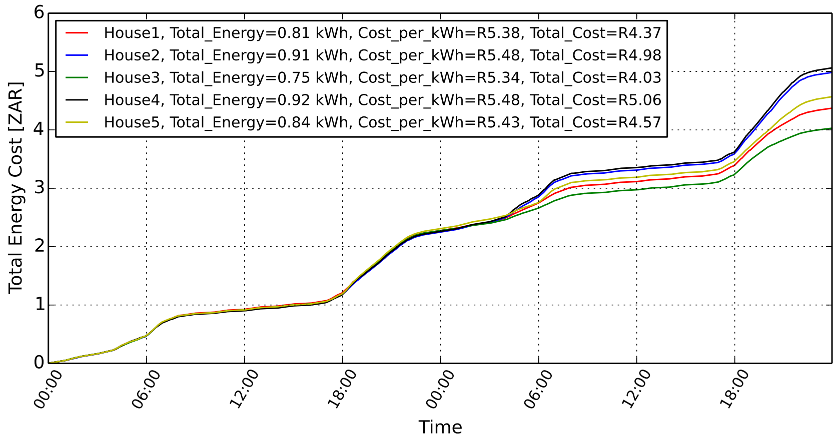



**Figure 5.11:** Cumulative energy cost for each of the five houses over the two-day simulation period.

With House 5 remaining unchanged in its plan over the two-day simulation (to serve as a reference), Figure 5.11 clearly shows deviation from the running energy cost curve during Day 2. The households with the more aggressive power-purchasing approach experience an increase in power purchased and also an increase in cumulative cost, with the opposite being true for the houses with less-aggressive bidding strategies on Day 2. This outcome would naturally be expected since the houses with the increased total had agreed to purchase more energy than the others. However, Figure 5.11 also shows an increased average cost of electricity (ZAR/kWh) for these houses (2 and 4). This is due to a higher rate of consumption during peak hours when the market price was high (the morning and evening hours shown in Figure 5.12).

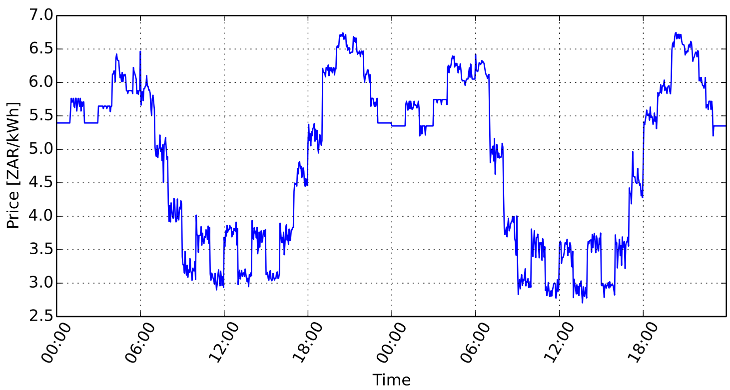



**Figure 5.12:** The market clearing price for energy as a result of resource trading within the microgrid.

Figure 5.13 to Figure 5.17 show the effect of the sv-TEMS on the two-day profile of each village household, with the configuration shown in Table 5.1 still being applicable. For House 1 (Figure 5.13) and House 3 (Figure 5.15), which possibly experienced budgetary constraints, a notable increase in curtailment could be observed on the second day. House 5 (Figure 5.17), for which the bidding configuration remained unchanged, showed very little change in profile between the two days, and the small changes that are noticeable are due to the change in market conditions caused by the bidding conditions of the other households. As expected, houses 2 (Figure 5.14) and House 4 (Figure 5.16) experienced a very noticeable reduction in curtailment, but are currently burdened with the increased cost of energy (ZAR/kWh) as discussed earlier.

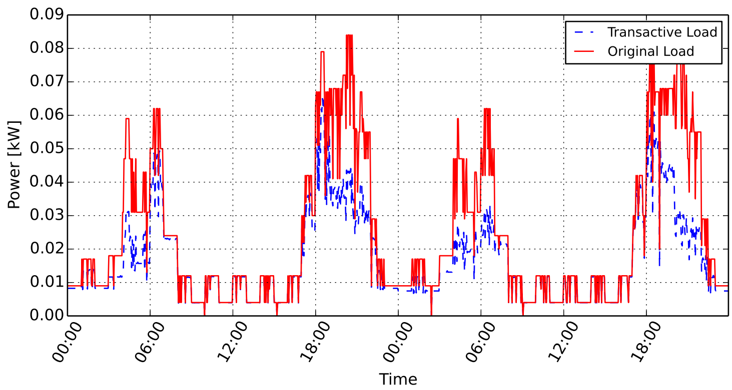



**Figure 5.13:** Two-day load profile for House 1 showing the potential load profile without TEMS (Original Load) versus the curtailed profile resulting from energy trading (transactive load).

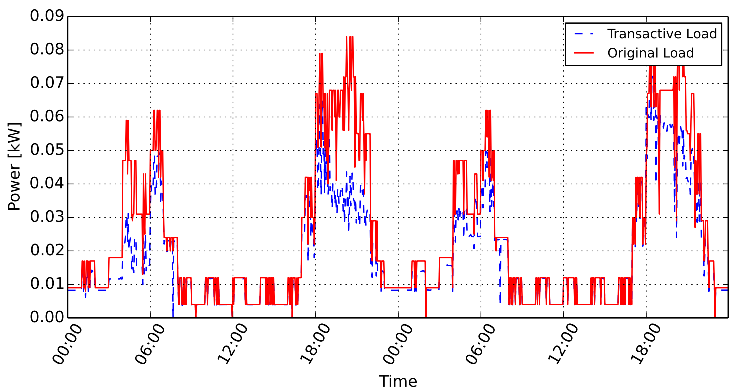



**Figure 5.14:** Two-day load profile for House 2 showing the potential load profile without TEMS (Original Load) versus the curtailed profile resulting from energy trading (transactive load).

It is imperative that the Smart Village EMS further allows for flexibility in payment since a rural household energy budget can fluctuate significantly on a day-to-day basis for a low-income rural family. It has been demonstrated that the village energy consumer has the ability, within this sv-TEMS, to exercise a certain amount of control

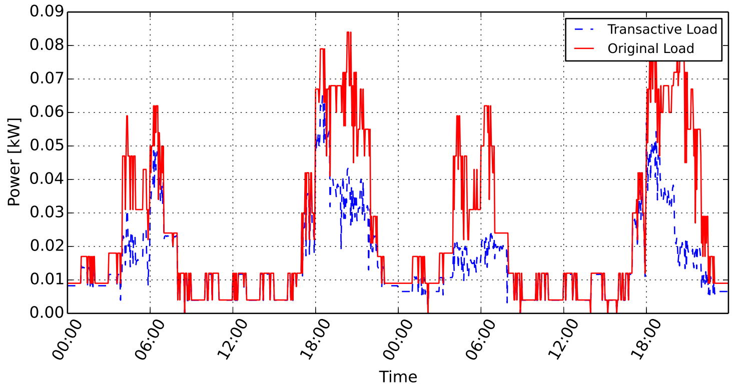



**Figure 5.15:** Two-day load profile for House 3 showing the potential load profile without TEMS (Original Load) versus the curtailed profile resulting from energy trading (transactive load).

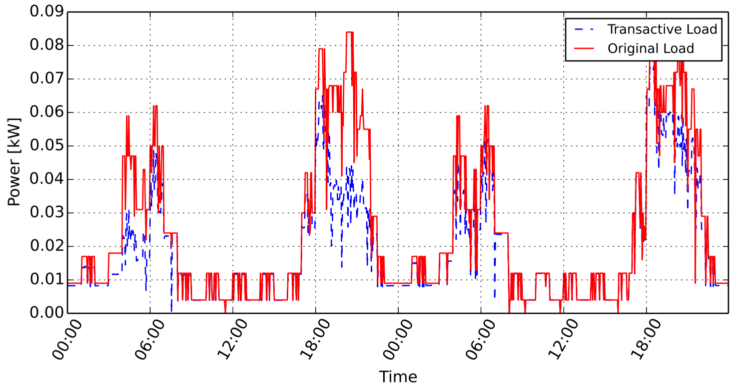



**Figure 5.16:** Two-day load profile for House 4 showing the potential load profile without TEMS (Original Load) versus the curtailed profile resulting from energy trading (transactive load).

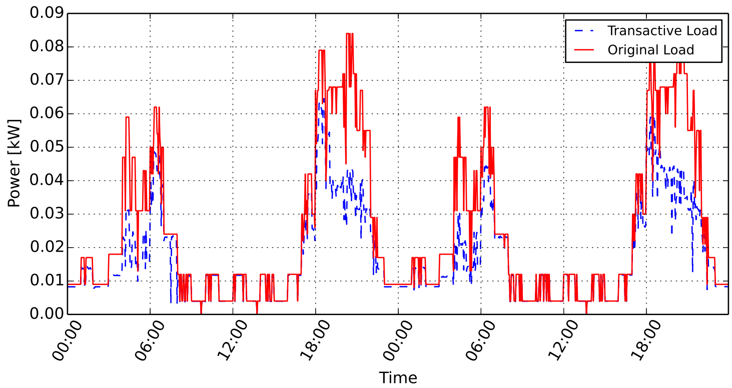



**Figure 5.17:** Two-day load profile for House 5 showing the potential load profile without TEMS (Original Load) versus the curtailed profile resulting from energy trading (transactive load).

over the household's daily expenditure on energy and the cost thereof. However, the previous section noted that adjustments made by the user to the bidding configuration would be limited in terms of control, other than to promote an increase or decrease in expenses. Owing to a high number of factors affecting the cost of energy (bidding strategies of each device in the village), the task is too complex for a human (operators or prosumers) to predict the day-ahead household energy costs and a GP forecasting method was introduced. It has the ability to analyse and overcome the system complexities to make meaningful predictions about energy expenditure. Using Household 1 as an example, the user may want to reduce spending on the television, cellphone-charging, and security lighting while increasing the priority configuration of the lights and the refrigerator. This was carried out based on the systems feedback after the first day of operation. Given this updated load priority configuration, the GP day-ahead price forecasting tools are able to predict the household energy expenditure to within a 10 % margin for the following day (to within 3 seconds). The day-ahead household energy expenditure forecast is shown in Figure 5.18.

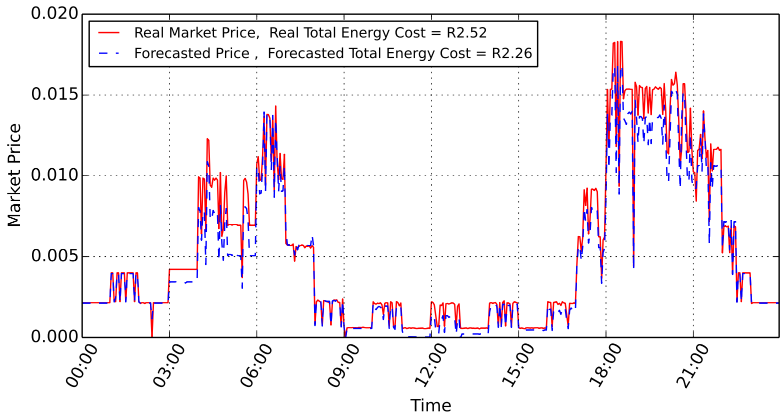



**Figure 5.18:** House 1 day-ahead energy expenditure and total energy cost forecast using Gaussian process.

The valuation post-processing and archiving procedures allow the Smart Village energy user to access detailed system information, such as the accrued cost per load group, which contributed to the household energy expenses. In doing so the user is able to evaluate the current cost of energy per device per day and can decide which devices to target to bring about the desired change. This concludes the simulations results section where the model demonstrated the ability to interact with the rural village energy user.

## 5.6. Summary and Conclusion

The IEEE Smart Village slogan "Power a village, empower a community" inspires the deployment of decentralised energy solutions to isolated rural communities where these installations may be tactically more realistic and cost-effective than those of the national grid extension. For a customer-focused microgrid network to reduce the reliance of rural low-income communities on traditional fuels, an intelligent Smart Village energy network was modelled and discussed. A model-based design approach was used to develop a Smart Village microgrid concept platform that is based on the principles of distributed market-based control in a multi-agent transactive architecture to facilitate customer engagement and automated transactive demand response. It involved the tailoring of a Smart Grid control approach to prepare for the implementation of control and automation solutions for *Smart Village-type distributed micro-processor-embedded standalone Smart microgrids*. This approach has been successfully used in the control of a society of cyber-physical economic agents in distributed control for multi-agent electronic markets for utility Smart Grid solutions.

This Smart Village concept merges the principles of cybernetics, mechatronics, and process science in a cyber-physical Smart Grid environment to perform autonomous energy management and strategic resource coordination activities on a functional energy-as-a-commodity (EaaC) trading and transport platform. The system decision mechanisms inherently creates arbitrage opportunities for village households or devices in the microgrid network to produce and sell energy to one another, or to neighbouring villages, the system monetises, aggregates and controls devices through energy arbitration. By treating Smart Village loads as multi-tier priority categories that are programmed by the customer, the system can engage and dis-engage devices through appliance power outlets or distribution panels on multi-bus level control interfaces. It facilitates the implementation of a retail energy pricing operation with an integrated demand response component based on the Purdue automation hierarchy through a TEMS mechanism. The combination of the DC microgrid hardware topology proposed in Figure 5.4, and the multi-priority bus-bar system (example output shown in Figure 5.6) enables pragmatic user interaction with the system. Embedding the sv-TEMS, which is based on market-based control, in the this user-interactive hardware platform creates a type of Interactive Market-based Control (i-MBC). This conceptualised rural Smart Village microgrid control automation concept extends on the basis of the theoretical models of pure market-based control (MBC) for the Smart Grid energy markets of the future by Kok [19] and Warmer *et al.* [345].

User-interactive features allow the village micro-utility owner/operator to match individual home power usage and trends to fluctuations in the renewable power outputs of the village with minimal interaction required. While the consumer can adjust the priority parameters for each load class in each bidding iteration, the load control functions reflect how the devices will change participatory behaviour in the local power market for a given trading period. Price-sensitive, single- and double auction "computational thinking" ensures consumer interaction with the EMS which optimises the village/household energy cost. By capturing customer preference in the agent bidding configuration and behaviour, prosumers are actively and directly participating in the automated process in their decisions to purchase energy. This, in turn, leads to greater control over energy expenditure.

These features are also relevant when looking specifically at South Africa where they can help low income households to remain within the monthly FBE rebate budget.South Africa is unique among other Sub-Saharan countries since it has a much higher electrification rate, but even here rural electrification projects are often met by misfortune. Since the same principles (“pay when I can” and the user perceived value of energy) apply to energy-poor families in this region of Sub-Saharan Africa, these methods can have a positive impact on struggling rural electrification projects. The methods discussed in this paper should not face too many challenges when integrating with rural electrification projects here since the electricity providers and consumers are already familiar with mobile payment methods, pay-as-you-go electricity systems, and the ideas of deferrable loads and load curtailment.

Future work will include an optimised investment algorithm, aimed at advising users regarding potential financial benefits of private in-home storage and additional generation resources. In addition to the interests of reduced curtailment and the avoidance of peak energy prices, these components will have a positive effect on energy trading throughout the microgrid, transforming the customers from consumers to prosumers (producer/consumers). These outcomes will ensure a more dynamic decentralised system with less volatility in the local energy market, reduced curtailment on load devices, reduced peak loads, and the potential for peak shifting and for generating an additional income for prosumers through a process whereby they can sell power back to the microgrid during peak times. In addition, a future extension of the transactive-block-chain continuum will permit retail energy revenue models for healthy growth to promote local peer-to-peer energy trading in energy surplusses among neighbouring villages.

# Chapter 6

# Summary and Conclusion

This study presents a case for the application of Smart Grid control strategies in rural village microgrids towards future Smart Village microgrids. This approach aims to address the current knowledge gap in which more advanced microgrid resource management platforms are needed to achieve Goal Seven of the UN Sustainable Development Goals (Figure 1.1). It also aims to address the long-term strategic requirements whereby smart energy systems are expected to become the energy component of future Smart Villages. Research toward this long-term goal is expected to play an important role in the future when rural villages are transformed into automated technology-driven Smart Villages. Owing to the catalytic qualities of modern energy access to spur societal transformation and growth, it is essential to have some concepts in place to inspire the Smart Village transformation, or at least be prepared when it occurs.

This chapter brings the research project to a conclusion. A brief overview of the research focus area and the formulation of the research design is presented in §6.1. This is followed by the conclusions in §6.2, as deduced from the findings of the research objectives presented in the main body of the document. The concluding remarks on the research aim and the research questions of the study are also included in §6.2. The discussion of the strategic research conclusions in §6.3, also includes the findings of this research that fall beyond the scope of the research questions to highlight the impact of this study on academics and industry. Finally, §6.4 highlights the contributions made by this study, while §6.5 closes with a brief discussion of important directions for future research.

## 6.1. Research Summary

Today, more than a billion people live without access to electricity while more than three billion people have no access to clean cooking facilities [4]. The vast majority of this population group live in rural areas in developing regions of the world [3, 4]. The geographical context of energy poverty in non-electrified rural villages in African countries offers insight into the impact of energy poverty on everyday living, especially in terms of the daily collection of traditional energy resources (dung, firewood, crop waste, paraffin) [5, 7]. Under conditions of increasing scarcity and supply deficit, the burden of spending large parts of the day on collecting and carrying fuelwood over considerable distances rests mostly on women and children. This daily demand for traditional fuels impacts directly on school time and work opportunities, resulting in many communities being deprived of valuable time to pursue educational and economic opportunities [346, 347].

It is also the women and children who disproportionately suffer the health consequences of household air pollution associated with the use of these fuels [348, 349].

The application of funding toward solving the global energy crisis has overly focused on large-scale power plants with lengthy deployment times which has had only a minimal impact on rural communities [5, 70]. The notion of encouraging urbanisation by focusing predominantly on city-centred urban electrification has brought into question the morality of spurring rural communities on with incentives of improved economic opportunities and access to modern energy services. This encourages them to abandon their traditional lands only to live in underserved settlements on the outskirts of the cities. As such, there has been a call to shift focus towards increased distributed generation to reach the energy deprived rural off-grid communities which encourages ruralisation and enables sustainable economic growth and community prosperity [350].

To help make Smart Villages a reality, Chapters 1 to 5 of this dissertation highlight the value of the off-grid microgrid installations in the context of rural electrification. The IEA expects that microgrids will provide energy services to nearly half of the rural population in Sub-Saharan Africa who should have gained access to electricity by 2040 (140 million out of the 315 million) [6, 76]. The case for swarm electrification further highlights the role of microgrids in Sub-Saharan Africa since it is expected that the vast number of off-grid installations (mostly solar home systems) are expected to become interconnected to also form microgrids [82]. These off-grid installations have quick deployment times and can rapidly increase connections, but often lack the reliability and serving capacity needed for improved productivity and economic growth, as shown in Figure 1.12 [71, 80]. While energy access has the potential to be a catalyst for development, the initial energy-related priority is, in many cases, to simply provide rural villages with access to lighting and cellphone-charging through solar home and battery charging systems [107, 351]. Although access to these entry levels of energy has proved to be a significant improvement, the planning for a true Smart Village needs to extend beyond these initial priorities. It should facilitate a move towards a more ICT oriented approach to support the rural metamorphosis of a traditional rural village towards a Smart Village [4, 105, 232, 233].

This dissertation therefore investigated conceptual options for future rural microgrid platforms that will suit next generation IEEE type Smart Villages. By integrating multidisciplinary knowledge from Mechatronic Engineering, Software Engineering, Micro-Economics, and Computer Science disciplines, the study was able to demonstrate that there is significant room for technological innovation in the rural village energy field. Chapter 2 and Prinsloo *et al.* [225] underscore the value of the SUN hybrid solar/gas cogeneration system in rural African village applications, while also identifying a need for a dedicated microgrid platform with advanced energy management capabilities. To ensure increased relevance in off-grid rural village environments, this advanced microgrid must be able to integrate the cogeneration system alongside other DERs, while enabling it to achieve peak levels of reliability and efficiency [85, 94]. Chapter 1 calls attention to the fact that most rural village microgrids are not capable of the desired levels of resource management. Implementing a rural village microgrid with advanced resource management is no ordinary challenge, as few definitive guidelines are currently available to guide such developments [269, 232, 314]. The most significant shortcomings caused by the lack of detailed R&D village microgrid roadmaps is the delay in the development of design frameworks and standards, income and cost recovery models, developmental tools, and in advancing supporting policies [21]. This limitation leads to severe challenges in terms of financing and de-risking mechanisms for investment bankers who want to get involved in rural village microgrids projects [79]. These challenges hinder rural village microgrid market growth as the investment pool is limited to high-risk averse angel investors.

A lack of advanced resource management capabilities in current rural village microgrids led this research to investigate future techniques planned for implementation in next generation microgrid technologies for industrialised countries. Chapter 1 highlights the future microgrid drivers and trends observed during this investigation, and puts the spotlight on a possible future overlap in technological trends for the energy markets of the Global North and the Global South. This overlap, graphically illustrated in a conceptual layout of Figure 1.13 and Figure 6.1, became the core of this research hypothesis. According to this hypothesis, the study envisions an integrated energy future with Smart Village energy capabilities that are on par with Smart City energy capabilities. As such, this dissertation aimed at exploring options towards a conceptual smart rural village microgrid platform that could address the current knowledge gap. It further intends to give direction concerning future developmental pathways for a next generation Smart Village microgrid, based on future Smart Grid principles. This aim has foreseen the incorporation of decentralisation principles in the future envisioned microgrid-based Smart Grid, which is far-removed from the contemporary top-down electrification planning models and their reliance on centralised energy supply and delivery systems [76, 352].

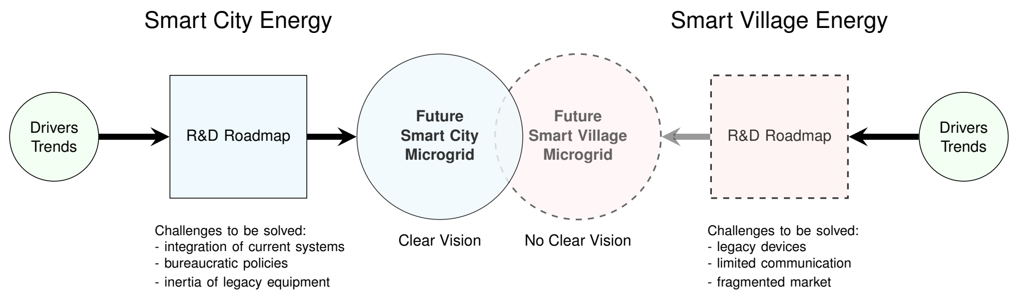



**Figure 6.1:** The purpose for this research is to address the current knowledge gap in rural village microgrids and to ensure that the recommended next generation microgrid will be relevant in future Smart Villages.

A modern model-based design-thinking approach to rural village microgrid design allowed the study to demonstrate the value in adopting and tailoring Smart City energy systems techniques to suit the energy needs of the rural village. Various model-based control automation solutions are detailed and discussed in Chapters 3 to 5. They demonstrate that the development of future Smart City energy systems offers several attributes that can be of great value to rural village microgrids. Those particular attributes that are causing excitement in energy circles are concerned with automated decision-making, resource management, and customer engagement. Prinsloo *et al.* [236] and Prinsloo *et al.* [291] in particular started out addressing the higher levels of customer engagement and computational intelligence offered by the Purdue enterprise reference architectural model for industrial automation. This approach engaged system-level computational intelligence attributes and transaction-based capabilities facilitated by Purdue's cascaded control layers. The Purdue reference model and its Smart Grid extended variant, the SGAM model, were chosen to ensure enhanced functionality for a proposed Smart Village microgrid. This functionality includes automated supply/demand balancing and optimised resource management within the framework for layered-reference control abstraction.

The proposed control automation models, which integrate customer engagement with automated, interactive, demand response and resource coordination, are featured in Chapters 3 to 5. It includes self-service capabilities offered through a smart configuration console that allows the village energy user to dynamically adjust prosumer device operation priorities as time-dependent functions. Such agent tuning capability offers interactive, dynamic demand response as a self-service, giving a competitive advantage to the rural Smart Village microgrid platform. Its features proved to be particularly valuable under synthesised rural energy systems conditions as it adds the opportunity to model social behaviour modality as part of the engaged rural customer microgrid control solution. The state-of-the-art Smart Grid concept of transactive energy management (specifically distributed market-based control theory), detailed in Chapters 4 and 5, demonstrated qualities that make it an ideal platform for rural village microgrids. This dissertation thus introduced the concept of **interactive-Market-based Control (i-MBC)** as a unique concept that extends the theory of distributed Market-based Control (MBC). As a control automation concept in the rural Smart Village microgrid, it emphasises the direct and interactive engagement of rural customers (or customer devices) that participate in agent-based distributed device control in rural Smart Village energy networks. Simulation experiments, using scenario narratives to hypothetical challenges, are able to demonstrate the qualities of the proposed i-MBC transactive energy strategy in a modelled rural African village microgrid. i-MBC-type customer interactive Purdue-type enterprise integrations are expected to be an important factor in allowing for potential pathways to Smart Village power systems of the future. The rest of this chapter details the research conclusions concerning a proposed next generation microgrid platform that can be considered in future IEEE-type Smart Village applications.

## 6.2. Research Conclusions

This section presents the journal paper contributions towards achieving the aim and objectives of this study and lays the foundation for the narrative in order to answer the research questions. The conclusions, deduced from the research findings, are drawn from substantiating evidence published in local and international peer-reviewed journal publications incorporated in Chapters 2 to 5, and are supported by the data and information from additional international papers and conference proceedings listed in the Interlude of this dissertation. §6.2.1 and §6.2.2 presents the conclusions related to Objective 1 and 2 respectively. These objectives were concerned with creating a testing environment that would be representative of a Smart Village environment in rural Sub-Saharan Africa, while also considering developments sourced from our research group. This served as a case-based evaluation platform for the conceptualisation of the strategic microgrid control approach that followed. The third objective (§6.2.3) examined opportunities for designing Smart Village microgrid platforms. These designs were based on the vision to deliver contextually-aware intelligent energy services within the social energy dynamics of remote rural communities, specifically in Sub-Saharan Africa. This demonstrates that a transactive energy management approach, specifically in the form of market-based control, is well-suited for resource coordination and strategic control in a rural African village microgrid. The aim and the research questions are discussed in light of these conclusions in §6.2.4 and §6.2.5 respectively.

### 6.2.1. Toward Objective 1: Rural village generation modelling

*The modelling of the hybrid solar/gas cogeneration system* was conducted to perform a simulation-based generation performance analysis. The computer modelling approach is presented in Chapter 2 and Prinsloo *et al.* [225], and details the operational characteristics of the cogeneration system. Chapter 2 of this study saw the use of the developed models in a simulation-based generation performance analysis at various rural village sites in Africa, in order to *study potential fuel reform and the implications of electro-fuel transition at these locations*. The simulation model engaged direct normal irradiation from typical meteorological year (TMY) datasets to calculate the prospective solar power generation capabilities of the system at the selected rural locations, as displayed in Figures 2.5 to 2.7.

Regarding electrical power, simulation results for a reference site in rural South Africa showed that the SUN micro-cogeneration system can generate approximately 1500 kWh$_e$ per year (see Figures 2.5 and 2.6), while the recovered thermal energy output of the micro-cogeneration system reached outputs of about 4500 kWh$_t$ per year. This places the average targeted rural community household (between five and seven houses) in Southern Africa in Tier 2 of the Multi-Tier Framework for electricity access (Table 1.2). The thermal energy component of the cogeneration system was converted to fuelwood equivalents for each of the selected rural African village regions. The system results showed potential fuelwood reductions of up to 58 kg per day at some of the village locations (see Figure 2.7). More importantly, the output ratio of thermal to electrical energy (about 3:1) would later prove to closely match the typical energy profile of rural African villages. In addition, the reliability of the system is improved by the hybrid fuel capability, similar to a PV system with diesel generators as back-up [103]. Further contributions toward the attainment of Goal Seven include the reduction in the use of fuelwood which addresses the need for clean cooking methods. Under Objective 1, the developed model supports the notion of smart energy systems in which Smart Cities have multiple energy streams at their disposal that work towards highly efficient systems [337, 353]. The smart energy systems efficiency goals are shared by Smart Village microgrids to which the cogeneration system demonstrated strong qualities.

This model *achieves Objective 1* in that it facilitates the study of control requirements, and can also help to optimise the Smart Village microgrid distribution system model when eventually incorporated. Furthermore, it supports peformance metric verification, both in the technology selection and testing phases of system planning and development. This demonstrates the contribution of Objective 1 towards the *research aim* in which *computer modelling and simulation instruments are used to generate models for experimenting with proposed platform concepts in simulated rural village environments*. In the Smart Village environment, a village power system can be viewed as a local micro-utility, which operates as a micro-enterprise. In this context, the hybrid solar cogeneration system is expected to act as the anchor generation resource in the village, or to form part of a multitude of DERs in a multi-carrier microgrid environment. The parametric Stirling micro-cogeneration computer model enables case-based simulation studies for any arbitrary location for which the required weather data inputs are available. This model unlocks the ability of the micro-cogeneration system to be engaged in simulated microgrid operational analysis and supply/demand balancing and to be used as a predictive locational impact and benefit analysis tool in sizing requirements and determining cost-benefit analyses. The model outputs would later (Chapters 4 to 5) be associated with dynamic energy pricing to support future experimentation with Smart Village microgrid control.

### 6.2.2. Toward Objective 2: Rural village microgrid load characterisation

For the objective of investigating demand side modelling in the context of a rural village microgrid, this study *researched the energy consumption (thermal and electrical) profiles that can be expected in a rural African village*. The demand side load profiles constitute the simulated energy orders/requisitions in the energy market of the local village microgrid. To this end, the journal paper** in Prinsloo *et al.* [230] features energy consumption load models in rural villages. A scoping study was used to determine the baseline load profiles for recently-electrified village households through an analysis of data in the literature. The scoping exercise results showed morning and evening peak characteristics (twin-peak duck curve) for the electrical profiles in rural village households. Further analysis showed energy demand and consumption patterns for newly-electrified rural family households in Sub-Saharan Africa which rely on a mix of modern energy and traditional fuels (firewood, charcoal, biochar, biomass, candles, kerosene and paraffin). This analysis was done to gain the following information as part of the demand side of the Smart Village microgrid platform. Firstly, baseline electricity and hot water consumption load profile archetypes for isolated off-grid rural African villages were needed. Secondly, it was done to formulate realistic reference rural African village energy consumption load profile models as discrete disaggregated time-series samples. Finally, it was done to establish load archetypes in digital formats suitable for experimentation with computer-modelled solar micro-cogeneration systems and rural village smart microgrid control automation solutions.

The outcome of the exercise (Prinsloo *et al.* [230]) offers digitised model-ready (hourly, half-hourly, minute-based data) electricity and hot water draw-off profiles as interval energy data suitable for use in simulations. These results were later used to *create a load profile generator to emulate device-profiles of disaggregated loads that are representative of a future Smart Village* (Prinsloo *et al.* [229]). The load modelling tool uses appliance energy levels and behavioural patterns in terms of device-use as the basis for simulating consumption profiles for disaggregated archetypal load energy for typical off-grid rural villages. This offers digitised disaggregated load models in formats that are suitable for the analysis of dynamic microgrid platforms.

The development of this model *achieves Objective 2* in that it features energy consumption load models for rural villages. By developing a model-based load profile generator as a load modelling tool, it is suitable for microgrid demand side simulations. This

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highlights the contribution of Objective 2 towards the *research aim* in which *computer modelling and simulation instruments are used to generate models for experimenting with proposed conceptual platforms in simulated rural village environments*. This model was later extended into a Python-based Load Profile Generator that produces appliance disaggregated load simulations for a Smart Village. This load profile generator filled the role of a demand-side simulator in rural Smart Village microgrid modelling and in investigations into simulation platforms. These profiles are based on the use of high-efficiency devices, such as DC appliances and solid state lighting, that are expected to be integrated into the IEEE P2030.10 Standard [89] for DC Microgrids in Rural and Remote Electricity Access Applications. These load profiles would later be associated with dynamic energy pricing information to support economic optimisation and transactive operations in Smart Village microgrid simulation experimentations (in Chapter 5).

### 6.2.3. Toward Objective 3: Smart Village microgrid platform modelling

The supply and demand resources were modelled as part of Objectives 1 and 2, and the conceptualisation of the Smart Village energy system commenced with an initial investigation into the resource management of multi-stream generation in Chapter 3 and in Prinsloo and Dobson [232]. Advancing towards the objective of the *Smart Village microgrid energy management platform conceptualisation*, this study demonstrated the optimisation of resource allocation (supply/demand balancing), while performing dynamic economic optimisation of the storage capacity. Chapter 3 demonstrates the formulation and implementation of microgrid resource coordination and scheduling procedures which act as an energy management system residing in the secondary/tertiary control tiers of the control abstraction model in Figure 6.2(a). The aim was to apply computational intelligence through techniques that optimise the overall solar/gas utilisation and maximise balanced energy delivery in a local village energy distribution network [231]. This energy management technique requires careful formulation of the operational constraints, with the objective- and cost- functions approached as a multi-objective mixed-integer linear programming optimisation problem. This microgrid energy management platform is based on contemporary Smart Grid optimisation approaches to the unit commitment problem that are often used in renewable DER environments, such as NREL's Continuously Optimised Reliable Energy (CORE) Microgrid [354] and DER-CAM's cloud-based control-scheduling optimisation tools [355]. Simulation results demonstrate the ability of this control approach (the topology shown in Figure 6.2(b)) to perform optimised resource scheduling, which improves service reliability, the balancing of supply/demand, and minimises the operational and energy costs of the rural village microgrid. It further shows that the incremental optimisation of storage capacity in the proposed platform model ensures improved efficiency in energy management and reduces operational and customer billing costs. Moreover, the optimisation of storage costs in ideal weather conditions resulted in a 66 % reduction in the daily operational costs of the microgrid. Also, there was a reduction in lost/unused electricity that amounted to an average annual cost of about $ 200 per installation. These cost savings could be applied to investments into the microgrid storage capacity or additional generation resources.

The centralised microgrid energy management approach in Chapter 3 employed mixed-integer linear programming techniques to solve the finite capacity scheduling

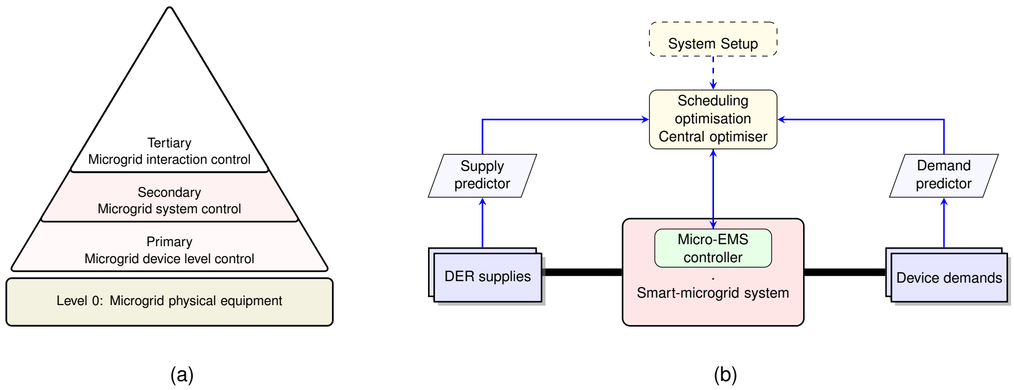


**Figure 6.2:** Microgrid platform with a centralised optimisation strategy (a) engaging strategic energy management principles in the lower levels of the cascaded control hierarchy, and (b) the microgrid control topology for this centralised optimisational approach.

problem toward the research objective of *the modelling of the conceptualised rural Smart Village microgrid platform*. This proved to be an effective supply/demand balancing and cost minimisation platform under the stable simulated operating conditions of the rural village microgrid. However, rural village customisation efforts identified some practical challenges that limit the platform's application as a future prosumer-based Smart Village energy system. The most relevant challenges are listed below and are also discussed in Chapters 4 and 5:

⇒ Reliability: The control schedules are optimised at a central location and communicated throughout the village microgrid, which creates a single point of failure. In the case of system failure, the delayed response times often associated with installations at sites in Sub-Saharan Africa (supply-chain challenges, the cost of replacement of hardware, lack of communication for remote technical assistance), it may take several days/weeks to bring the system back online [106]. During the EMS down-time, there will be a high risk of damage to expensive equipment, especially battery storage, that can enter into high stress conditions due to unregulated use [94].

⇒ Communication: Another challenge is the operating conditions in a rural village environment, where communication links to cloud-based computational platforms for bulk data processing would be unreliable. With increasingly complex objective and cost constraint functions to accommodate the system's operational dynamics, a rural energy system fitted with the centralised optimisation microgrid platform of Chapter 3 would face difficulties in the transition from a load-following paradigm to a supply-following paradigm.

⇒ Scalability: The large number and variety of controllable devices (generators, storage, and loads) expected in the future prosumer-based Smart Village microgrid will cause exponentially-increasing levels in the complexity of optimisation. Dimensionality can be reduced by eliminating impractical or impossible combinations in device schedules, but the computational power needed to solve these problems will still increase significantly.

⇒ Adaptability: In addition to the scalability challenges caused by entering a prosumer operating environment, there are also adaptability challenges. The cost function in representing each village energy user during the optimisation process, is affected by factors that continuously change. To truly represent the user in the network-based objective function, the representative cost function would need to be adaptive. This would lead to increasing layers of complexity as the designer needs to consider the vast number of current and future boundary conditions that would be relevant to the optimisation procedures [59]. These limitations create even more challenges as the interoperability (between devices and between microgrids) features of future Smart Village microgrids come into play, which will vastly increase the operational considerations.

⇒ Payment flexibility: The higher levels of payment flexibility that are needed to accommodate prosumerism, the fluctuating budgetary restrictions of rural energy users, and monthly subsidies, such as FBE and IBT offered by the South African government, further complicate the optimisation process. This adds to the complexity caused by controllable devices which makes for a computationally-expensive approach as the system grows toward a Smart Village microgrid.

The centralised optimisation platform demonstrates some capabilities needed under the simulated conditions to perform the automated advanced resource management considered as part of the purpose of the study. However, this study also showed a limited capacity to make a full transition to a Smart Village microgrid platform where dynamic user interaction and volatile operating conditions are of the order of the day. To accommodate future functionality towards becoming Smart-Village-enabled, "smarter" operational adaptations to the microgrid platform would be needed to overcome the challenges faced by centralised optimisation.

Prinsloo *et al.* [236]** demonstrates the blending of Ubuntu-type rural African lifestyle principles (based on working together towards a common goal) with entry-level transaction based energy management concepts. Figure 6.3(a) shows this pro-active energy management addition as the incorporation of the business planning layer in the control abstraction, while more dynamic user interaction is allowed in this control topology shown in Figure 6.3(b). This was done by adding a time-re-configurable price-reaction component to the centralised optimisation approach. Prinsloo *et al.* [236] shows an example of distribution panel settings in which users configured their devices on the basis of a willingness to purchase power at certain cost-of-energy threshold levels. The cost of energy is calculated at the central EMS through category membership functions and communicated to the devices. This means that the complexity of defining the representative cost function of the user is distributed among several devices. This dynamic, interactive, price-based demand response concept addresses some of the challenges from the previous approach. It significantly reduces the complexity and computational burden of the optimisation problem (which improves scalability) by eliminating the need for the user-specific cost function at the central controller. It also improves adaptability as user inputs now directly affect the outcome, making the village energy user the main constraint regarding adaptability. If a household needs more power, its members simply have to allow their devices to participate in the purchasing process at higher prices, after considering the budgetary constraints of the household (assuming energy is available in the network). A load-differentiating hardware architecture was introduced to allow

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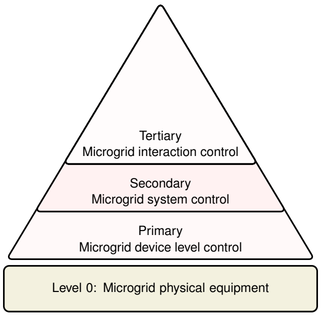
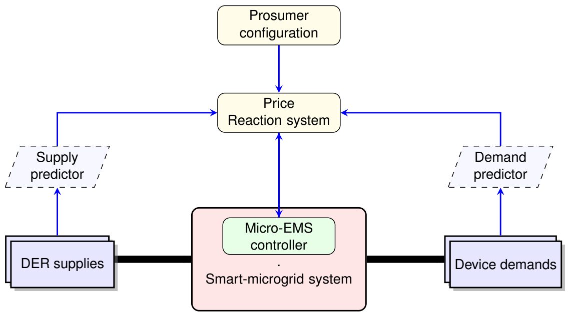
for time-sensitive, price-induced automated demand response as part of a transition to an entry-level transactive approach. This is based on user-configurable load priority categories that allow low-cost appliances to participate in a price-driven control environment. Devices typically encountered in rural African communities include lights, radios, televisions, cellphone chargers, refrigerators and so forth. The proposed hardware architecture is based on switch gear for multi-circuit power electronics, which allows the user to assign the various household devices to different priority busbars, depending on the user's willingness to pay the associated load priority price.




(a)




(b)

**Figure 6.3:** Microgrid platform with a time-configurable price-reaction control strategy (a) engaging limited customer/business layer aspects on a cascaded control hierarchy, with (b) microgrid topology incorporating customer engagement capabilities, according to the present dissertation.

While this entry-level transaction-based concept of Prinsloo *et al.* [236] addressed some of the challenges associated with centralised optimisation, it also had shortcomings. Firstly, user devices were given price-of-electricity spending-limits which had limited feedback to the systems operator as to the value of these limits. Since customers were able to constantly re-configure their devices (Figure 6.3), the relatively static operating conditions of the village microgrid were no longer optimal for all participants. Secondly, users had minimal control over true overall cost impacts when changes were made to the priority settings of the devices. Thirdly, the balance between supply and demand was disrupted since the optimised scheduled generation had less control over consumption scheduling and could not anticipate the reaction of the devices, which caused over- or under- supply. It would be possible for the load forecasting system of a central EMS village to characterise the underlying budget constraints so that generation could be scheduled accordingly, but this would have to be reset every time a user adjusted the priority for a device.

Despite these challenges, the transaction-based EMS approach presented in Prinsloo *et al.* [236] demonstrated the ability of interactive, price-based demand response to bring the conceptualised platform closer to meeting the desired requirements for the automated user-centric Smart Grid. It was found that a more sophisticated information feedback loop was needed to address the associated challenges brought on by this approach. This feedback would allow for transparency between the user devices and supply resources to improve user control over household spending and help to re-gain the supply/demand balancing functionality of centralised optimisation in the village microgrid. These challenges were addressed in the model adaptations of Chapter 4.

Regarding the research objective of the *conceptualised modelling of rural Smart Village microgrid platforms*, Chapter 4 demonstrates an early version of the next generation Smart Village microgrid concept. Figure 6.4(a) shows the control abstraction layers included for this approach with the more interactive prosumer added in Figure 6.4(b). The underlying network energy management strategy was re-designed as a fully decentralised value-based supply/demand balancing control automation solution with improved communication capabilities to address the challenges of the entry-level transactive energy management approach in Prinsloo *et al.* [236]. In this value-based approach, the *value-of-energy* becomes the key operational parameter and is determined by using microeconomic principles of supply and demand balancing in a virtual auction environment [356].

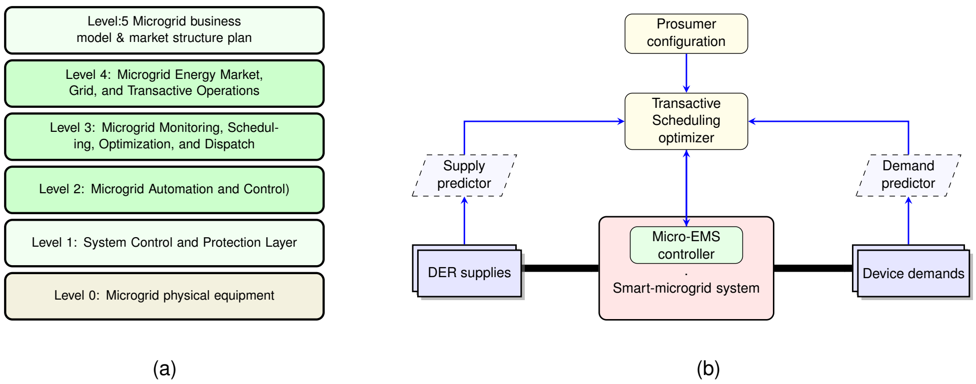



**Figure 6.4:** Microgrid platform with (a) transactive control optimisation engaging cascaded control layers 1 to 4, in (b) an improved smart village microgrid topology that allows for active stakeholder representation, according to the present dissertation.

To facilitate the increased communication, Chapter 4 introduces an intermediary intelligent bus-bar configuration (Figure 4.7) as a load coalition proxy to the communication and decision-making capabilities of smart devices. This configuration is an extension of the proposed concept used in the time-configurable price-reaction simulations of Prinsloo *et al.* [236] and allowed legacy household appliances to be clustered and proxy-represented. The configuration (examples of settings displayed in Figure 5.6) allows the village energy user to dynamically adjust device operation priorities as time-dependent functions. This enables the user to adjust the load priorities of certain device groups during specific time periods of the day. In so doing, the user devices can be incentivised to engage in a type of load-shifting procedure according to the user preferences (e.g. increasing the priority for TV during news hours).

This conceptual approach to energy management, shown in Figure 6.5, makes use of distributed market-based control, which is a combination of Control theory and Economic theory [19, 345]. In this approach, each device is controlled and represented by a software agent (an artificially intelligent software object as the network subject) that can be configured to make automated decisions based on user-configurable parameters. The generation and load device agents in the village microgrid (the microgrid becomes a multi-agent system) collectively negotiate to determine their level of participation for the incoming control time steps. This extends the Smart Grid multi-agent energy network models of Kok [19] and Warmer *et al.* [345], by including a dynamic means of control to accommodate social behaviour in the microgrid control feedback loop. Figure 6.5 allows the preferences of the energy user to be actively represented in the open market negotiation process as a function of time-of-day. Thus, the combination of the multi-priority load-shifting features and market-based control theory in a cyber-physically-oriented platform introduces a unique approach for distributed market-based transactive energy management in a rural Smart Village microgrid platform.

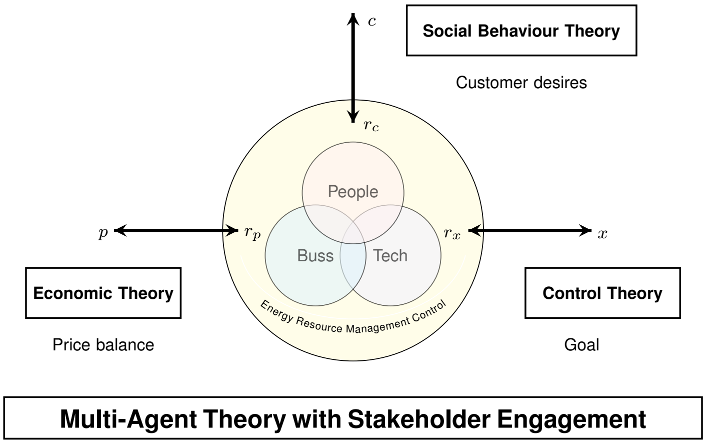



**Figure 6.5:** Interactive market-based control as an extension of multi-agent theory using dynamic stakeholder engagement to strengthen the unified micro-economic- and control- theory environment (extension to models of Kok [19] and Warmer *et al.* [345]).

The integration of value-based parameters (function of customer preferences) provides new computationally-intelligent behaviour dynamics that enrich the microgrid platform as a cyber-physical eco-system (see the contribution in [163]). Since the interests of all the individual actors (generation and load resources) are balanced against each other at the local energy market, the system adheres to the principles of a Pareto optimal solution [19, 165]. Figure 4.12 demonstrates the ability of the microgrid EMS to manage the energy transaction schedules regarding supply resource trading dispatch commands which result from the mutual trading (buying and selling) of energy in the local village microgrid energy market.

Chapter 4 demonstrates the ability of a transactive energy management approach to be customised for use in a rural village microgrid to facilitate the balancing of supply and demand on a social behavioural participatory platform (maintaining Ubuntu principles - device agents working together toward a common goal). This achieves the high level of adaptability (and self-optimisation) necessary for a prosumer-based Smart Village environment. On account of varying user requirements, it also eliminates the complexity associated with the repeated re-formulation of the load prediction aspects of the optimisation function. This approach allows for high levels of user interaction and shows the potential for the desired Smart Village requirements of reliability, scalability, and affordability (flexibility in payment). In addition, transactive energy management is based on the concept of market-based price determination, which is familiar and intuitive to many rural energy users.

Promising features demonstrated by the multi-agent distributed market-based control approach in Chapter 4 prompted the further development of this transactive concept as a possible Smart Village microgrid platform. To this end, Chapter 5 models the rural off-grid village microgrid using a multi-agent nodal approach and formulates distributed market-based transactive control as a discrete-time system (Figure 5.1). The diagram showing the control topology with expanded transactive activity is presented in Figure 5.3. The device agents were conceptualised as algorithmic elements in discrete-time mathematical formulations and allowed to operate as digital software agents. These agents represent all microgrid network devices, including DERs, non-smart appliance devices, and storage devices.

In Chapter 5 the Smart Village microgrid control automation concept of the present study proposes the newly developed concept of i-MBC automation as an extension to the modern Control theory and Economic theory (market-based control), as shown in Figure 6.5 [19, 345]. It includes a means of dynamic control to accommodate Ubuntu-type social value and social behaviour in the control feedback loop of the village microgrid. The proposed model of Figure 6.5 implements village customer participation through the interactive time-function settings described in Prinsloo *et al.* [236] and Figure 5.6, jointly used with the load priority circuit diagrams of Figures 5.4 and 4.7. By using these mechanisms, the village prosumer can dial-up or dial-down the priority levels of appliance devices to increase or decrease their respective probability of operation (trading in energy) at certain time-intervals of the day. The same procedure holds for the prosumer generation devices, as their time-priority configurations also determine their bidding strategies. These include generation resources owned by a village prosumer and those that are part of the micro-utility. i-MBC is essential as a new interactive-type of multi-agent dynamic stakeholder engagement approach that functionally strengthens the unified micro-economic- and control- theory environment proposed by Kok [19] and Warmer *et al.* [345].

A case-based Smart Village microgrid simulation experiment engages the discrete parametric cogeneration model from Objective 1 (Chapter 2), with weather inputs for a rural village in the Eastern Cape region of South Africa as one of the supply agents. The load agents of this simulation originate from disaggregated rural household load profile archetypes generated by the load profile generator, and include several typical appliance load groups, such as lights, refrigerators, televisions, radios, cellphone chargers, etc. The rural village load profile generator from Objective 2 (Prinsloo *et al.* [230]) adopted a dynamic probabilistic factor, which is based on the rural user behavioural habits and, creates more realistic load conditions. The load device agents also incorporated a more dynamic bidding approach, which allowed them to adjust the level of bidding aggressiveness while representing devices in the virtual auction market in Chapter 5. The system monetises, aggregates, and regulates the microgrid device operations through energy transactions. This also creates energy arbitrage opportunities for village households or devices in a distributed energy microgrid network to produce and sell energy to one another or neighbouring villages.

Chapter 5 demonstrates the budgetary effects of these dynamic bidding strategies in the context of a Smart Village microgrid by comparing the average price of energy, the impact of inclined block tariff pre-payment regulations, total energy expenditure, and the level of aggressiveness of bidding with multi-client household devices (Figures 5.10 to 5.17). Households with more spending power configured some of their devices to adopt more aggressive bidding strategies (as in Table 5.1), which resulted in reduced curtailment for those devices. However, this caused an increase in the overall market price for village energy during times when these devices were competing for resources, which resulted in an increased curtailment for devices with less aggressive bidding strategies. Less aggressive bidding strategies also affected the market price and tended to drive down the village cost of energy when bidders participated in the energy auction. Chapter 5 further demonstrates the market price fluctuations caused by the introduction of less expensive solar power during the day, and the higher-priced battery storage at night. The addition of statistical- and machine-learning features allowed users to have more control over the total day-ahead spending, as the method provides for the generation of cost estimations based on household load priority settings and previous energy market reactions. These predictions were shown to be within a 10 % margin, which leads to greater control over energy expenditure and helps rural village households remain within their energy budget (Figure 5.18).

This approach to strategic microgrid control, as presented in Chapter 5, demonstrates the capabilities needed for a user-centric Smart Village energy management platform. It brings together the requirements of energy reliability and affordability in a way that the user is placed in control over both. This is because the market-based control approach maintains a balance between supply and demand by using the *value-of-energy* factor as the operating parameter. This value parameter is determined in the village-wide energy market and is influenced by all participating devices represented in an automated manner by their device agents. The device agent participates in the virtual energy auction market by communicating the amount of energy that the device is interested in purchasing, as well as the price range that the device is willing to operate in. The manner of device representation is determined by the aggressiveness of the device in terms of its power-purchasing strategy based on settings defined by the user. Since the primary consideration for these user device configurations is related to household budgetary restrictions (“pay-when-I-can, use-when-I-can”), it means that the value of the energy parameter encapsulates its reliability (Table 1.2) and affordability factors. The user can thus directly influence reliability by allowing devices to spend slightly more, while still maintaining control over affordability by having control over device-bidding strategies. The supply resources make use of a similar approach in which their bidding strategies are determined by the micro-utility owner and/or operator.

This section (including Chapters 3 to 5) *achieves Objective 3* as it demonstrates the *modelling of a conceptual Smart Village microgrid platform* by proposing the theoretical conceptualisation of the microgrid control automation platform, and by developing models for applying and integrating Smart Grid principles. It incorporates case-based scenarios (from Objective 1 and Objective 2) to evaluate the performance of the conceptualised platform model through simulations of a rural African village environment. Further evaluation of this conceptualised Smart Village microgrid platform is discussed in the following section that describes the significance of the concept for a Smart Village microgrid platform within the context of the research aim.

### 6.2.4. Towards the aim of creating a Smart Village microgrid platform

The illustration in Figure 6.6 reflects back on the model-based design-thinking approach described in Chapter 1 (Figure 1.17) that was used to conceptualise this Smart Village microgrid platform. The aim was to investigate the current knowledge gap in respect of the lack of off-grid rural microgrids with advanced resource management capabilities, in such a way that it would also be relevant in the envisioned Smart Villages of the future. The investigation focused on Smart Grid operating principles that are expected to play a key role in future Smart Cities. The core functions of an advanced microgrid include the automated balancing of supply/demand and also a schedule representing the use of available resources in an optimal fashion, as shown in Figure 6.6. While the design-thinking approach placed the energy user at the center of these optimal scheduling processes, the requirements of other stakeholders (USAID, IEEE, microgrid owners/operators, local government policies) were given significant consideration as discussed in Chapter 1.

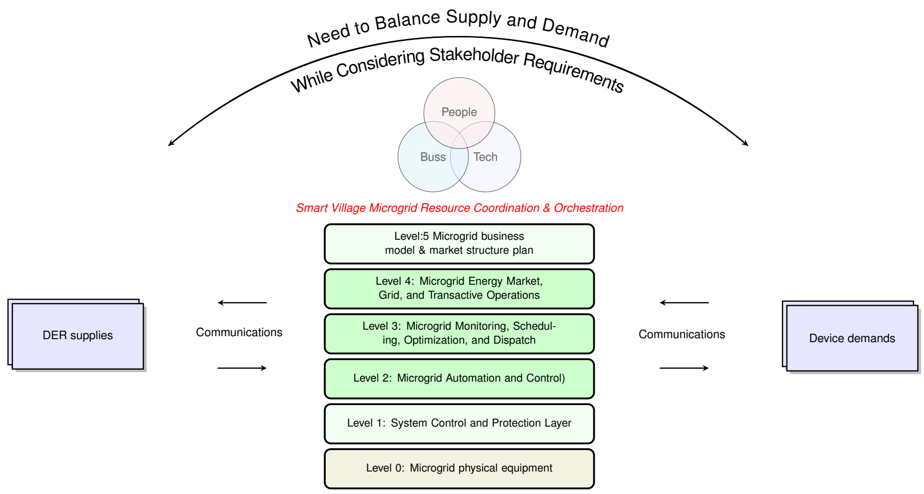



**Figure 6.6:** Conceptual layout of proposed Smart Village microgrid platform, based on cascaded distributed market-based control, integrating Technology, Business and Customer as design-thinking aspects, according to the present dissertation.

The transactive energy management platform presented in Chapters 4 and 5 is based on distributed market-based control theory that was adopted from future Smart Grid operating principles, and tailored to be suitable for a rural African village microgrid. This approach includes functionality from the upper layers of the control abstraction in Figure 6.6, which supports process-specific production rules and enterprise activities in energy manufacturing operations (production, inventory, quality control) to overcome challenges from centralised optimisation. This modified market-based energy management approach is able to coordinate optimal microgrid operations through a vertically-integrated transactive control stack, shown in Figure 6.6. It employs bi-directional communication with a decentralised control approach, which has moved away from the conventional centralised optimisation to a platform where control is distributed among participating microgrid devices. The distributed control approach results in a system with the inherent features of reliability, resiliency, and scalability. Like the centralised optimisation, this approach is able to balance stakeholder requirements during optimisation (Venn diagram Figure 6.6), but can do so in a more dynamic user-interactive environment, which is expected to be the norm in future Smart Cities and Smart Villages. These capabilities, and the inherent features of this control approach, as discussed in Chapter 4 and Chapter 5, make it an ideal platform for future Smart Village microgrids. §6.3 presents further strategic research conclusions regarding the use of this control approach in future Smart Village microgrids. This brings to a conclusion the contribution of the research objectives, confirming that the *aim of the research has been achieved*.

### 6.2.5. Responding to research questions

The research questions are closely related to the research hypothesis, which states that the energy component of future Smart Villages will be played by smart microgrids that are similar to the Smart Grid microgrids of Smart Cities. This means that it is important to start formulating ideas of what these future Smart Village microgrids might look like to ensure that they are ready when the time comes. The **first research question** to be answered was presented as: *Can a next generation Smart Village microgrid platform be conceptually based on future Smart City operating principles to serve off-grid rural villages in Sub-Saharan Africa?*

As concluded in §6.2, the research demonstrates that it is possible to conceptually base a Smart Village microgrid on the operating principles of a future Smart City, and that the answer to Research Question 1 is an unequivocal **Yes**. Through the proposed scientific research methodology and experimental rural African village scenario narratives, the study incorporated computer models to demonstrate that a next generation Smart Village microgrid platform can be based on the energy system principles of a future Smart City to overcome some of the challenges listed in §1.3.1. This is especially true when those technological principles include the facilitation of the so-called grid-as-open-network type of platform technology for transactive hierarchical control.

The needs of the rural energy user match well with the role of energy prosumers in developed energy markets. Other trends and drivers, that showed similarities in this respect, also support this hypothesis. The hypothesis further states that Smart Village microgrids do not have to go through all the iterations of grid evolution, but that they could leapfrog ahead by copying from the Smart Grid microgrid as it follows along its development pathway. The aim and objectives of this research were to develop conceptual Smart Village microgrid platforms that could be used to give direction towards such an energy system for a future village, while also developing a means to answer the research questions. In this context, the **second research question** that needs to be answered is: *Could such an intelligent Smart Village energy system (from question one) have a meaningful impact on the needs and requirements of rural village microgrid stakeholders?*

As concluded in §6.2, the research demonstrates that the answer to this research question is once again **Yes**. The impacts on the stakeholder requirements eminating from the state-of-the-art control concepts of the Smart City and Smart Grid microgrid roadmaps do translate to the rural village microgrids. Conclusions from Chapters 4 to 5 demonstrate that tailored Smart Grid energy management control principles can have a significant impact on the key stakeholder requirements of affordability, reliability, scalability, flexiblity/adaptability.

These outcomes ("yes" to both questions) support the present study's hypothesis for the energy roadmap blueprints for the future Smart City to be potentially adopted in the rural energy landscape in order to leapfrog to the future vision of *Smart Village energy systems*, as shown in Figure 1.14. The research objectives (towards answering these questions) were accomplished by following an integrated model-based design thinking approach that combines principles from best practices of rural microgrids with theoretical tenets from future Smart City microgrids to conceptualise options for next generation digital Smart Village microgrid control platform. Such an approach investigates options for technological platforms that allow for the integration of legacy devices and future smart devices in the conceptualised Smart Village microgrid. In its turn, such an approach also unlock capabilities of automated decision-making and control optimisation in an off-grid rural village environment. It explores cascaded Smart Grid principles in vertically-integrated rural village microgrids, thereby offering the opportunity to integrate prosumer participation in the objectives of business models and technological platform control. Computer modelling and simulation instruments are used to create and experiment with proposed platform concepts in simulated rural village environments. Finally, this study takes a standpoint on research development directives intended to guide future research operations on rural Smart Village microgrids.

## 6.3. Strategic Conclusions and Recommendations

This section presents further conclusions regarding the significance of the findings of this research within the context of the answered research questions, and the study's contribution to the general body of knowledge. It reports on the potential impact of the study in terms of the academic and practical utilities of the research, and presents recommendations and required actions based on the study conclusions. §6.3.1 details certain high-level strategic research conclusions drawn from the study that strengthen the study hypothesis towards allowing for theoretical formulations and pathways for future academic research. The potential value of the research findings and conclusions in terms of impacts on the energy industry and academia is discussed in §6.3.2. In its turn, §6.3.3 discusses the potential value of the proposed conceptual next generation Smart Village microgrid platform.

### 6.3.1. Conclusions strengthening hypothesis and methodology

This section is concerned with discussing the research findings beyond the purpose and the aim of the study as it brings the underlying attributes of the proposed platform and the design methods used in its formulation to light. Strategic conclusions that support the study hypothesis are presented alongside a discussion on the value of energy as a control parameter in §6.3.1.1, while the underlying attributes of the methodology in the proposed platform are presented in §6.3.1.2.

#### 6.3.1.1. Strategic research conclusions that strengthen the study hypothesis

This section presents a reflection on the research hypothesis to find meaning in the drivers and trends that helped to formulate it. This discussion is presented around Figure 6.7 as a means to visualise the conclusions. The upper half of Figure 6.7 represents the problem statement and research hypothesis that together form the core of the study (for a detailed discussion on this, revisit Chapter 1). This study is based on the philosophy that Smart Villages will develop microgrids that are on par with future Smart City energy networks. Chapter 1 accentuated the fact that there is a need to define advanced Smart Village microgrid roadmaps in order to describe the technical aspects of future rural energy systems since no clear vision is available (Figures 1.26 and 6.7). Therefore, the study explores the opportunity to apply state-of-the-art control approaches from the future Smart City roadmap to rural village microgrids as part of the investigation toward the research hypothesis.

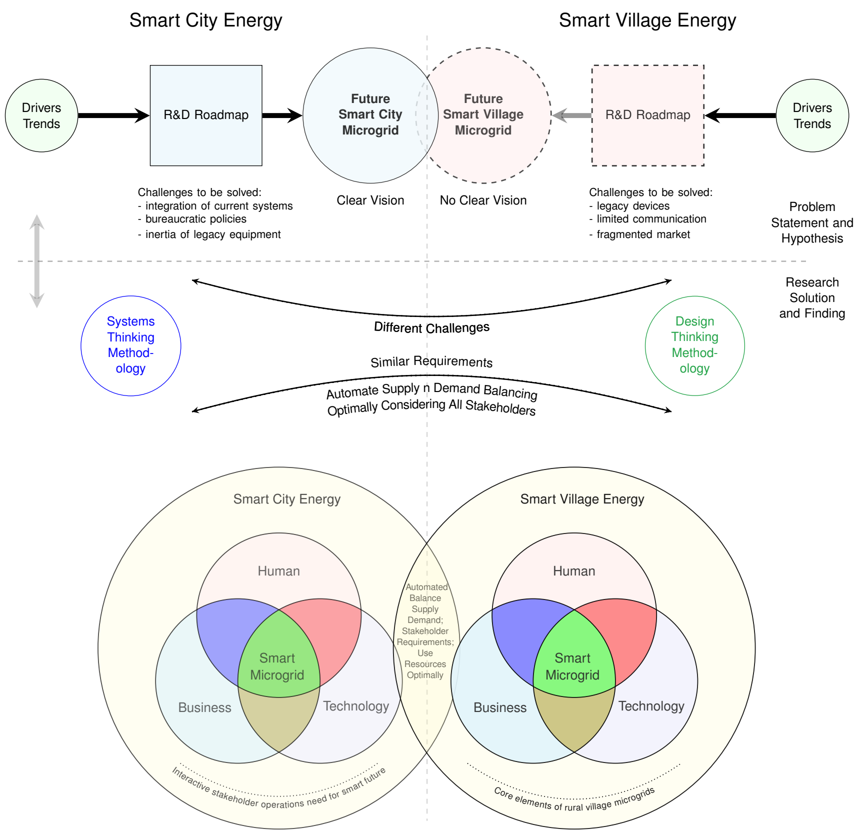



**Figure 6.7:** Graphic depiction of overall research investigation, illustrating the value in exploiting the anticipated similarities between next generation Smart Village Energy requirements and future Smart City Energy principles, according to the present dissertation.

This study also proposed an interactive market-based transactive energy management approach (Figures 6.5 and 6.6) for a next generation Smart Village microgrid platform. It highlights the fact that, while Smart City microgrids and Smart Village microgrids face different transitional challenges, there are overlapping requirements to drive the two developments in the same direction. The core of these requirements is related to microgrid supply/demand balancing, and the need to optimise the use of available resources (Figure 6.7). The proposed Smart Village platform (based on i-MBC automation) was developed on the basis of the positive impact of Smart Grid operating principles on the key stakeholder requirements pertaining to the rural village microgrid, most notably the flexibility in payment (affordability), reliability, and scalability. This led to the conclusion that the answers to both research questions were in fact positive (yes). The significance of these results goes beyond the development of new R&D pathways that result from the possibility of applying these future Smart Grid approaches to rural microgrids. They also go beyond the proposed i-MBC-driven transactive energy microgrid platform as an energy component of the future Smart Village. More importantly, this research extends the hypothesis to also philosophise as to *why* state-of-the-art Smart Grid principles apply to the rural village microgrid landscape.

To answer this question, this discussion shifts the focus away from the energy market drivers and trends that led to the observation of converging pathways (which initially led to the hypothesis). Instead, the focus is placed on the core operating principles of future Smart Cities and how they are anticipated to operate (lower part of Figure 6.7). Understanding the correlation between the core principles of Smart Cities and the best practices of the rural village microgrid is the key to understanding this new question of "why" state-of-the-art Smart Grid principles have a positive impact on rural microgrid performance indicators.

The core principles of future Smart Cities are based on user-centric automated operations through cyber-physical systems in order to achieve optimal operating conditions (the balancing of stakeholder requirements). This was discussed in §1.4, where the well-known relevance of production automation methods, like Purdue and RAMI, which fulfil these requirements in Smart Grids, was highlighted. These methods employ a systems-engineering type of approach, where all the stakeholder requirements are considered throughout the project's lifetime to ensure balanced operations. This means moving away from load-following energy networks to more interactive systems based on the bi-directional flow of energy and communication for increased stakeholder involvement (particularly from the consumer and prosumer). It is these principles of a more interactive system that resonates with the rural village microgrid best practices.

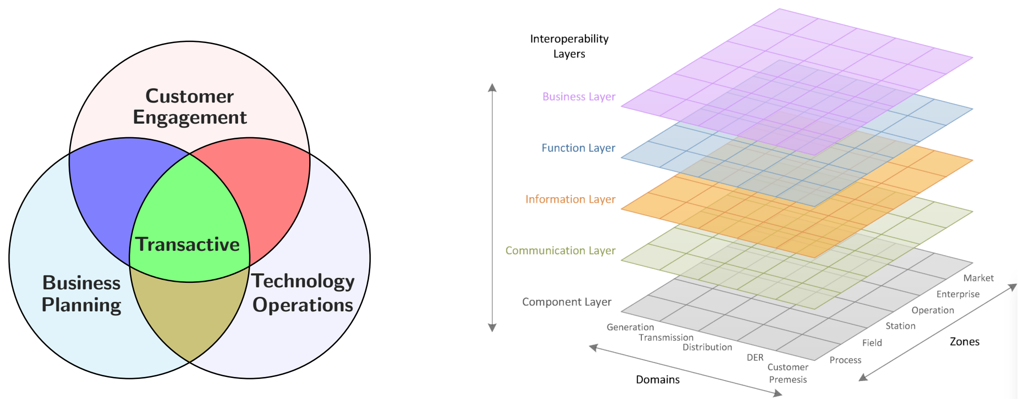
The proposed Smart Village microgrid platform is based on a transactive Smart Grid control approach that dynamically manages the balance between the requirements of the various stakeholders (discussed in §1.3.3) based on the **"value of energy"**. This brings to the fore the critical importance of this **"value of energy"**, and how it can help to achieve optimal operations in the volatile conditions of a rural microgrid. The general misconception around the true value of energy being in the eye of the customer is one of the flaws of command-and-control in global energy markets. Central utility energy planners want to prescribe the value of energy by basing it on *the costs of network electricity*. Because the *price of energy* is not equal to the *value of energy*, the quantification of energy as a value often causes confusion between suppliers and consumers. *Energy worth is a function of customer demand (desire)* and therefore only the customer knows the value of energy [356]. Moreover, from the customer's point of view, the value of energy varies as a function of location, time-of-day, income level and disposable income.

This highlights the value of the research described in Chapters 4 and 5 which was able to accommodate this dynamic *value of energy*. The inherent flexibility offered by the proposed conceptualised Smart Village microgrid platform allows it to serve as a model-agnostic platform for driving microgrid solutions that require the use energy internet-type principles in future rural village microgrid designs. The Smart Grid control approach (based on the value of energy), that is proposed by this dissertation, aligns well with the best practices of rural village microgrid projects discussed in Chapter 1. The same elements (the stakeholder requirement categories of human, business, and technology) have to be balanced up against one another for optimal operations (centre of the Venn diagram Figure 6.7). This means that the core operating principles of future Smart Cities (based on a more user-centric approach to energy management) directly overlap with the core principles that have been demonstrated to work well in rural microgrid projects. Providing a rural village microgrid with the capabilities to achieve these optimal operating conditions in an automated fashion will drive the sustainability of these projects and accelerate the growth of the rural microgrid industry.

#### 6.3.1.2. Underlying attributes of the proposed platform

Regarding the research directives of the present study, rural microgrids need to be transformed under the vision of a Smart Village microgrid to fulfil their role as the energy component in the envisioned Smart Villages of the future. This study applies a model-based design-thinking approach to the conceptualisation process of a proposed microgrid platform suitable for future Smart Village microgrids. This approach has shown significant value as it emphasises the same elements used in rural village microgrid best practices.

This is shown in Figure 6.8, where the three elements to be balanced in design thinking (Figure 6.8(a)) show correlations with the elements of the hierarchical control framework of the microgrid (Figure 6.8(b)). These correlations highlight how the design-thinking elements (that directly overlap with rural microgrid best practices) are embedded in the Purdue hierarchical elements. In a sense, this explains the importance of design-thinking for projects geared to the development of rural energy systems.




(a) (b)

**Figure 6.8:** Broad elements of (a) the design-thinking method embedded in (b) the hierarchical microgrid control abstraction framework.

It is clear from Figure 1.15 that the three remaining intersections hold functional values that differ from the innovations at the intersections of the design-thinking elements. In this context, this **dissertation recommends** that future work should continue with the application of the design-thinking paradigm towards promoting value creation through innovation. In terms of Figure 1.15, the continuation of the proposed approach of the present study will help future microgrid designers to consider the intersections as the innovation conceptualisation space for *Emotional Innovation*, *Process Innovation* and *Functional Innovation* [110]. In this way, design thinking may be able to bring even further stakeholder benefits through offering design features and platform attributes to domesticate and humanise Smart Village microgrid technology.

To this end, this study specifically highlights the value of the research in terms of completing the full circle of thought. The use of a design-thinking research methodology, more generally used by the software engineering industry, but now being applied to a Mechatronic Engineering problem, helped to bring principles around human-centric design, human-centric energy management, and human-centric rural development in line. As depicted in Figure 6.9, the proposed modern scientific research methodology enabled the design process to transition from "design-thinking" goals to "Smart Village" goals, by engaging modern interactive market-based "transactive" control principles as a catalyst. This shows how the design for the proposed Smart Village microgrid platform followed a conceptual train of thought that consistently integrated requirements from all the stakeholders with specific focus being placed on the rural village energy user (people/customer/user).

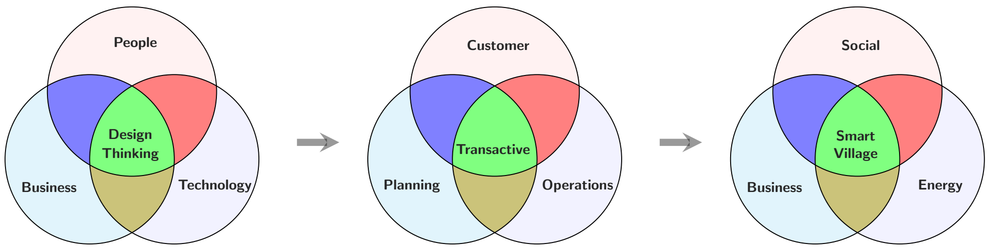



**Figure 6.9:** The proposed scientific research methodology strategically enabled a transition from design-thinking goals to Smart Village goals by engaging transactive energy framework principles as a catalyst.

The three unifying perspectives in Figure 6.8 and Figure 6.9 highlight the reason why the modern local market-based transactive energy framework should be a preferred approach for attaining next generation Smart Village goals. It is because design thinking (Figure 1.15) inherently carries the same "DNA" or heuristics as the Smart Village. This is the same tri-elemental unifying perspective that has made design-thinking so useful as a scientific research methodological approach. At the same time, in electronic control automation terms, the intersecting elements of technology, business and stakeholders are embedded in the Purdue business automation model that offers advanced cascaded control (see Figure 6.8(b)). Figure 6.9 highlights the value of design thinking as a design method that can bring new value in the rural energy space by offering user-centered approaches to domesticate and humanise technology. This may further extend into service-design-thinking, aimed at supporting the cooperation between different disciplines towards the goals of business-level success through technological (automation) processes in pursuing village enterprise objectives.

### 6.3.2. Significance of findings to academia and energy practitioners

The concept of converging developmental pathways between future Smart City microgrids and Smart Village microgrids (Figures 6.5 and 6.7) offers many opportunities for further developmental research. Firstly, since future rural village microgrids need a more structured technological pathway to development, the present research creates *opportunities for academics* in terms of the opening of new avenues for further research into rural electrification. The previous section argued that the next generation Smart Village microgrid approach could encapsulate the core of the principles of the future Smart City microgrid. Secondly, regarding the practical utility of the present research for *energy access practitioners, organisations and other stakeholders* in accessing rural energy, there are significant opportunities for future product development, the implementation of technology, and the development of design and developmental standards. §6.3.2.1 to §6.3.2.6 discusses these opportunities for practical and academic utility in detail.

#### 6.3.2.1. Potential for Smart Village microgrids to leapfrog central grid energy

The strategic research conclusions (§6.3.1) suggest that future Smart Villages are able to adopt Smart Grid technologies and processes owing to shared core values (see Figure 6.7). However, it was also shown that a certain amount of re-contextualisation of the technology would be required as the roadmap to a Smart City aims to overcome different challenges as opposed to those faced by rural village transformation. All cities (Global North and South) have to make significant efforts to incorporate their current infrastructure and operating systems while heading in this Smart City direction. For rural villages on the other hand, there are minimal transitional challenges as they face few limitations in the transition from previous methods and technologies. In addition, the necessary technologies are already making their way into these rural energy markets, creating an ideal environment for a smooth transition to Smart Villages.

The microgrid control platform proposed by this study (adopted from state-of-the-art Smart Grid control approaches) includes operational characteristics that show the potential to help rural communities leapfrog their early development stages to reach smart energy systems and Smart Village microgrids (Figure 1.14). This also means that new research and development fields have been made relevant for innovation to take place in since other Smart Grid innovations can be explored in the rural energy landscape. The following sections propose some considerations that may impact the rural pathway in Figure 1.14.

On a philosophical level, this dissertation helps to *dispel potential misconceptions* caused by the esoteric narratives that the reliance of future Smart Grids on computational intelligence and cloud infrastructure would be creating an increased risk for the energy impoverished to be left further behind. This study offers an *opposing view that the Smart City vision may, in fact, be a liberating force to leapfrog rural electrification*. The smart technological adoption trends in the rural village energy space will continue to push village energy systems toward the smart digital microgrid frontier.

#### 6.3.2.2. Need for Smart Village microgrid R&D roadmap exercises

If the status quo for rural electrification (no definitive R&D roadmaps) prevails, the direction that the development will take and the level of project funding for rural energy projects in emerging markets will remain a challenge. The primary challenge currently caused by the pronounced lack of, and delay in the development of, a future rural village microgrid roadmap is the limitation posed in financing and de-risking rural energy projects [79, 93]. This causes doubt in the minds of typical project investors and in investment bankers when evaluating the potential income streams, technology development directions, and the future direction of rural energisation markets.

This research benefited from a perusal of the Smart City microgrid R&D roadmap, and based on the study findings (the shared core-operating principles in Figure 6.7), future research toward the attainment of the goal of Smart Village microgrids will continue to benefit from such an exercise. However, it will become essential to conduct a technology foresight exercise in order to develop a dedicated Smart Village microgrid R&D roadmap as the overlap between the Smart City and Smart Village concepts. This means that the development of Smart Village microgrids might be accelerated with the support of a targeted roadmap to guide researchers and designers toward smarter village microgrids. Therefore, this **dissertation recommends** that organisations such as the ARE, DOE, IEEE, NIST, Gridwise and the World Bank should consider organising R&D roadmap exercises for defining future research pathways into next generation off-grid rural microgrids.

In formulating a roadmap, special consideration should be given to the methods of production automation, such as those expounded in Purdue and RAMI, as many of the Smart Grid control approaches are founded on these methods (§1.4). The Smart Grid roadmap is aimed, in part, at overcoming the challenges faced in the transformation process and since the rural energy space will face different challenges, there will be stages when the Smart Grid roadmap becomes less relevant. During these stages, the production automation methods will be a valuable source of inspiration as they have the proven capability of balancing various stakeholder group requirements (§1.4).

In support of the rural version of the Smart City model (smart transport, smart water, smart energy), this research emphasises the support needed for defining R&D roadmaps for off-grid rural electrification, especially in the case of new technological pathways such as the rural customisation of Smart City grids. This study further demonstrated the fact that modern IEEE Smart Village type microgrids are likely to form a significant part of the future energy systems in developed markets, and, as such, the Smart Village platform will be a pivotal role-player in defining the transition to a fully-integrated future Smart Grid system.

#### 6.3.2.3. Need for Smart Village microgrid engineering standards

This study found that the best practices for rural village microgrid design are in line with the operational models of future Smart Grids. On account of some similarities in the requirements, it is possible to observe their planned pathway for further development while being mindful of the different challenges that they face. It is imperative to systematically establish rural microgrid standards to guarantee normalised rural energy system development. Highlighting the importance of standards in microgrid development, Figure 6.10 traces the developmental stages for the future microgrid industry, showing that significant growth can be expected once standards have been set in place [55]. In the context of rural village energy, this trace shows that engineering standards could help fast-track larger-scale replicability of standalone, off-grid microgrid deployments to increase capacity and revenue. Policies towards standardisation will place a more prominent international emphasis on decentralised energy markets and allow for the development of the *off-grid energy access market* towards access to distributed energy.

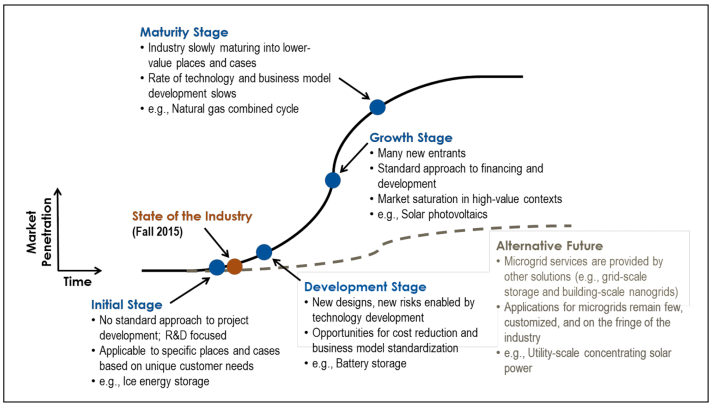



**Figure 6.10:** Development stages for the microgrid industry showing significant growth when standards are set in place [55].

The IEEE P2030.7 Standard on microgrid specifications specifically recognises that microgrid control functions may be performed by multiple devices, rather than by a single centralised management system [52]. These specifications are therefore compiled for functions rather than for devices, with the intention being to provide platform-independent interfaces that make smarter microgrids more modular and interoperable without limiting functionality or inhibiting the customisation of components and approaches to optimisation. This **dissertation recommends** that the IEEE working groups developing the IEEE P2030.10 DC microgrid standards specifically take into consideration the ideas of distributed decision-making and control through multi-agent systems. The findings of the present research are already featuring in discussions in the IEEE P2030.10 regarding DC microgrid standards currently under development [93].

#### 6.3.2.4. Transactive Energy Challenge aimed at Smart Village microgrids

Continuing along the line of regulations and standards, the aspect of transactive framework protocols also needs to be addressed. This **dissertation recommends** that organisations such as NIST and GWAC consider defining a “Smart Village Transactive Energy Challenge” as one of soliciting boilerplate proposals for an intelligent transactive microgrid open-source system. This call may take the form of the NIST Transactive Energy Modelling and Simulation Challenge for the future Smart Grid [357]. Such a challenge would help identify and advance modelling and simulation tools or platforms to support the development of interactive transactive energy in rural off-grid microgrid energy systems.

This dissertation shows that a dedicated transactive energy challenge is needed because contemporary transactive energy simulation platforms, such as the cloud-based electronic transactive energy market information exchanges (TESP, eMix-TeMix-Oasis, GridLab-D, PowerMatcher [297, 358, 359]), make use of a "prices-to-devices" concept in smart devices and smart-home-device management. The concept of the rural Smart Village microgrid platform proposed in this dissertation demonstrates the fact that transactive microgrid topologies may need more tailoring to better serve rural village citizens and homeowners unable to buy expensive new smart electronic appliance devices.

#### 6.3.2.5. Cyber-physical Systems in Smart Village microgrid roadmaps

The proposed Smart Village microgrid platform allows for future design and implementation stages to focus on a cyber-physical systems design and implementation approach in order to prepare the concept platform as a modern service-oriented architecture. Considerations for the integration of the microgrid platform on cyber-physical systems principles (soft-grid-as-network platforms) are discussed in Chapter 5. This implementation will allow for future Control-as-a-Service, Platform-as-a-Service, and Infrastructure-as-a-Service opportunities. These are advanced styles of "service oriented" cyber-physical software design principles for computerised energy network environments [164]. As such, transactive agent-based objects in an object-oriented software environment are able to use communication protocols to offer a means for controlling the provision of energy services to the other application-driven components of service-oriented Smart Village microgrids. In a rural village environment, the next generation Smart Village (i-MBC driven) transactive platform can be empowered to process microgrid-aware signals to/from village households and devices to automate monitoring (diagnose village devices) to provide optimised energy management and control.

#### 6.3.2.6. Smart Village digital SoftGrid-on-a-Chip vision

Technological developments in the Smart Village microgrid, such as the proposed interactive market-based transactive energy construct, can accomodate a growing number of interactive mutual awareness approaches. These facilitate argumentative distributed intelligence in the more advanced device networked microgrids of the future (aiming at an energy cloud embedded on a micro-controller).

In preparation for the integration of the IEEE P2030.7 rural village microgrid standards, this **dissertation recommends** that the proposed Smart Village microgrid platform be commercialised in a microgrid-in-a-box or as a digital Smart Village Soft-Grid-on-a-Chip microgrid solution. The IEEE P2030.7 standards already recognise the need for microgrid control functions to be shared among multiple devices (platform-independent interface specifications and IEEE standards for functions rather than devices).

To accommodate device- and microgrid- embedded distributed control in off-grid rural Smart Villages, a cellular microgrid-type Smart Village hardware/software chip platform can be incorporated on a grid-chip or in a grid-box device. As such, it can work towards achieving an open and flexible network with potential growth in customer self-sufficiency in independent and dynamic rural village smart microgrids. This direction of development supports the Grid-Edge World Forum, arguing that the marketplace for energy solutions may operate in the future in the same way that Amazon revolutionised customer engagement in buying and selling activities [360], thus driving down transaction costs and boosting transparency in new energy consumer markets.

### 6.3.3. Potential impacts of proposed Smart Village microgrid platform

Development of the next generation Smart Village microgrid platform, as formulated in this dissertation, had two main goals which are mutually interconnected. It would serve as a means of addressing the research questions regarding the study hypothesis, and would consider the current knowledge gap, while also predicting a future need for smart microgrids in the rural electrification landscape. §6.3.3.1 to §6.3.3.5 below discuss the additional impacts of this platform development as a technological enabler within these two broader goals.

#### 6.3.3.1. Avenues for Ubuntu Swarm Electrification of rural communities

As presented in the summary of this chapter, the IEA estimates that around 140 million people in rural Sub-Saharan Africa will gain access to electricity through microgrid-, and another 80 million through off-grid installations [76]. An unintended consequence of this research is that the inherent nature of the proposed rural Smart Village microgrid platform supports the notion of *Swarm Electrification*. This energy parallelization through swarm Intelligence refers to a collective electrification paradigm in which solar home systems, and other standalone small-scale installations or nanogrids, can become interconnected to form peer-to-peer microgrid mesgsystems [81, 82, 361]. As an arbitrary mesh network of power entities, it creates the potential for un-electrified neighbours to be connected through a hosting household, as has already been demonstrated by Kirchhoff *et al.* [82]. The swarm logic approach can support reliable, affordable, and sustainable energy products and services towards a unified community that shares energy and works together with energy management (as do Ubuntu principles that feature prominently in Prinsloo *et al.* [236] and Chapters 4 to 5).

The concept of the proposed Smart Village microgrid platform presented in this dissertation offers multiple avenues to support this emerging swarm approach as a rural electrification model as it inherently supports distributed decision-making in parallel computing architectures to enable peer-to-peer energy trading barter-trading principles, as pointed out in Chapters 4 and 5. It promotes the coupling of networks and distributed intelligence in a decentralised flow of information (market processes, price signals), offering reliability through decentralised coordination. This **dissertation recommends** that an investigation should consider customisation options towards Swarm Electrification for the Smart Village microgrid platform proposed in this research. Further research towards this future development has already been initiated. It will see the model being applied to referenced rural villages in South-East Asia in collaboration with researchers at the Delft University of Technology [362]. If proven successful, the combination of these methods could help to promote the interconnection of off-grid installations, and thus the formation of microgrids. These systems can improve the reliability and resiliency of energy services for a significant portion of the global rural population (80 million off-grid connections in Africa expected to be reached by off-grid installations).

#### 6.3.3.2. Smart Village microgrid offering Blockchain integration opportunities

Since the proposed Smart Village microgrid platform of this dissertation is founded on local retail-type, transactive i-MBC automation, it can easily accommodate pairing with symbiotic blockchain algorithms to facilitate activity-based costing and economic identity in power/energy ledgers. This **dissertation recommends** that blockchain electronic ledger modules be developed for the Smart Village microgrid platform as discussed in Chapters 4 and 5.

The underlying transactive i-MBC automation modality of the Smart Village microgrid platform can accommodate the integration of blockchain platforms, thus enabling modern crypto-currency (e.g. Bitcoin, OpenCoin, etc.) trading in a local electronic energy market. The control variables, from Economic Theory (see Figure 6.5), become particularly crucial in current goal oriented transaction energy systems focusing on costs, as an enabler for blockchain trading technologies. Experimental transaction-based platforms are already combining blockchain with energy trading schemes in the so-called internet of value to demonstrate the potential electronic accounting operations in developed energy markets [321, 363].

A blockchain module integration would be invaluable to the Smart Village microgrid as it offers distributed trading with local electronic records management in decentralised energy markets through activity-based micro-pricing with cryptocurrency technology [364, 365]. Since regulations in rural areas are less restrictive [322], blockchain can simply be integrated on top of the proposed transactive i-MBC automation to enable peer-to-peer energy trading as part of the rural microgrid electrification plan. While it lays the foundation for engaging future virtual crypto-currency and electronic cash system wallets, it will make the solution commercially more attractive to flexible payment methods, small businesses development, and capex-investment financing by rural electricity cooperatives or independent power producers in off-grid or grid-edge areas.

#### 6.3.3.3. Small business opportunities for Smart Village microgrid platform

In an era of crypto-currencies, accounting and energy market operations have the potential to play a role as a catalyst for distributed transaction-driven small businesses. The proposed i-MBC automation in the Smart Village microgrid (discussed in Chapters 4 and 5) offers a transactive-block-chain continuum that permits new micro-utility revenue models through flexible income methods and localised business model engineering. These models facilitate new local business opportunities, such as peer-to-peer energy trading among neighbouring village customers, to ensure healthy organic market growth. Activities such as local peer-to-peer (inter-household and inter-village) energy trading fits the IEEE Smart Village empowerment program [96] towards the vision, *"Power a Village, Empower a Community"*. This goal thus extends beyond the energy access aims of supporting local economic activities (e.g. battery-charging, micro-dairy, cold-storage drinks, LED lighting, milling-grinding, micro-factories, irrigation).

Technically, the proposed i-MBC-type Smart Village microgrid platform (Chapter 5) thus offers opportunities for the "energy-as-a-commodity" microgrid to operate as an entrepreneurial platform and create a variety of future energy business ventures. The village community can thus develop and operate income generating equipment over and above community battery-charging stations (entrepreneurial and job creation opportunities on par with the IEEE Smart Village SunBlazer [351, 366]). Another added-value spin-off is that the conceptualised Smart Village platform can operate as a digital soft-grid solution, meaning it can accommodate software objects as future participating agents in the microgrid network, thus enabling options towards a more service-oriented automation architecture for service-oriented applications, similar to mobile phone apps.

#### 6.3.3.4. Smart Village microgrid platform offering flexible payment methods

The process of rural electrification often overlooks the generation of more conducive conditions for payment, energy delivery, and the development of a supportive ecosystem through technological innovations toward flexible payment options for end users [220, 367, 368]. Flexibility in payment is one of the leading considerations from the stakeholder requirement category as part of the "pay-when-you-can" directive of this study. As such, the proposed Smart Village microgrid platform discussed in Chapters 4 and 5, and based on the i-MBC control approach, has inherent features to accommodate flexibility in payment and ownership. The value of flexible payment options in this automation solution may thus show prevalence in PAN African/BRICS countries (Brazil, Russia, India, China and South Africa), where the home base or village-wide community system can be community-owned, family-funded or micro-financed.

Rural smart microgrids have fewer regulatory hurdles to obstruct the pathway to cultural energy innovations, enabling local energy merchants to engage on-site power generation to deliver behind-the-meter decentralised energy as independent power producing businesses (fewer challenges than typical businesses). In this context, blockchain-driven i-MBC features would thus hold great potential for developing countries, as they allow village households to incorporate transactive energy trading models based on barter- and blockchain- type trading and payment models. A registry of transactive dealers promotes accountability, stock keeping, and the provenance of energy commodity items, while blockchain ensures compliance to cost accounting for tender economics and financial balances in block-chain jurisdictions on distributed ledger services.

#### 6.3.3.5. Smart Village platform gaining stakeholder investment support

As significant investment funds are available for rural electrification [66, 78], it remains for the technology to allow options that would unlock opportunities with good business model approaches (see Chapter 5). The proposed Smart Village microgrid platform creates opportunities for flexible business models as well as value sharing among various stakeholders (investors, end-users, third parties, co-owners or utilities). In microgrid economic terms, this approach can be based on the formula: Microgrid Value = Project Income + Avoided Costs - Project Costs - Operating Costs [207]. By basing the control platform on proven best practice elements (Figure 1.16) and then improving on this by automating the decision-making and systems processes, the solution can give additional assurance to investing stakeholders. By applying a blockchain accounting module, the proposed Smart Village (i-MBC) microgrid platform can give the further assurance of tariff collection and secured recovery (accrual to return on investment).

Since several billion dollars of revenue are locked down on account of restricted cellphone usage, investment support can come from the telecommunications industry that stands to gain significantly from increased access to more affordable cellphone-charging [220, 369]. Modular microgrids across the African diorama can assist companies with the introduction and incubation of local projects while also extending their customer base [370, 371]. Energy sales would be a secondary benefit as opposed to the actual value emanating from market expansion as there are many opportunities to add mobile phone users and develop product loyalty (technology and services) in Africa. The proposed Smart Village microgrid platform encapsulates these required modular characteristics (Chapters 4 and 5) and presents the opportunity for the telecommunications stakeholders to enter the rural electrification space.

## 6.4. Summary of Dissertation Contributions

This dissertation highlights the critical role of microgrids toward solving a global energy crisis and places specific emphasis on its role toward rural energisation (see Chapter 1 for the potential role and impact of microgrids in driving socio-economic change across villages). This is a particularly important problem to solve in Sub-Saharan Africa, where the conditions related to the attainment of Goal Seven are in decline compared to other regions of the Global South where the situation is seen to be stabilising or improving. Within this rural energy context, the study identifies a need for microgrids with more strategic control capabilities to unlock their full potential toward Goal Seven. Also, the study observes trends toward future Smart Villages where services and commodities are managed with increasing efficiency. This is in-line with the idea of Smart Cities but becomes even more important in a village environment where supply-chain challenges often place additional constraints on resources.

The current movements that promote Smart Villages recognise the role of microgrids as the key energy component for future Smart Villages (similar to the role of Smart Grids in Smart Cities). This study points out that there are few concrete ideas on how these microgrids should evolve as *Smart Village microgrids* in order to meet future expectations. This research aims to provide a conceptualised plan for a Smart Village microgrid platform (based on Smart Grid approaches), which in its turn would serve as the energy component of future Smart Villages, while concomitantly also considering the current knowledge gap. The following list provides an overview of the research contributions, while a more detailed discussion regarding the academic and practical utility of the overall research contributions is presented in §6.3. In terms of specific research aspects, the dissertation made the following contributions:

⇒ The study proposes a bold view and hypothesis on rural energisation that calls for a shift in focus toward applying state-of-the-art Smart Grid control approaches in establishing rural village microgrids (§1.2.3). This study presents evidence in support of this research hypothesis which could have significant implications for academia, rural energy access practitioners, the rural energy user, and other governmental and humanitarian stakeholders (Chapter 6).

⇒ The study demonstrates the feasibility of setting a unique market-based control approach in place to manage resources in a rural village microgrid environment (locations in Sub-Saharan Africa). This conclusion was reached while this researcher succeeded in developing a conceptualised rural village microgrid platform (Chapter 5) that is representative of what he envisions as the Smart Village energy system of the future, and what it would entail.

⇒ It implements innovative adaptations (DC microgrid architecture tailored for user interaction), which allowed for the re-contextualisation of state-of-the-art Smart Grid control approaches (market-based control) to accommodate the valuation of energy as perceived by the user. This allows cultural values and traditions to be taken into consideration during the microgrid control processes as this approach allows for the inherent incorporation of such values (relevance to the Ubuntu lifestyle is discussed in §6.2 and §6.3.

⇒ This study demonstrates the value of a design-thinking methodology, an approach typically used in the software design industry. The resultant user-centred (value-based) control approach was therefore proposed. It was based on model-based design in combination with ideas and principles identified by re-contextualising the design-thinking approach.

⇒ Based on the research conclusions, this dissertation presents a new hypothesis regarding the direction of Smart Village development. The initial hypothesis stated that future Smart Grid operating principles could be applied to rural village microgrids, and they could have a meaningful impact on performance indicators. This philosophy was based on a perceived convergence in the energy markets of the Global North and the Global South. This research demonstrate that these ideas are in fact possible (at least for transactive energy management approaches) and went on further to identify the reasons why the convergence will continue. It gives clear directives for further R&D and ensures that the appropriate areas of the Smart Grid development pathway will be focused upon, to further develop the Smart Village microgrid platform (Chapter 6).

⇒ The characterisation and modelling of the Smart Village microgrid resource management platform that incorporates the market-based supply- and demand- balancing mechanism, the agent-based representation of microgrid devices (both supply and demand), and the bidding strategies pertaining to the prosumer device software agent representatives (Chapters 4 to 5). The model can be used in the simulation based evaluation of village microgrid projects that are interested in employing transactive based energy management approaches.

⇒ Proposed and demonstrated intelligent decision-support mechanisms to assist rural village dwellers in effectively operating and extending their Smart Village microgrid systems. A budgetary decision-support mechanism can analyse village-wide data and overcome the system complexities to make meaningful energy market price forecasts (Chapter 5). These forecasts are used to guide the village energy user in the load priority setting decision-making process which has a significant impact on assisting the user to remain within the household energy budget (refer to the importance of “pay-when-I-can” and “value of energy” in §1.4.7 and §6.3.1 respectively). In addition, the study presented a secondary-stage optimisation loop function as a storage capacity decision-support system (Chapter 3) which alerts the community when operating costs can be reduced through an investment into increased storage capacity for the village microgrid.

⇒ The characterisation and modelling of an envisioned Smart Village supply- and demand- subsystems places the rural energy user in a central role in major decision-making. This model supports ongoing research at Stellenbosch University and aligns with Goal Seven of the SDGs (reliable, affordable, modern energy services). The above mentioned models, and their significance in respect of the Goal Seven targets, are discussed in §6.2.1 and §6.2.2. Computer models of particular value include the following:

- The empirically-based characterisation of the hybrid solar/gas cogeneration system on the TrnSys simulation platform (Chapter 2), which forms part of the Smart Village computerised model for an integrated rural microgrid configuration driven by solar power.
- The characterisation of energy consumption profiles for rural villages in Sub-Saharan Africa (Prinsloo *et al.* [230]). The data are incorporated into a rural village load profile generator (Prinsloo *et al.* [229]). Based on equipment ratings and household appliance behaviour patterns, these models are used to represent residential energy consumption in disaggregated discrete time-series sequences (Chapters 3 to 5). These models are of academic and practical value as they can be used in the evaluation of energy management and in the optimisation of resource planning and scheduling procedures.

This concludes the broad overview of the contributions emanating from this research project. For a more complete overview of the significance of these contributions, this section should be considered in tandem with the strategic research conclusions in §6.3.

## 6.5. Limitations and Directions for Future Research

This section points to the current limitations of this research with the specific focus being on the proposed Smart Village microgrid platform. In this context, these limitations present opportunities for future research and make recommendations as to how to approach the further expansion, or development, of the Smart Village microgrid platform. These recommendations are supplementary to those discussed in the Strategic Research Conclusions (§6.3) and aim to provide key directives for further development towards a Smart Village microgrid. This study recommends the continued development of the proposed Smart Village microgrid platform in an environment that is predominantly modelling- and simulation- based, with areas for consideration listed below:

⇒ The characterisation of the behaviour of a rural energy user in a value-based transactive environment:

An accurate representation of the behaviour of an energy user in a rural village is a critical component of the simulation-based evaluation. Accurate human representation in a value-based (transactive energy) environment is incredibly complex since it requires a deep understanding of the *value of energy* as perceived by the user. This means that the functional, social significance, epistemic, emotional, and cultural values for the village being modelled must be understood [372]. In addition to these challenges, there is a severe lack of measured load data for rural village microgrid users in Sub-Saharan Africa. This is even more true for device-specific load data.

*Current approach and limitations*: In light of the above, the case-based simulations were done in such a way that a rural village energy user was represented as closely as possible to the baseline user. Budgetary constraints and user preferences concerning load priorities were based on reports and operator feedback and incorporated into the dynamic bidding strategies of the user-device agents.

*Recommendation*: This study recommends the further development of the Smart Village microgrid load profile generator based on field data from organisations such as the IEEE Smart Village, KiloWatts for Humanity, and any other program that is willing to share the relevant data or experiences. While device-specific (disaggregated) load data may typically not be available, the rural village load profiles recorded by these organisations can give insight into the behaviour (and its evolution over time) of a rural energy user. These behavioural observations should be combined with the value-theory frameworks associated with rural electrification. One such framework, developed by Hirmer and Cruickshank [372]), can make significant contributions towards improving the rural village load profile generator.

⇒ Continued development of the DC microgrid as hardware platform for Smart Villages: The simulation models focus on the use of DC microgrids as this technological approach is widely regarded as more successful in rural microgrid applications. Simplicity of design, safety, and efficiency, are some of the contributing factors to the selection of the DC microgrids as the preferred option. The availability of DC appliances is also expanding rapidly in the markets of the Global South [66].

*Current approach and limitations*: The proposed Smart Village microgrid platform is modelled on a low-voltage DC microgrid presented in Chapter 4. This limits the capacity of the current model simulations to the use of DC appliances, which means that further development is necessary to allow for the full-scale participation of all legacy (AC and DC) devices. Another shortcoming is that the current model also has a limited capacity to evaluate fluctuations in the quality of the power.

*Recommendation*: This study recommends that further development of the low-voltage DC microgrid should be in line with the IEEE P2030.10 standard (once this is released). Currently, this standard is set to allow for the necessary functionality to allow for fully transactive systems.

*Recommendation*: The study also recommends the further development of models that accurately represent the DC microgrid power electronics on a platform that can perform model-in-the-loop (MIL) simulations (such as OPAL-RT). This will allow for an evaluation of power quality performance indicators (i.e. resistive voltage drop, percent ripple, DC ripple, and switching noise), while also monitoring the number of faults per day and possibly evaluating the means for surge protection. This should be incrementally expanded using a hardware-in-the-loop (HIL) approach.

⇒ The further development of machine-learning capabilities:
Energy management and the optimisation of resource scheduling rely on accurate forecasts to make optimal resource allocations (discussed in Chapter 3).

*Current approach and limitations*: Extensive research has been done on machine learning methods (Support Vector Machines and Artificial Neural Networks supported by Gaussian Processes) to generate accurate forecasts of village load profiles during this research (currently unpublished). It focused on forecasting consumption data from a village kiosk installation in Filibaba, Zambia (data was provided by the KiloWatts-for-Humanity organisation). While the current microgrid platform can collect detailed device-specific data, it has limited capacity to autonomously process and interpret this data for dynamic forecasting.

*Current approach and limitations*: Also in the current stages of development, the proposed microgrid platform energy market is relatively exposed to device agents with significant power ratings (compared to other devices on the network) and spending capacity. These devices (or their owners) could potentially, given the right conditions, influence village market energy prices for personal gain or otherwise.

*Recommendation*: It is recommended that there should be continued research, and further integration, into these machine learning methods, as they enable additional capabilities needed in future Smart Villages. Some of these capabilities were demonstrated in Chapter 5 where day-ahead electricity market prices in the village energy market were predicted to assist users in the selection of their device priorities (this serves as a guide on how to remain within their daily energy budget). Future work should include an optimised investment algorithm (based on these forecasting methods), aimed at advising users about potential financial benefits of private in-home storage capacity and additional generation resources. The methods proposed in Chapter 3 can be used as a starting point for further development toward this investment algorith.

*Recommendation*: Forecasts can also be applied as a fault-detection method in rural village microgrids, which could have a significant impact on operator/technician response time. Finally, it can be applied in the detection of fraud or tampering in the village microgrid. This can be related to the dangers of hardware tampering, or to the risks of market manipulation expressed above.

⇒ Blockchain accounting module development:
As a final direction for future research, one of the main priorities should be to adopt a blockchain accounting module for the proposed Smart Village platform. The value of this facility, and recommendations for doing so, are discussed in more detail in Chapter 4, Chapter 5 and Section 6.3.

This chapter presented a brief summary of the research to re-state the general purpose of this study (a pressing intellectual problem in the field of rural energy systems) and the underlying hypothesis (in §6.1). §6.2 presented an overview of the findings in respect of each of the research objectives, which were aimed at addressing the problem and answering the research questions. This section (§6.2) continued to demonstrate that the aim of the research had been achieved and that the research questions had been addressed. After presenting these main research conclusions, a set of strategic conclusions were then discussed in §6.3. These strategic conclusions entered into a discussion regarding the underlying drivers of the research hypothesis and presented new ideas (an evolution of the hypothesis) on the future of developments in the rural energy market. This section (§6.3) then proceeded with a discussion on the significance (academic and practical utility) of the research conclusions, the strategic conclusions, and the proposed Smart Village microgrid platform. These discussions were carried over to §6.4, where a more condensed list of research contributions was presented. This was followed by the current limitations and directions for future research presented in §6.5. This brings Chapter 6 to a conclusion, and also concludes the dissertation.

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