DEVELOPING A PATHWAY TO SUSTAINABLE RESIDENTIAL COOLING IN WEST AFRICAN CITIES: THE CASE STUDY OF TEMA, GHANA

by

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Dissertation submitted in fulfillment of the
requirements for the degree of

Doktor-Ingenieur (Dr.-Ing.)

Technische Universität Darmstadt

10 February 2021

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Mertens, Marriette: Developing a Pathway to Sustainable Residential Cooling in West African Cities: The Case Study of Tema, Ghana,
Darmstadt, Germany, Technische Universität Darmstadt,
Year of publication of the dissertation on TUprints: 2021
Date of oral exam: 10 February 2021

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Essen, 30 October 2020 Marriette Mertens

ABSTRACT

Air conditioning is not just a matter of individual comfort in many tropical countries but a precondition of public health, work productivity and economic growth. Residential cooling is energy-intensive, raising profound concern to exacerbate global warming and in turn the need for more residential cooling as the prevalence of air conditioners especially in Africa is expected to skyrocket in the future. This work develops a pathway to sustainable residential cooling for West African cities to address this challenge. As meaningful data are basically non-existent, electricity end use monitoring and survey of 60 households in Tema city is conducted. This is the first measurement study of residential electricity end use in Ghana. A detailed building energy model, representative in terms of archetype and cooling demand, is developed based on and calibrated with the collected data. The validated model is used for dynamic energy simulation to study the impact of key determinants on cooling energy demand and identify specific reduction measures. Dynamic energy simulation of the cooling schedule is used to demonstrate the potential for rooftop solar photovoltaic to meet this energy demand if operated in a smart way. The work is complemented by policy recommendations to incentivize renewable energy deployment and an economic assessment of the various identified demand reduction measures and solar photovoltaic systems. To walk this pathway successfully and turn sustainable residential cooling for West African cities into reality, it is vital to have barriers for implementation removed and create win-win situations for cooperation of stakeholders across the electrical energy system.

KURZFASSUNG

In vielen tropischen Ländern sind Klimaanlagen nicht nur eine Frage des individuellen Komforts, sondern eine Voraussetzung für öffentliche Gesundheit, Arbeitsproduktivität und wirtschaftlichen Fortschritt. Die vermehrte Kühlung von Wohnräumen ist energieintensiv und droht die globale Erwärmung (und damit den Bedarf an noch mehr Raumkühlung) zu verschärfen, da in Zukunft eine sprunghaft ansteigende Verbreitung von Klimaanlagen insbesondere in Afrika erwartet wird. Die vorliegende Arbeit entwickelt einen Weg zur nachhaltigen Wohnraumkühlung für westafrikanische Städte um dieser Herausforderung zu begegnen. Da aussagekräftige Daten weitgehend nicht existent sind, wird eine kombinierte Umfrage und Messkampagne zum Endverbrauch von elektrischem Strom in 60 Haushalten in Tema, Ghana durchgeführt, die erste derartige Studie in dem Land. Auf Grundlage der gesammelten Daten wird ein detailliertes Gebäudeenergiemodell entwickelt, das in Bezug auf den Archetyp und den Kühlenergiebedarf repräsentativ ist und mit den gesammelten Daten kalibriert wird. Das kalibrierte Modell wird zur dynamischen Gebäudeenergiesimulation verwendet, um den Einfluss von Schlüsselparametern auf den Energiebedarf der Raumkühlung zu untersuchen und spezifische Maßnahmen zur Bedarfsreduktion abzuleiten. Die Raumkühlung wird dynamisch simuliert um das Potential von Solar-Photovoltaik auf dem Hausdach zur Deckung des Energiebedarfs zu demonstrieren wenn die Klimaanlage in intelligenter Art und Weise betrieben wird. Ergänzt wird die Arbeit durch regulatorische Vorschläge zur Förderung des Einsatzes erneuerbarer Energien und durch eine Investitionsbewertung der verschiedenen Bedarfsreduktionsmaßnahmen und Photovoltaik-Systeme. Um diesen Weg erfolgreich zu beschreiten und nachhaltige Wohnraumkühlung in westafrikanischen Städten Wirklichkeit werden zu lassen, ist es von entscheidender Bedeutung, dass Bestandshindernisse beseitigt und Win-Win-Situationen zwecks Zusammenarbeit der verschiedenen Interessengruppen über das gesamte elektrische Energiesystem hinweg geschaffen werden.

ACKNOWLEDGEMENTS

This dissertation was prepared during my work as a doctoral candidate at the Institute of Design and Sustainable Building and Darmstadt Graduate School of Energy Science and Engineering. Many people contributed in diverse ways to make this work a success. I would like to express my sincere appreciation to all of them. Special thanks goes to my supervisors: Prof. Dr.-Ing Rolf Katzenbach for his support and encouragement at Faculty of Civil Engineering from January 2015 to March 2017, Prof. Christoph Kuhn for his guidance and support; and for his spontaneous willingness to take over my supervision in March 2017 upon the retirement of Prof. Katzenbach and allowing me the opportunity to complete this doctoral research project under his chair, Prof. Dr. Ingo Sass who originally conceived the topic of this dissertation and Dr. Samuel Gyamfi for instructive discussions on energy policy and energy use monitoring in Ghana. Sincere gratitude goes to the Darmstadt Graduate School of Energy Science and Engineering for providing the financial resources to support this project and the STIBET program at TU Darmstadt for providing a scholarship for the completion of this dissertation. Special thanks to Dr. Tanja Drobek, Mrs. Heide Rinnert, Mrs. Vera Becker and colleague Dr.-Ing Jie Zheng of the graduate school as well as Mrs. Eva Nickel and colleagues Dipl. David Sauerwein, Dipl. Christoph Drebes of the Institute for their enthusiasm in providing countless administrative support and contributing in their own ways to make me feel at home in new surroundings. I am grateful to Ms. Stephane De La Rue Du Can, Dr. Wei Feng and the entire staff of the International Energy Studies Group of Lawrence Berkeley National Laboratory for reviewing the energy audit survey questionnaire and providing me with tools, information and guidance on modelling of residential cooling energy demand. I am also grateful to Mr. Maxwell Mensah, Ing. Kow Eduakwa Sam, Mr. Delight Sedzro and his team at Maritime University Ghana who conducted the ground survey. My sincere gratitude goes to my parents Davy and Dorothy (of blessed memory) for their support and well wishes. I thank Nana Kusi Awuah-Antwi for his role in making my six months stay in California a success. Finally, I am grateful to my husband Nicolas for his relentless patience and support especially in trying times. I dedicate this work to him.

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LIST OF CHARACTERS

Latin character	*Designation*	*Unit*
C_0	Specific cost for West Africa Pipeline gas	[US$/$GWh_{th}$]
e	Margin of error, determination of sample size	[-]
e_p	Annual rate of electricity price increase	[-]
E_t	City-level electricity savings in year t	[GWh_{el}]
$EC_{sat,i}$	Measured electricity consumption on a typical Saturday	[kWh/d]
$EC_{sun,i}$	Measured electricity consumption on a typical Sunday	[kWh/d]
$EC_{wk,i}$	Measured electricity consumption on a typical weekday	[kWh/d]
f	Sample design effect, determination of sample size	[-]
g	Annual rate of natural gas price increase	[-]
G_E	Emissions factor for power generation in Ghana	[$GgCO_2e/GWh_{el}$]
G_N	Cumulated avoided carbon emissions	[$GgCO_2e$]
h	Average household size, determination of sample size	[-]
i	Annual discount rate	[-]
i *(subscript)*	Running index	[-]
I_0	Upfront investment cost	[US$]
I_{base}	Baseline investment cost	[US$]
I_Δ	Efficiency premium	[US$]
k	Survey non-response factor, determination of sample size	[-]
l	Annual rate of AC efficiency loss	[-]
M_i	Measured value	[kWh/m^2/week]
n	Total number of summands	[-]
p	Share of target population, determination of sample size	[-]
r	Estimation of key indicator, determination of sample size	[-]
R^2	Coefficient of determination, regression	[-]
S_0	Annual utility bill savings	[US$/yr]
S_t	Simulation result	[kWh/m^2/week]
S_n	Cumulated generation cost savings	[US$]

t	Running index of year	[-]
UEC_i	Unit electricity consumption of appliance i	[kWh/yr]
x_i	Independent variable, regression	[-]
y	Dependent variable, regression	[-]
Z	z-score, determination of sample size	[-]

Greek character	*Designation*	*Unit*
β_0	Intercept, regression	[-]
β_i	Regression coefficient	[-]
ε	Random error component, regression	[-]
η_{gen}	Efficiency factor of thermal generation, heat to power	[-]
η_{grid}	Efficiency factor of electrical transmission and distribution	[-]

NOMENCLATURE

AB..Apartment building

AC ....Air conditioner, Air conditioning

ASEAN ....Association of Southeast Asian Nations

ASHRAE ....American Society of Heating, Refrigerating and Air Conditioning Engineers

BAT..Best available technology

BAU ....Business as usual

BEES ....Building energy efficiency standards

BR..Bedroom

BST..Bulk supply tariff

CAD...Computer-aided design

CDD ....Cooling degree days

CIF ....Climate Investment Funds

CH_4..Methane

CO_2..Carbon dioxide

COP ....Coefficient of performance

CO_2e..Carbon dioxide equivalent

CVRMSE ....Cumulative variation of root mean square error

DN ....Dining room

DSM...Demand side management

DSO ....Distribution grid system operator

EC..Energy Commission

ECG...Electricity Company of Ghana, DSO

ECOWAS ....Economic Community of West African States

EE ....Energy efficiency

EER..Energy efficiency ratio

EPBD ....Energy Performance of Buildings Directive, EU

EPC..Enclave Power Company, DSO

EU ....European Union
FIT ....Feed-in tariff
GAMA..Greater Accra Metropolitan Area
GCSA..Government consent and support agreement
GDP..Gross domestic product
GHG...Greenhouse gas
GRIDCo ....Ghana Grid Company Limited, national TSO
HTH..High tariff homes
HVAC...Heating, ventilation, air conditioning
IM ....Improvised housing
IPP...Independent power producer
KNUST ....Kwame Nkrumah University of Science and Technology
LFG...Landfill gas
LLH...Lifeline tariff homes
LR ....Living room
LTH...Low tariff homes
MEPS..Minimum efficiency performance standards
MET..Medium efficiency technology
MFH..Multiple family home
MLR ....Multiple linear regression
MTH ....Medium tariff homes
N_2O ....Nitrous oxide
NEDCo ....Northern Energy Distribution Company, DSO
NO_x ....Nitrous oxides
NPV ....Net present value
OLS ....Ordinary least squares
PPA ....Power purchase agreement
PRG ....Partial risk guarantee
PURC..Public Utilities Regulatory Commission
PV..Photovoltaic

RE..Renewable energy
REC..Renewable energy certificates
RECS ....Residential electricity consumption survey
ROI ....Return on investment
RPS...Renewable portfolio standards
SFD ....Single family detached home
SFSD..Single family semi-detached home
SNEP ....Strategic National Energy Plan
SO_x...Sulfur oxides
SFD ....Single family detached home
SPT...Static payback time
SREP...Scaling-up Renewable Energy Plan
ST..Study Room
TSO ....Transmission grid system operator
UENR..University of Energy and Natural Resources
VRA ....Volta River Authority, state-owned power producer
WACC ....Weighted average cost of capital
WMO...World Meteorological Organization
WWR ....Window-to-wall ratio

Chapter 1

INTRODUCTION

Cities today are home to about half the global population, but account for almost two-thirds of global energy demand and 70% of carbon emissions from the energy sector (S. Leahy 2018; UN-Department of Economic and Social Affairs Population Division 2018). The population of Africa's cities is expected to grow by 600 million over the next two decades, outpacing the increase experienced by China's cities during the country's 20-year economic and energy prosperity. These expansions will have far-reaching consequences that will steer the continent's economic growth and infrastructure development. The associated energy demand is projected to rise 60% to about 15000 TWh in 2040, based on current policies and plans (IEA 2019a). Majority of urban areas in emerging economies are not yet fully developed, and about 40% of the world's current building stock will be built in developing and emerging economies between now and 2050 (IEA 2019c). The associated demand for energy services would double global cities' energy-related CO_2 emissions if development is conducted without transition from carbon-intensive energy infrastructure to modern renewable energy technologies that can provide equal comfort levels (IEA 2019c).

In Africa, the average daily temperature in homes to estimated 700 million people exceeds the 25^{o}C threshold for thermal comfort and necessitates cooling (Figure 1.1). This number reaches 1.2 billion by 2040 as population grows and temperatures rise with climate change (IEA 2019b). West Africa experiences the highest need for cooling with cooling degree days reaching 6000. Majority of residents present a different threat, a rising lower-middle class who are only able to afford cheaper, inefficient air conditioners with very high electricity consumption (Sustainable Energy for All 2019). This sets the stage for variability in power generation and supply notably from hydropower as is the case in Ghana due to increased frequency and intensity of extreme weather events such as droughts and floods (IEA 2019b). How this growing challenge is met, is crucial for the region's economic and energy future and has profound implications for climate change and public health.

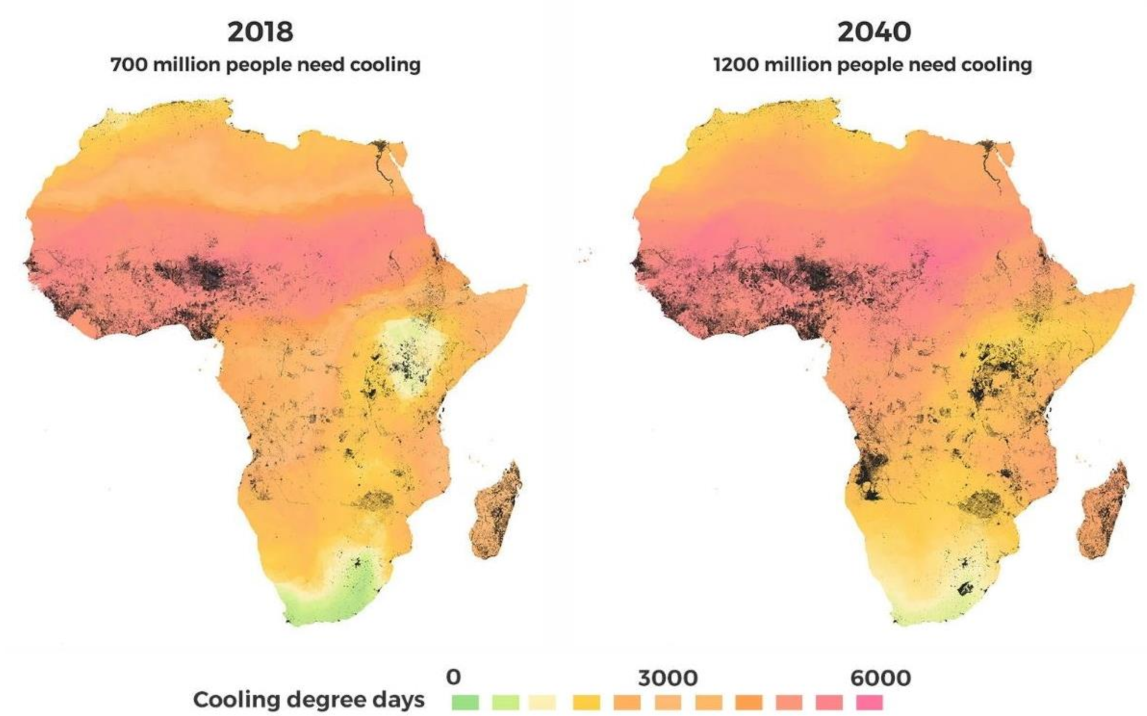

Figure 1.1: Cooling degree days in IEA Policies Scenario, 2018 and 2040 (IEA 2019b).

Sustainable cooling solutions with strict focus on efficiency could ensure cooling energy demand is in line with available sources of renewable electricity supply. However, design of such solutions requires understanding of precisely measured cooling needs of households (Porcaro 2019). This work uses measured household cooling electricity consumption to simulate potential savings from implementing building energy efficiency measures in a first step, and evaluates the potential of rooftop solar power to supply residential cooling load when the operating schedule of the air conditioner is aligned with the timing of solar power generation in a second step. Results of this work address the electricity supply threat posed by cooling in lower middle-class to middle-class households by offering specific solutions to reduce cooling electricity demand, investigate low cost options for energy efficiency and explore the potential of solar PV for sustainable cooling.

Rooftop solar PV systems could technically meet about 40% of cities' electricity demand by 2050 if new urban buildings are designed to cover their own electricity demand (i.e. become so-called prosumers)(IRENA 2019). Cities, as centers of innovation, population and economic growth in West Africa, are ideal proving grounds for robust sustainable urban energy systems (Day et al. 2018). Cities as test beds for rooftop solar PV systems for instance, can provide database and solar maps giving valuable information on expected electricity yields and its cost-effectiveness for various building types (Day et al. 2018). Africa has the richest solar resources in the world but less than 1% global installed capacity of solar PV at only 5 GW. Considering the vast renewables resources and falling technology costs, the potential exists for double-digit growth in deployment of utility-scale, distributed solar PV and other renewables across the continent (IEA 2019b).

Ghana and Cabo Verde have the highest economic development in the West Africa sub-region, indicated by their higher GDP per capita and human development indices. The rate of urbanization in Ghana is higher, and more representative of the region (OECD 2019). Through deployment of non-hydro renewable energy systems, successful implementation of energy efficiency initiatives and renewable energy development support policies, Ghana plays a leading role in sustainable energy development in West Africa (Sakah et al. 2017). In this study therefore, the city of Tema in Ghana is selected for detailed case study of residential electricity end-use as it is completely urbanized and a flagship city for Ghana and the West Africa sub-region in terms of prospective electricity use reduction. The pilot of the Refrigerator Energy Efficiency Project Ghana for example was conducted in Tema.

1.1. Characterization of Tema City

Tema city is located on latitude 5.67°N and longitude 0.00°E, in the coastal savannah zone, on the Bight of Benin and Atlantic coast of Ghana (Tema Metropolitan Assembly 2014). It is 25 km east of Ghana's capital city; Accra, in the Greater Accra region, and is the capital of the Tema Metropolitan District (Tema Metropolitan Assembly 2014). The city has a dry and warm equatorial climate, with high temperatures all year round (Nyarko 2014a). Average annual temperature typically varies from 23°C to 34°C, with 83% relative humidity (Meteoblue 2018). Tema is the hub of Ghanaian industrialization (Apeaning and Thollander

2013). Growth in industrial and commercial sectors of the city has progressively driven rapid urban migration. With an average annual growth rate of 3%, Tema is one of the fastest growing cities in Ghana (Tema Metropolitan Assembly 2014). The population of Tema metropolis, according to the 2010 Population and Housing Census, is 292773, comprising 70797 households (Nyarko 2014a). Low income housing provides accommodation for about 60% of the population (Tema Metropolitan Assembly 2014). Still, the city is experiencing an increasing shortage of housing units to accommodate its expanding population. The resultant deficit has led to proliferation of unauthorized extensions and expansions to the low and middle income housing units in the older residential communities as well as development of informal settlements (Acquah 2001). The ensuing unpredictable demand for energy services, in addition to the electricity needs of planned new developments, place a major strain on the city's energy infrastructure (Tema Metropolitan Assembly 2014).

While Tema houses about half of Ghana's installed thermal power generation capacity, it has no dedicated power plant, and the city relies on the national grid for all of its electricity supply (Volta River Authority 2018; Tema Metropolitan Assembly 2014). Residents of Tema therefore periodically suffer electricity shortages lasting typically six to twelve hours via load shedding that characterizes Ghana's electricity supply security or lack thereof (Sakah et al. 2017). This supply constraint could be curtailed by actively promoting transition to renewable-based electricity supply and energy efficiency in existing and new buildings particularly in planning and development of new settlement areas through the use of incentives, regulations, and demonstration projects.

1.2. State of the art

Though net zero energy buildings is one of the most active areas of research towards sustainable urban development , there is very limited work on sustainable residential cooling as most studies are on heating applications. The very few studies towards some sort of sustainable cooling investigate substitution of conventional air conditioning systems with phase change materials (PCM) for passive cooling (Alam et al. 2017; Akeiber et al. 2016), optimized natural ventilation (Lan, Wood, and Yuen 2019), solar thermal polygeneration (Mohan et al. 2016), ground source heat pumps/exchangers (Serageldin et al. 2020; K. Zhou et al. 2020; Weeratunge 2020), combined diurnal radiative cooling and indirect evaporative cooling (Katramiz et al. 2020), adsorption cooling systems (Choudhury et al. 2013), and district cooling systems (Alajmi and Zedan 2020; Lake, Rezaie, and Beyerlein 2017).

Akeiber et al. (2016) reviewed application of PCMs for sustainable passive cooling in building envelopes and found that while most studies highlighted the high capability of PCM for cooling applications, there are huge gaps in humidity control, cost analysis and economic evaluation. It was noted that relying on passive cooling techniques alone for thermal comfort provision is inadequate due to their extreme dependence on climatic factors. Lan, Wood, and Yuen (2019) investigated a holistic design approach for residential net-zero energy building in Singapore by optimizing the utilization rate of natural cooling and daylighting in the first phase, and optimizing energy efficiency, renewable energy capacity and life cycle cost in the second phase. While results show it is achievable to build a net-zero energy landed house with only rooftop solar panels, there is no economic analysis to ascertain the cost-effectiveness of investment in this system which also requires suitable climatic conditions. Mohan et al. (2016) developed a solar thermal polygeneration system consisting of solar collectors for production of thermal energy, single stage LiBr– H_2O absorption chiller for providing air conditioning to office cabins and membrane distillation modules for producing clean water and domestic hot water for the conditions of United Arab Emirates. Its application is limited due to high investment costs (i.e. US$165,000 for rooftop installations) and required operation hours between 08:00 and 18:00 for office buildings as opposed to residential building occupancy. The uptake of ground source heat pumps has been limited due to high initial cost involved in the drilling of boreholes for exchanging heat with the ground via high density polyethylene pipes (Weeratunge 2020). This technology is generally not suitable for Ghana and the West Africa sub region due to climatic variations and high (21.5°C - 31.9°C) groundwater temperature (Ewusi et al. 2017). Katramiz et al. (2020) investigated the performance of a hybrid passive cooling system that proved 53.4 % more energy efficient compared to a typical AC system during the cooling season in Kuwait. However, the system is complex and cannot be implemented in humid climates as this would negatively affect performance. Choudhury et al. (2013) reviewed developments in adsorption refrigeration systems and found that low specific cooling power of the system, leading to bigger sizes of the chillers and comparatively higher investment cost, is a major hindrance to successful commercialization of the technology. District cooling systems require high capital investment for the necessary infrastructural layout, making it uneconomical especially for built-up areas and in low rise residential applications (Alajmi and Zedan 2020). Lessons from Spain and the UK suggest that fuel and operating costs, electricity prices, tariffs and subsidies are needed to attract private investment (Lake, Rezaie, and Beyerlein 2017).

While the above described technologies for sustainable cooling show some promise in specific high-income countries, they do not meet some of the basic requirements for residential cooling in Ghana and the West Africa sub region, namely: affordable cost, capacity to dehumidify, robustness and technical maturity. The approach selected for this work is to combine readily available potential in building design, building materials, AC efficiency, rooftop solar power and smart operation, and develop a sustainable pathway to residential cooling that is a viable alternative for developing countries with tropical climate.

1.3. Originality and scientific contribution

In this work, guidelines for transition to sustainable residential cooling at the city-level are developed for West Africa using the case study of Tema city in Ghana. Five innovative aspects 1 – 5 of the project can be distinguished with respect to the existing body of literature:

1. To the authors' knowledge this is the first study that combines both survey results and end-use monitoring of household appliances to yield a comprehensive analysis

of city-scale residential electricity end uses in Ghana. For the first time, such data is generated and made available to the scientific community.

2. A pathway to economically viable sustainable residential cooling in West-African cities was developed based on the generated dataset. A detailed building energy model was developed and validated with the measured cooling energy consumption. The calibrated model was used to determine the potential savings of energy-efficient design of the building envelope and efficient air conditioning, to verify that AC load can be shifted without impairing thermal comfort and to align the air conditioning schedule with the timing of power generation from decentralized solar PV. To the author's knowledge, this is the first study in Ghana that assesses the potential of decentralized solar power for sustainable residential cooling.
3. Residential energy end-use in West African countries is dominated by cooling demand for thermal comfort, which means that suitable retrofit and building design must focus on efficient heat removal, de-humidification and circulation of air rather than improving thermal insulation.
4. Although energy retrofit of the current building stock is relevant, improving building energy efficiency for new construction projects is even more important due to rapid population growth and associated housing need as well as continuous increase of living standard and air conditioning use in the West Africa sub region.
5. The setting in a developing economy implies that for energy efficiency i.e. appliances and buildings, greater weight must be put on technical maturity, effectiveness, robustness, simple handling, cost-effectiveness and use of local materials vis-à-vis the technological state of the art. Other differences include quality of utility infrastructure, security of grid supply (or lack thereof), socio-economic barriers as well as (in) effectiveness of government in enforcing laws.

To develop a strategy for renewables-based cooling in developing economies, it is essential to first take stock of the existing energy supply landscape, and the electricity end-use profile. It is also important to consider the political context and barriers for large scale implementation of renewable energy systems. Before investment is made in renewables, it is essential to improve the energy efficiency of the building as well as electrical loads to ensure energy is not being wasted. Renewable energy generation timing does not always align with demand, particularly residential cooling demand. There is need therefore, to shift the cooling load of the home to coincide with the timing of renewable energy generation from adequately sized systems without impairing the thermal comfort of residents. Lack of capital is a major impediment to uptake of decentralized renewable energy systems in Ghana and West Africa. It is crucial to demonstrate financial viability of investment in the proposed renewable cooling systems with regards to energy bill savings, and how these savings as return on investment, will change in the future with changes to external economic factors. The resulting pathway is a comprehensive strategy for implementing city-level energy transition to renewables-based residential cooling in urban Ghana, whereas the case study serves as original reference for best practices on sustainable residential cooling in the West-Africa sub-region. The findings are transferable to developing economies around the equator with similar, tropical micro-climate.

1.4. Structure of the thesis

The thesis is divided into seven chapters, which build upon one another.

- Chapter 1 introduces the motivation for the study and characterizes the case study, Tema city in Ghana.
- Chapter 2 takes stock of existing power generation sources to profile the electricity supply structure in Ghana with regards to fuel sources, primary energy factors and emission factors. It also takes stock of Ghana's renewable energy resources and presents a review of policies that govern their development and deployment.
- Chapter 3 characterizes residential electricity use in the city with the results of a ground survey and end-use monitoring of household appliances.

- Chapter 4 evaluates the potential of residential building energy efficiency to reduce cooling electricity demand.
- Chapter 5 assesses the feasibility of aligning cooling load with solar power generation for peak load shaving and reduced grid dependency.
- Chapter 6 investigates the financial viability of investment in building energy efficiency and rooftop solar PV systems.
- In Chapter 7 the findings and conclusions of the work are summarized
- Chapter 8 presents suggestions for further research.

Chapter 2

REVIEW OF POLICIES FOR RENEWABLE ENERGY DEPLOYMENT IN GHANA

2.1. Introduction

Increasing energy demand, security of energy supply and climate change mitigation pose the toughest environmental challenge for sustainable development globally (Day et al. 2018). How to meet energy needs without impairing both the economy and the environment remains an urgent problem for every country (Hua, Oliphant, and Jing 2016). Ghana has been faced with serious electricity supply challenges in recent times. A supply deficit amounting to 25% of peak power was reported for the year 2014/2015 (CIF Climate Investment Fund 2015). Existing power plants were unable to attain full generation capacity due to fuel supply constraints. Non-perennial rivers together with inadequate and unreliable rainfall arising from climate variability particularly in northern Ghana have significantly reduced inflows into hydroelectric power plants. Thermal power now dominates Ghana's energy generation portfolio. Approximately 51% of the country's electricity is generated from imported fossil fuels (Energy Commission 2017). The country's energy system is likely to suffer additional strain from rising energy demand fueled by population growth, rapid urbanization and economic development. Security of future energy supply is therefore at risk especially in light of government's commitment of achieve 100% electricity access by 2020 (Kemausuor et al. 2011). Given the positive correlation between energy access and human development, access to modern energy services is crucial for sustainable socioeconomic development. Ghana therefore needs to integrate a broad range of non-conventional energy technologies into its generation portfolio to improve energy security and provide insulation against external shocks such as price spikes of fossil fuels. Sustainable energy systems provide such an opportunity. Transition to renewable energy technologies however requires long term planning and commitment on the part of government (Kelly-richards et al. 2017). Deployment requires support of well-designed policies and programs to overcome country specific barriers (ECREE 2012). Many countries have prioritized renewable energy for development by law (IEA International Energy Agency 2016). Introduction of the "Renewable Energy Law" in China for example increased the share of RE in power generation to 22.16% for all resources including hydro (He et al. 2016b) and 1.2% excluding hydro (Hua, Oliphant, and Jing 2016). In Africa, 35 of the continent's 54 countries adopted a renewable energy policy by early 2014, while 37 adopted one or more renewable energy targets. This is a significant improvement on 2005 when neither policies nor targets existed for non-conventional renewable energy development and deployment. About 13 ECOWAS member states have now set RE targets ranging from 5 - 35% of national energy generation to be achieved by 2020 – 2030 (ECREEE 2014b).

Ghana enacted the "Renewable Energy Act", Act 832 in 2011 to provide for the development, management, utilization, and adequate supply of renewable energy for generation of heat and power and for related matters (Parliament of the Republic of Ghana 2011; Togobo 2016). It's target is to increase the share of sustainable electricity in the national generation mix to 10% by 2020 (EC Energy Commission 2006). Ghana is one of the leading countries with substantial RE regulatory and fiscal policies on the African continent. The right mix of policies which can address unique domestic challenges to help achieve its specific development goals however remains insufficient. For instance, notwithstanding the substantial RE policies supporting developments in the electricity sub sector, deployment of non-conventional RE has slowed especially for grid-tied electricity where the share is less than 1% (VRA Volta River Authority 2015a). Several authors have investigated renewable development in Ghana. Gyamfi et al in (Gyamfi, Modjinou, and Djordjevic 2015) focused on various resources for improving the security of electricity supply. Others focused on single resource potential including municipal solid waste in (Ofori-boateng, Teong, and Mensah 2013), solar PV in (Amankwah-amoah and Sarpong 2016), wind in (Adaramola, Agelin-chaab, and Paul 2015), biogas in (Arthur, Francisca, and Antwi 2011) and agricultural biomass in (Mohammed et al. 2013; Arranz-piera et al. 2016). Adom et al in (Adom et al. 2017) investigated the effects of renewable energy integration on electricity pricing. Policy framework to support renewable energy development has been investigated in (Iddrisu and Bhattacharyya 2015; Ahmed, Betey, and Gasparatos 2017) for biofuels and (Atsu, Okoh Agyemang, and Tsike 2016) for solar PV. RE development and deployment require periodic assessment to investigate whether energy policies fulfil the objectives for which they were designed (Cheng and Yi 2017).

Reviews have been conducted globally for countries with established RE policy frameworks. Byrnes et al. in (Byrnes et al. 2013) reviewed Australian RE policies where they outlined key policy frameworks and presented a critical analysis of the barriers faced by the industry. Schmid in (Schmid 2012) studied the empirical effect of the introduction of the Electricity Act, 2003 and the Tariff Policy, 2006 on India's RE development. The results indicate that state-level policies and private sector participation have been instrumental in promoting growth of the installed capacity of renewable electricity. Sarraf et al in (Sarraf et al. 2013) studied the renewable energy policies, strategies and programs in Cambodia as well as their impact on project development. Chen et al in (W. Chen, Kim, and Yamaguchi 2014) reviewed development of RE policies and roadmaps for Japan, South Korea and Taiwan. Blok in (Editorial 2010) reviewed and analyzed the state of RE policies within the European Union. Other reviews on RE policy and RE deployment include (Lidula et al. 2007) for ASEAN countries, (Mekhilef et al. 2014) for Malaysia and (Shen and Luo 2015) for China.
There is very little information on Ghana's renewable energy policy in literature. No research has assessed the effectiveness of Ghana's renewable energy policy in developing and deploying sustainable energy technologies. This study attempts to bridge that knowledge gap. The specific objectives of this section of work are to: 1. review the regulatory framework, financing incentives and other provisions of Ghana's Renewable Energy Act, 2. critically examine policy strengths, weaknesses, opportunities, treats and its impact on renewable energy project development, 3. recommends specific policy features based on comparative lessons from renewable energy policy implementation in other countries.

The contributions of this chapter are twofold. First, it provides policy and implementation strategy adjustments to the existing policy framework which could further increase the installed RE capacity. The study explores policy features that have accounted for successful renewable energy deployment in industrialized and developing economies for possible adaptation in Ghana. Second, it provides key learning and experience curve to guide other African countries such as: The Gambia, Sierra Leone, Benin, Liberia, Togo, Zimbabwe, Libya, Sudan, Cameroun etc. who currently have limited but similar schemes. For example, though feed-in policies are most widely used mechanisms to promote renewable power generation worldwide, only a handful of countries have successfully implemented it. It remains absent in a large majority of West African countries. Adopting and instituting measures as provided in the case of Ghana could fundamentally help the West Africa sub-region in achieving the "Sustainable Energy for All" objectives especially for access to electricity.

2.2. Background

2.2.1. Structure of the Ghanaian state

Ghana is a multiparty constitutional democracy governed by the Rule of Law via three Arms of Government: the Executive, Legislature and Judiciary each of which is independent of the other. Laws and Bills are passed by the Legislature, implemented by the Executive and interpreted by the Judiciary. However, majority of the executive are drawn from the largest political party within the legislature, which by their electoral majority constitute the ruling government. Hence, practically, policy formulation and its implementation are controlled by the ruling government. The president is the Head of State and Government (Friedrich Ebert-Stiftung Ghana 2011). The Ministry of Energy and Petroleum acts on behalf of government on energy matters in Ghana. The ministry also formulates policies that govern the electricity sector as well as monitoring and evaluation of sectoral programs/projects (Ministry of Energy and Petroleum Ghana 2015) . A Ministry of Power was created in the last quarter of 2014 to bring a sharper focus on the generation and efficient delivery of power to match the growth in economic development and to ensure stability and security of power supply (Government of Ghana 2015). Renewable energy policy formulation therefore reflects a combination of constitutional responsibilities, inter-ministerial and inter-institutional agreements. The success of Germany's renewable energy development has been attributed to policy design and an enabling political environment (Yoon and Sim 2015). The presence of advocacy coalition in both the ruling government and the opposition party according to (Lipp 2007), influenced the institutional framework of the RE policy. Performance of sustainable energy policy was found to depend on political and economic context irrespective of the choice of policy model in EU countries (Ringel 2006) and Latin America (Jacobs et al. 2013). It is therefore important to separate policy design and the broader enabling environment for an efficient analysis of impacts on renewable energy development.

2.2.2. Energy sector regulation and governance

The power sector in Ghana can be divided into three groups; the Ministries (energy, power), the Regulatory bodies (Energy Commission, Public Utilities Regulatory Commission) and the Industry which comprises utility providers and consumers. Figure 2.1 illustrates the role and ownership of power sector institutions in Ghana. Volta River Authority (VRA) was responsible for power generation, transmission and distribution throughout Ghana up until 2008, when the power sector reforms unbundled its functions and established Ghana Grid Company Limited (GRIDCo) to solely transmit electricity nationwide (UN-Energy 2008). Power generation and distribution have since then been opened to private sector participation to promote efficiency, diversification and competition (Lartey 2009).

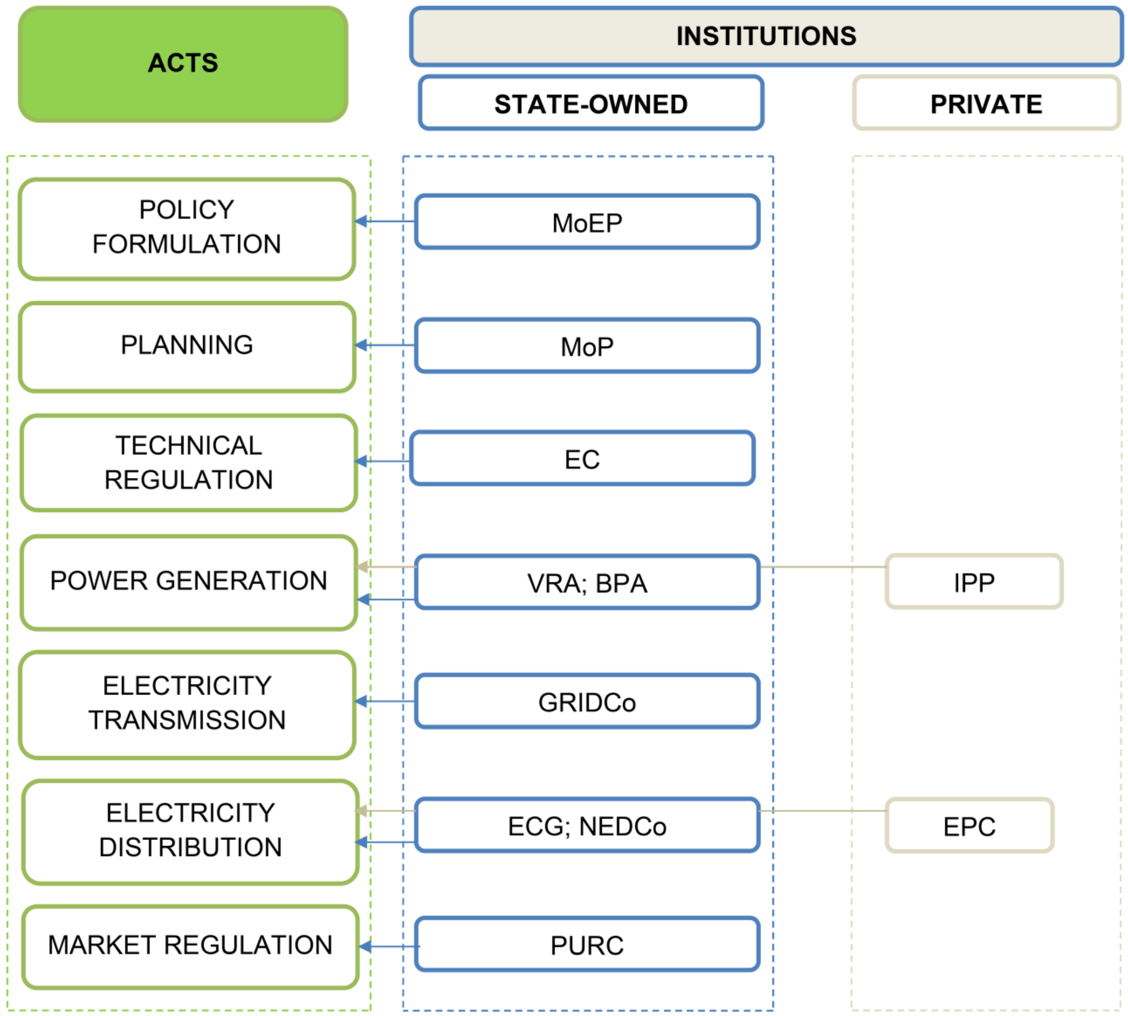

Figure 2.1: Power sector regulation and market structure (abbreviations explained in text) (Government of Ghana 2015; Ministry of Energy and Petroleum Ghana 2015; UN-Energy 2008).

Currently, about 87% of the generation capacity is controlled by state owned companies VRA and Bui Power Authority (BPA), while Independent Power Producers (IPPs) account for the remaining 13% (EC Energy Commission 2015b; VRA Volta River Authority 2015b; Norton Rose Fullbright LLP 2013). Three companies are in operation at the distribution sector. Electricity Company of Ghana (ECG), which was established following the unbundling of VRA, purchases electricity from VRA at a bulk tariff for distribution in southern Ghana. Northern Electricity Distribution Company (NEDCo), a wholly owned subsidiary of VRA distributes power to the northern parts of Ghana while Enclave Power Company (EPC) distributes power to bulk consumers. Independent Power Producers (IPP) who require transmission of generated electricity must enter into an agreement with GRIDCo (IAEA International Atomic Energy Agency 2013).

The statutory regulatory bodies i.e. EC and PURC were instituted to act independent of governmental influence. Only PURC however, has its independence enshrined in its Act which states emphatically that "...the Commission shall not be subject to the direction or control of any person or authority in the performance of its functions" (PURC Public Utilities Regulatory Commission 2015) Section 3 of the EC Act on the other hand empowers the Minister of Energy to influence activities of the institution by stating categorically that "The Minister may give to the Commission such directions of a general character as appear to him to be required in the public interest relating to the discharge of the functions of the Commission"(EC Energy Commission 2015a). Table 2.1 shows the core mandates of the EC and PURC as set out in legislation pertaining to their activities in the electricity sector.

Both regulators have minimum requisite legal power except for the authority to enforce standards and rules. For example, EC has the power to suspend and revoke the license of an operator, but neither the EC nor the PURC has the authority to enforce sanctions such as fines. That remains within the jurisdiction of the High Courts.

Some academic institutions are involved in RE development in Ghana. KNUST and UENR conduct research on RE technologies, regulations and technical standardization (KNUST Energy Center 2015; UENR 2015). Still, Ghana depends largely on technologies developed in foreign countries. There is very limited capacity in manufacturing facilities for RE technologies (EC Energy Commission 2014) and thus exposes developers/investors to variations in technology costs and foreign exchange. The assembly plant for solar technologies in Ghana is a monopoly (The Herald 2016) and hence there is no competition to either drive technology efficiency or reduce market prices.

Table 2.1: Core mandates of statutory regulatory institutions (UN-Energy 2008; EC Energy Commission 2015a; PURC Public Utilities Regulatory Commission 2015).

Public Utilities Regulatory Commission	Energy Commission
Provide guidelines on rates chargeable for provision of utility services	Recommend national policies for the development and utilization of indigenous energy sources
Examine and approve rates chargeable for provision of utility services	Advise the Minister on national policies for efficient, economical, and safe supply of electricity to the national economy
Monitor standards of performance for provision of services	Prepare, review and update periodically indicative national plans to ensure that all reasonable demands for energy are met
Initiate and conduct investigations into standards of quality of service given to consumers	Secure a comprehensive data base for national decision making on the extent of development and utilization of energy resources available to the nation
Promote fair competition among public utilities	Receive and assess applications, and grant licenses to public utilities for the transmission, wholesale supply, distribution , and sale of electricity
Conduct studies relating to economy and efficiency of public utilities	Establish and enforce in consultation with the PURC standards of performance for public utilities engaged in the transmission, wholesale supply, distribution and sale of electricity
To make such valuation of property of public utilities as it considers necessary for the purposes of the Commission (PURC)	Promote and ensure uniform rules of practice for the transmission, wholesale supply, distribution and sale of electricity
To collect and compile such data on public utilities as it considers necessary for the performance of its functions	
To advise any person or authority in respect of any public utility	
To maintain a register of public utilities	

2.2.3. Ghana's power outlook

Electricity supply to Tema city is sourced from the national grid, and generated using a mix of different primary energy carriers and technologies. Although Ghana has crude oil and natural gas resources, the quantities are not comparable to other African countries such as Nigeria, Angola, Egypt, Libya, Algeria, South Africa or the Democratic Republic of Congo. Ghana's only oil refinery does not have the capacity to domestically refine the country's crude oil or to supply the quantities in demand. Ghana therefore depends entirely on foreign sources for all of its refined crude oil and majority of its natural gas supply used in thermal power generation. The mix and shares of energy sources used for power generation in Ghana for the year 2017 is shown in Figure 2.2.

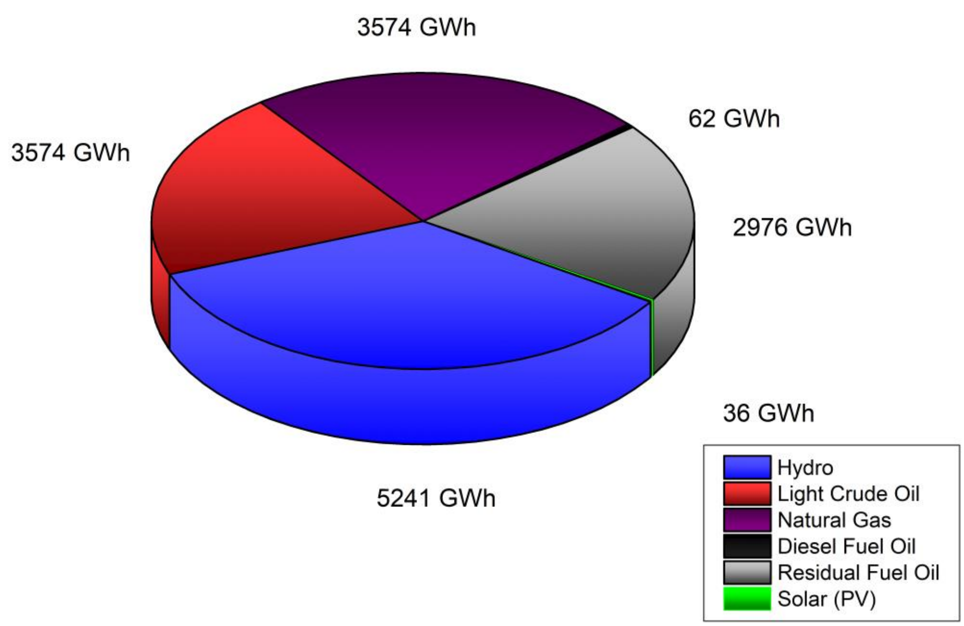

Figure 2.2: Shares of energy sources used for power generation in Ghana for the year 2017 (Energy Commission 2017).

Fossil fuels dominate power generation with a share of 64.78 percent, indicating high vulnerability to fuel price volatility and supply disruption. Electricity from hydro constitutes 34.98 percent of power generation, reflecting comparatively low cost abundance of hydro resources and susceptibility to seasonal supply constraints when water levels of large hydropower dams are low. Solar PV accounts for 0.24 percent of power generation indicating very limited exploitation of renewable resources at the utility scale. Substitution of expensive oil and gas imports by renewables makes a strong value case.

2.2.3.1. Primary energy and emission factors

This section provides primary (source) energy factors and GHG emission factors to enable calculation of primary energy resource and emissions due to annual electricity consumption. The factors are first broken down by fuel types that comprise a composite unit of electricity generated at source, and then adjusted for transmission and distribution losses per energy type for delivered electricity. They therefore provide good metric for comparing the primary energy and emissions effects of different electrical energy carriers and technologies. Pre-combustion effects, i.e. energy and emissions from extracting, processing and transporting the fuels, are beyond the scope of this study and are thus not included. Greenhouse gas emissions accounted for are carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). By using appropriate global warming potential coefficients, GHG emissions from these various gasses are reported together, expressed as equivalent gigagrams of carbon dioxide ($GgCO_2e$). Factors per unit of composite electricity generated at source and per unit of delivered electricity including transmission and distribution losses are provided in Table 2.2 and Table 2.3 respectively.

Table 2.2: Combustion source and emission factors per generated electricity for 2017(Author's estimation based on fuel allocation in (Energy Commission 2017)).

Energy Source	**Energy Source Factor per Composite Unit of Power generation**	**Emission Factor Per Energy Source**	**Emission Factor per Composite Unit of Power generation**
	GWh_{fuel}/GWh_{el}	$GgCO_2e/GWh_{el}$	$GgCO_2e/GWh_{el}$
Hydro	0.350	0	0
Light Crude Oil	0.497	0.638	0.132
Natural Gas	0.606	0.515	0.123
Diesel Fuel Oil	0.016	1.004	0.004
Residual Fuel Oil	0.559	0.786	0.156
Solar PV	0.002	0	0

Table 2.3: Primary energy and emission factors for delivered electricity including transmission and distribution losses for 2017 (Author's estimation based on fuel allocation in (Energy Commission 2017)).

	Primary Energy Factor for Delivered Electricity	**Emission Factor for Delivered Electricity**
	GWh_{fuel}/GWh_{el}	$GgCO_2e/GWh_{el}$
Total Energy	2.488	0.509
*Fossil Fuel Energy	2.057	0.509
**Non-renewable Energy	2.057	0.509
***Renewable Energy	0.432	0

*Fossil fuel energy includes all coal, natural gas, petroleum fuels, and other fossil fuels
**Non-renewable Energy includes fossil fuel energy and nuclear
***Renewable Energy includes hydro, solar PV, wind, geothermal and renewable fuels

As expected, diesel fuel oil has the highest emission source factor at 1.004 $GgCO_2e/GWh_{el}$, followed by residual fuel oil at 0.786 $GgCO_2e/GWh_{el}$, light crude oil at 0.638 $GgCO_2e/GWh_{el}$ and natural gas at 0.515 $GgCO_2e/GWh_{el}$. These factors are influenced by the equivalent carbon content of the fuel and conversion efficiency of the generation facility. Hydro and solar PV are considered to have zero fuel emissions. The total primary energy factor which considers the mix of all the primary energies in all power plants of the grid is 2.488 GWh_{fuel}/GWh_{el}. The fossil energy factor which includes only the non-renewable amount of primary energy used, comprised of both fossil fuels and nuclear energy, is 2.057 GWh_{fuel}/GWh_{el} due to a fraction of 35.22 % renewables in the power generation mix of 2017. The corresponding GHG emissions factor for the fossil fuels (f_{co2e}) is 0.509 $GgCO_2e/GWh_{el}$. While the amount of delivered electricity to households is useful for understanding the electrical energy performance of buildings and building systems, these factors indicate the environmental impacts from resource consumption and greenhouse gas emissions associated with electricity use.

2.2.4. Ghana's renewable resources

Ghana has substantial potential for renewable energy exploitation from solar, wind, mini-hydro and bioenergy resources. Solar radiation averages 4.0 - 6.5kWh/m^2/day and sunshine hours averages 1800 - 3000hours/annum (Kemausuor et al. 2011). It is estimated that the country could harness approximately 35EJ of solar energy with a recovery factor of 10%. This quantum is 100 times greater than current utilization of solar energy (UN-Energy 2008). At hub-height of 50m and average wind speeds of 7.1 - 9.0m/s, wind energy resources could generate 7300GWh of electricity if exploited with current technology. Feasibility studies have been conducted on over seventy (70) possible mini-hydro sites (UN-Energy 2008; Kemausuor et al. 2011; Gyamfi, Modjinou, and Djordjevic 2015). The proposed plants have the potential to generate 1.2 – 1.4MW if developed as run off river stand-alone systems (Gyamfi, Modjinou, and Djordjevic 2015; Kemausuor et al. 2011) This capacity could increase to 4 – 14 MW if the plants are connected to the national transmission grid to store excess power output. Medium hydro sites additionally identified at Hemang, Juale, Pwalugu and Tanoso could together provide a potential generation capacity of up to 2000MW (Gyamfi, Modjinou, and Djordjevic 2015; Kemausuor et al. 2011). Yet, none of these have been exploited. Biomass resource is estimated to cover 20.8million hectares of the land mass of Ghana. There is appreciable potential for biogas generation from municipal waste, particularly for cities where 540-730Mg of waste is generated daily. There is suitable climate and fertile land across the country for energy-crop plantations such as Jatropha, whose oil could be converted to bio-diesel. The production cost of bio-diesel from Jatropha oil is estimated at USD5.35/GWh. This is only 8% higher than the price of imported crude oil (Gyamfi, Modjinou, and Djordjevic 2015).

Although knowledge of proven technologies for RE conversion is as common as knowledge of the availability of the resources themselves, only 0.7% of power generation is renewable. Renewable energy currently accounts for 0.1% of VRA's total power generation (VRA Volta River Authority 2015b) and 3.6% of electricity from IPPs (EC Energy Commission 2015b). This demonstrates low governmental prioritization of the renewable energy sector.

2.3. Targets, plans and strategies for renewable energy development in Ghana

2.3.1. Renewable energy plans and strategies

A renewable energy strategy was introduced in the Strategic National Energy Plan (SNEP) of Ghana's energy outlook in 2006. The aim was to increase the share of sustainable electricity in the national generation mix to 10% by 2020 (EC Energy Commission 2006). Policies and implementation strategies were proposed to support and accelerate the achievement of this target. The plan proposed 375.5MW renewable electricity which represents 10% of national installed capacity by 2020 as shown in Figure 2.3.

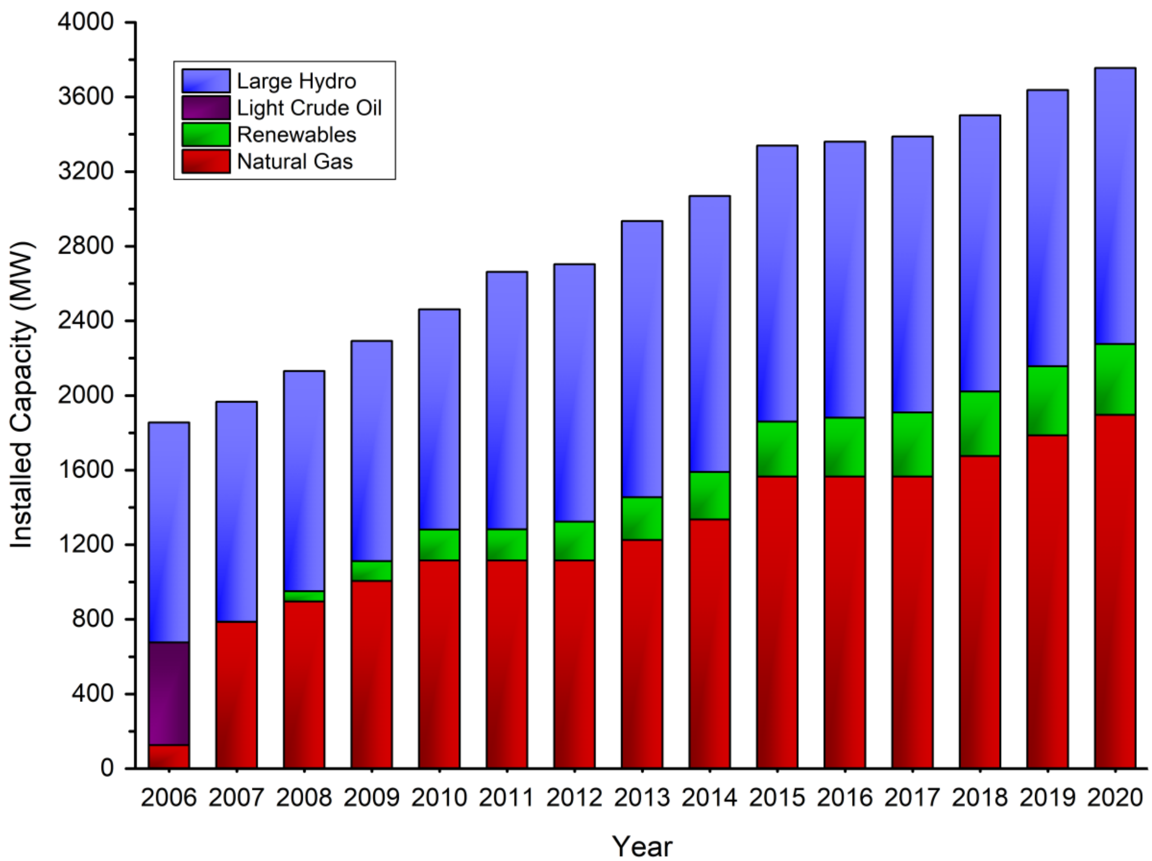

Figure 2.3: SNEP electricity capacity plan with 10% renewable energy by 2020 (EC Energy Commission 2006).

Renewable energy integration was planned to start at a share of 0.05% in 2007, and increase steadily to 10% in 2020. This was to be achieved by introducing and gradually increasing the generation capacities of wind, solar, LFG, biomass and mini hydro energy plants (EC Energy Commission 2006). Several sections of SNEP however remain unimplemented. Absence of legislation to govern development and utilization of RE thwarted successful implementation of plans and made them voluntary and unbinding. Lack of monitoring and compliance obligation of the EC made the institution weak.

In 2010, the Energy Sector Strategy and Development Plan were introduced as the National Energy Policy by the Ministry of Energy after a change in government. The new

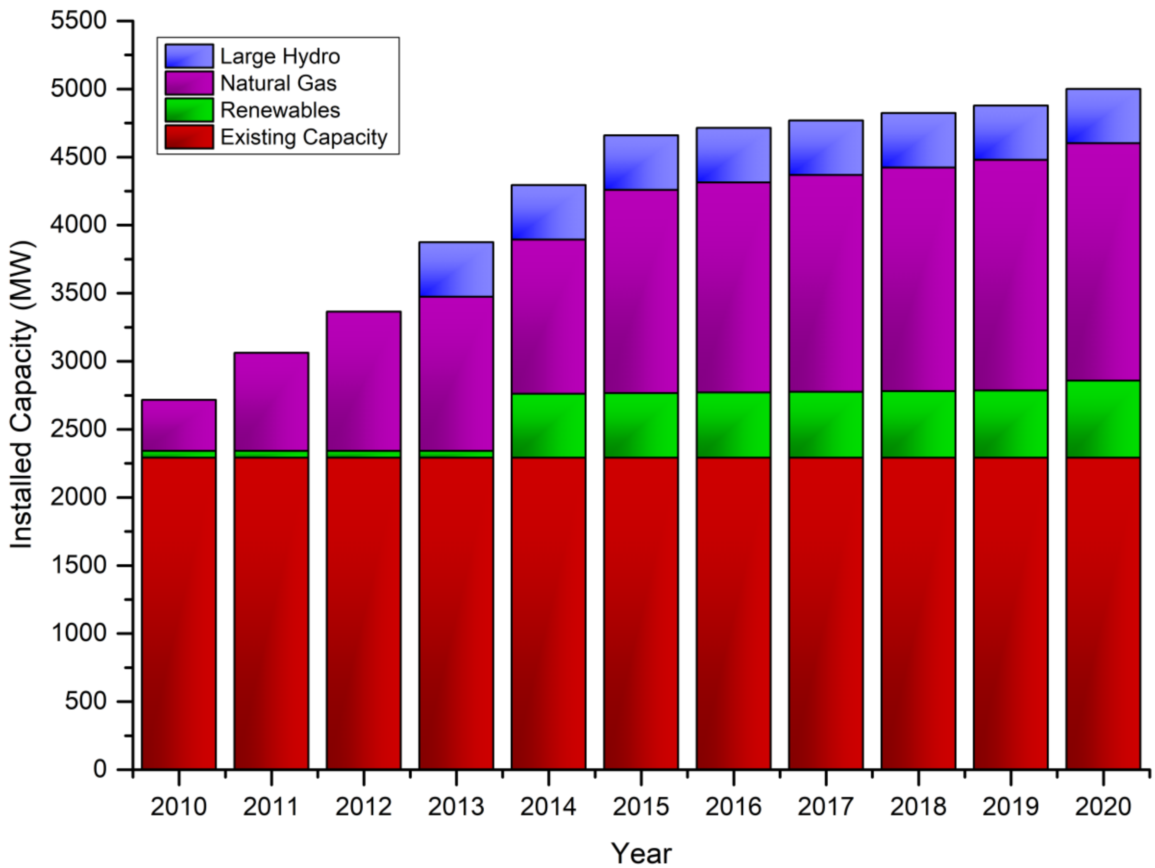

Figure 2.4: Ghana national energy policy with 500 MW renewable energy by 2020 (Ministry of Energy and Petroleum Ghana 2010a).

strategy shifted focus to two main technologies; mini hydro and wind power. The change in RE technologies indicates lack of coordination between the ministry, the EC and other governmental institutions which could cause barriers to implementation. Nonetheless, the new strategy set a rather ambitious RE target of 500MW by 2020 (Ministry of Energy and Petroleum Ghana 2010a, 2010b) as shown in Figure 2.4. Growth in the share of RE was proposed to start at 2% in 2010 and maintained through to 2013 when it would begin to rise rather sharply up to10% in 2014 through 2020.

The aggressive approach reflects government's recognition of renewable energy as a major factor that supports sustainable economic development. Still, instability of current RE strategy which may change with whichever political party is in power, causes renewable energy to suffer fitful deployment. Ghana's government has therefore taken steps to provide policy support and regulatory framework for the development and deployment of renewable energy technologies.

2.3.2. Policy evolution and implementation status

Ghana's renewable energy policies have evolved from single resource/technology targets to multiple renewable resource targets as shown in Table 2.4.

Their planning and implementation however appear disintegrated. For example, the feed-in tariff was brought in-force in 2013 while the supporting RE fund (2014) and quota obligations (2013) remain unimplemented. This has weakened the effectiveness of the FIT and has consequently, had no significant impact on the renewable energy industry. Though in-force, there is yet to be a beneficiary. Regulation policies, incentives and market mechanisms need to be combined harmoniously (He et al. 2016a) in order to realize the complementary or substitution potential between policy instruments (Cheng and Yi 2017).

Table 2.4: Policy development and implementation status for renewable energy in Ghana (International Energy Agency 2015).

Policy Title	**Year**	**Policy Type**	**Policy Target**	**Status**
Tax and Duty Exemption	1998	Economic Instruments>Fiscal/financial incentives>Tax relief, Economic Instruments>Fiscal/financial incentives>Taxes	Wind	In force
Renewable Energy Service Program	1999	Economic Instruments>Direct investment>Infrastructure investments	Solar, Solar Photovoltaic	In force
Strategic National Energy Plan 2006-2020	2006	Policy Support>Strategic planning	Multiple RE Sources: Power, Multiple RE Sources: Heating	In force
Ghana Energy Development Access Project	2007	Economic Instruments>Fiscal/financial incentives>Loans, Economic Instruments>Fiscal/financial incentives>Grants and subsidies, Economic Instruments>Fiscal/financial incentives>Tax relief	Wind, Solar; Solar photovoltaic	In force
National Electrification Scheme	2007	Research, Development and Deployment (RD&D)>Research programme >Technology deployment and diffusion, Economic Instruments>Fiscal/financial incentives>Grants and subsidies, Research, Development and Deployment (RD&D)>Research programme	Wind>Onshore, Bioenergy>Biomass for power, Multiple RE Sources>Power, Solar, Wind	In force
Ghana National Energy Policy	2010	Policy Support>Strategic planning, Policy Support	Solar, Hydropower, Geothermal, Multiple RE Sources>Power, Bioenergy>Biofuels for transport	In force
Renewable Energy Act 2011	2011	Policy Support>Strategic planning, Policy Support	Multiple RE Sources	In force

Feed-in-Tariff	2013	Economic Instruments>Fiscal/financial incentives>Feed-in tariffs/premiums	Multiple RE Sources, Multiple RE Sources>Power, Wind, Solar, Hydropower, Bioenergy	In force
Ghana Renewable Energy Purchase Obligation	2013	Energy Market Mechanism	Multiple RE Sources, Multiple RE Sources>Power, Wind, Solar, Hydropower, Bioenergy	Proposed
Ghana Accelerated Depreciation	2014	Tax-based Mechanism		In force
Ghana Biofuel Blending Mandate	2014	Energy Market Mechanism	Biomass, Biofuel	Proposed
Ghana Renewable Energy Fund	2014	Equity Finance Mechanism	Multiple RE Sources, Multiple RE Sources>Power, Wind, Solar, Hydropower, Bioenergy	Proposed
Net Metering Scheme	2015	Regulatory Instruments>Codes and standards, Economic Instruments>Fiscal/financial incentives>User charges	Multiple RE Sources>Power, Multiple RE Sources	Proposed

2.4. Analysis of Ghana's Renewable Energy Act

Renewable resources provide electricity for economic development in an environmentally sustainable manner. These social benefits are often neglected in decision-making on renewable energy investment. Most governments in developing and developed countries introduce a variety of policies and support instruments to encourage investments in renewable electricity (Phun et al. 2017; C. Chang and Lee 2016). Ghana's parliament enacted the Renewable Energy Act, 2011 to provide for the development, management, utilization, and adequate supply of renewable energy for generation of heat and power and for related matters (Togobo 2016; Parliament of the Republic of Ghana 2011). Support instruments for RE development may be classified as fiscal incentives, regulatory or financial frameworks. Technically and practically, none of these support mechanisms is self-sufficient or mutually exclusive (McGregor and James 2015). Many countries therefore combine investment incentives and promotional tools to create a complete enabling environment for RE development (Abdmouleh, Alammari, and Gastli 2015). The key policy measures to expedite renewable energy integration in Ghana are discussed under the above classifications in the next section.

2.4.1. Regulatory framework

2.4.1.1. Feed-in tariff (FIT)

Feed-in tariff is a guaranteed payment of a fixed price per kilowatt-hour (kWh) of electricity to renewable energy producers (Sijm and Paulus 2002). Experiences from southeast Europe indicate that, the attractiveness of RE for investors is largely dependent on the amount and duration of preferential FIT (Gatzert and Vogl 2016; Punda et al. 2017). Low tariffs increase the cost of renewable electricity while high tariff usually prove unsustainable (Gallego-castillo and Victoria 2015; Ramli and Twaha 2015). FIT rates need periodic revision to achieve the right balance across different technologies and scales of projects (Karatayev et al. 2016). Effective FIT designs often include the following criteria; guaranteed and preferential grid access, adequate minimum feed-in tariffs usually above market prices, technology specific FITs, cost reduction potential and legally guaranteed period over which the tariff is paid- to remunerate investment cost preferably covering the lifetime of the equipment (McGregor and James 2015; Abdmouleh, Alammari, and Gastli 2015; Liptow and Remler 2013). FIT schemes have been proven effective in deploying varied large scale renewable energy technologies particularly in Germany, Spain and Denmark (Wand and Leuthold 2011; Meyer 2007; Poullikkas, Kourtis, and Hadjipaschalis 2012). The key advantage is its ability to reduce investment risks based on guaranteed long-term financial gain (Poullikkas 2013).Resulting lower costs of capital makes it comparatively easy for new entrant generators (Woodman and Mitchell 2011) and thus encourages renewable innovation (Butler and Neuhoff 2008; Verbruggen and Lauber 2012). FITs dominate support mechanisms for renewable energy development globally with a market share of approximately 60% as of the year 2012 (Dusonchet and Telaretti 2015). The main aim of introducing FIT schemes in the developing world particularly in Africa and Asia is to reduce investment risk and hence increase access to low cost financing (Meyer-Renschhausen 2013).

Ghana's FITs consider the renewable energy technology being used; costs associated with construction, commissioning, operation and maintenance of plant; reasonable rate of return on investment, balance between consumer and investor interest and the readiness of generated electricity for grid integration. Fixed rates are guaranteed for 10 years and subject to review every 2 years. FIT rates are regulated by PURC (Parliament of the Republic of Ghana 2011). The current FIT schedule is as shown in Table 2.5. Table 2.6 compares Ghana's FITs with similar schemes around the world. The tariffs have been converted to US Dollars for comparison purposes.

Table 2.5: Feed-in-tariff rates in Ghana (last amended in October, 2014) (PURC Public Utilities Regulatory Commission 2014).

Renewable Energy Technology	**Maximum Capacity (MW)**	**FIT (USD/kWh)**
Wind (with grid stability systems)	300	0.1436
Wind (without grid stability systems)	300	0.1325
Solar PV (with grid stability/storage systems)	150	0.1660
Solar PV (without grid stability/storage systems)	150	0.1504
Hydro	10	0.1382
Hydro (>10MW)	100	0.1389
Biomass	No Limit	0.1443
Biomass (enhanced technology)	No Limit	0.1521
Biomass (plantation as feed stock)	No Limit	0.1631

Ghana's 10 year guarantee is too short compared to offers in other countries (Table 2.6) and also, to the lifespan of RE equipment which is assumed as 25-30 years (Pegels 2010). FIT rates in Ghana are quite low against that of industrialized countries but, fairly high compared to other developing countries like China and India. A lesson from Germany on the value of rates is that, favorable FIT premiums can create competitive distortions in electricity markets when power utilities are obliged to purchase all renewable energy at too high a rate over their conventional generation costs (Sijm and Paulus 2002; Walters and Walsh 2011). Technically, the cost effects of renewable electricity fed into the grid at high rates can be negligible if it is absorbed by all end users (Scheer 2007). However, in a liberalized and competitive power distribution market, this can lead to conflicts between those who are involved in the development of various renewable energy technologies, and those who ultimately pay the tariff (Meyer 2003; Lesser and Su 2008). A threat associated with high FIT rates is reduced financial risk which encourages over investment and prolific development of inefficient technologies (Jacobsson and Lauber 2006; Papadopoulos and Karteris 2009; Menanteau, Finon, and Lamy 2003). Conversely, when FIT rates are too low, production levels become stagnant. The market then relies on subsidies rather than market drivers, for renewable energy development. This scenario according to (Couture and Gagnon 2010; Jensen and Skytte 2003) is unsustainable and runs the risk of eventually deteriorating.

Table 2.6: Ghana's FIT compared to similar schemes in other parts of the world (Schallenberg-Rodriguez and Haas 2012; Feed-In Tariffs Ltd 2013; Mabee, Mannion, and Carpenter 2012; PURC Public Utilities Regulatory Commission 2014; Winston and Strawn 2014).

Country	**FIT (USD/kWh)**		**Guaranteed Period (Years)**	**Priority Grid Access**
	Wind Power	Solar Power		
Canada (Ontario)	0.14 – 0.16	0.45 – 0.48	20	Partial
Spain	0.1	0.38	25-30	Yes
Germany	0.06 – 0.13	0.28	15-20	Yes
UK	0.07 – 0.35	0.11 – 0.25	20-25	-
Kenya	0.11	0.12 – 0.20	20	Yes
Ghana	0.13 – 0.14	0.15 – 0.17	10	No
China	0.08 – 0.1	0.14 – 0.16	-	-
India	0.09	0.15	20	-

The lesson for Ghana is that, power utilities must be fully liberalized for vibrant private sector participation and in various geographical locations. This will prevent the problem of renewable energy cost diffusion and open up commercial competitiveness which can effectively lower the price of electricity. Subsidies on electricity prices must be scrapped so that the costs of clean energy can compete fairly with that of conventional energy.

Renewable energy development can then be stimulated and sustained by market drivers rather than subsidies and grants. Additionally, FIT rates should be adjusted periodically in the long term in line with the rate of deployment and maturity of technologies, quality and quantity of available renewable resources and the level of renewable energy target achieved.

2.4.1.2. Grid access

One of the biggest barriers to substantial renewable power generation is poor grid network characteristics or the cost of upgrading the network to connect high quantum of renewable energy (Punda et al. 2017). To effectively increase the share of renewable energy in the electricity market, grid companies i.e. transmitters and distributers must be obliged to give priority access to renewable electricity (Bayod-Rújula 2009). This approach eliminates the need for bureaucratic negotiations with utilities over PPAs. Nonetheless, a guaranteed grid access together with long term contracts through PPAs can reduce financial risks and hence reduce capital costs for renewable energy developers (Timilsina and Shah 2016).

Electricity transmission and distribution networks across Ghana are inefficient with losses estimated at approximately 25% (Energy Commission 2015). Ghana has grid access policies and limit the impacts RE integration on the weak grid infrastructure (Meyer-Renschhausen 2013). Generated power must conform to sub-codes of performance requirements for connecting variable renewable power to transmission and distribution networks. The costs of grid connection and enhancement to the metering point of the grid are borne by the renewable power producer. Ghana has maximum capacity limits to control the total share of solar and wind power fed into the grid. Power generators with integrated grid stability/storage systems are encouraged with higher FIT rates as shown in Table 2.5.

The actual amount of renewable power fed into the grid is tied to conformity to the interests of the grid company. This has serious implications on widespread deployment despite favorable FITs particularly, when the grid company is vertically integrated and has its own generation branch as it is for example with VRA and NEDCo. NEDCo is likely to defend its profitability by avoiding "standby costs" of unused capacities from conventional generation systems of VRA. Such risks can be reduced if there is public education to ignite support for renewable energy development and, PURC can ensure that the additional costs from FITs can be proportionally passed on to consumers. Power utilities could then be financially compensated for enhancing their grid network to accommodate higher shares of fluctuating renewable electricity.

2.4.1.3. Renewable portfolio standards (RPS)

RPS (also known as renewable obligations) is a quantity-driven quota system that obligates power utilities to source a specific fraction of their electricity from renewable energy (Komor 2004). It is often implemented with tradable green/renewable energy certificates (REC) (Johnstone, Haščič, and Popp 2010; Ford, Vogstad, and Flynn 2007) to track and verify compliance (Langniss and Wiser 2003; Gürkan and Langestraat 2014) . RPS alleviates deployment barriers related to infrastructure, funding and technology availability (Heinzel and Winkler 2011) to ensure that renewable energy targets are precisely met (Brown and Busche 2008; Ringel 2006) at least cost (T. Wang, Gong, and Jiang 2014) and with minimum continuous governmental involvement (Amrutha, Balachandra, and Mathirajan 2017; T. Berry and Jaccard 2001). It has been shown in (Wiser, Barbose, and Holt 2011; Bird et al. 2005; Brown and Busche 2008; Yin and Powers 2010) that the existence of state-level RPS is significantly correlated to higher percentages of renewables in overall power generation. Joint implementation of RPS and tradable RECs in major Indian states has ignited vibrant private sector involvement to give renewable energy a 16% share of India's power generation. This is in spite of lower FIT rates as compared to Ghana for example. India is an example of successful implementation of decentralized RPS (Schmid 2012; Ministry of Power 2006).

In the United Kingdom however, development of RE through RPS has been stalled despite strong commitments to move to a low-carbon economy. The cause of the hindrance is largely attributed to internal and external failures in policy design (Wood and Dow 2015; Bunn and Yusupov 2015). Chinese experience suggests that, RPS is ineffective without legal obligation unto utilities to purchase renewable electricity from IPPs or trade RECs. Although generators are obliged to source a fixed quota from renewables, none of the six largest utility companies have met their requirement. It appears there is difficulty in enforcing penalties for non-compliance as fines are yet to be imposed on the defiant grid companies (Hua, Oliphant, and Jing 2016).

The proposed RPS policy for Ghana when implemented will obligate power distribution utilities and bulk consumers to procure a specified percentage of their total electricity portfolio from renewable sources (Parliament of the Republic of Ghana 2011). Aside the penalty prescribed for non-compliance, there is no specification on how the obligations are to be met. It is not clear whether utilities can trade RECs or are required to self-generate their quotas. Ghana's RPS policy is thus too ambiguous to enforce. Due to political and economic instability in many developing countries, it is necessary to limit uncertainties in policy design to the minimum especially for new developers (Aquila et al. 2017). For this reason RPS is generally not recommended in developing countries if it is without standardized contracts or a guaranteed market (Holm 2013; Fouquet and Johansson 2008).

Considering that the power distribution market in Ghana is heavily monopolized by large governmental institutions, deployment of RE is likely to result from development of new projects by incumbent companies or their subsidiaries rather than new IPPs. It can therefore be argued that until these limitations are addressed by policy reforms, the current proposal appears unlikely to make any significant impact on grid connected renewable electricity in Ghana.

2.4.1.4. Net metering scheme

Deployment of distributed generation systems such as solar PV relies on capital policies such as installation subsidies or income subsidies(Shum 2017). Net metering describes the mechanism where electricity meters' measure both electricity production and consumption. The client is often referred to as prosumer. The prosumer can offset consumed electricity with produced electricity and end up with a balanced account or retail credit in kWh, which can be billed monthly or rolled over to the following month (Dufo-Lopez and Bernal-Agustin 2015; Darghouth, Barbose, and Wiser 2011). Net metering has been used extensively in the United States with buy back, rolling credit or combined buy back and rolling credit(freeingthegrid.org 2015; U.S. Department of Energy 2014). It was revealed in (Hack 2006; Wimberly 2008) that citizen concern about environmental issues does not extend where there is monetary cost. The decision to invest in decentralized renewable energy technologies ultimately hinges on economic attractiveness (Söderholm and Klaassen 2007; Menanteau, Finon, and Lamy 2003; Sauter and Watson 2007). The effectiveness of the scheme is therefore dependent on the price at which electricity exported to the grid is valued (Dufo-Lopez and Bernal-Agustin 2015). In Germany and Greece, financial incentives that improve the monetary gains of prosumers were instrumental in the development of distributed solar energy markets (Luethi 2010).

The proposed net metering policy for Ghana provides credits for electricity supplied to the grid. This credit could be used to offset electricity consumed by the generator. The generation capacity is limited to 200kW per installation with a rolling credit of 1 year. It is unclear whether an access charge applies to the use of energy credits. Distributed generation in Ghana suffers lack of acceptability particularly in off-grid and island communities due to high cost of generation, non-competitive prices of renewable electricity and low income level of residents. Renewable electricity prices in Netherlands achieved parity with power from conventional sources due to high environmental taxes on fossil fuels(Yoon and Sim 2015). Ghana could set national emission limits and violation taxes on fossil fuels to compensate for the environmental cost of their combustion. This can increase the competitiveness of renewable electricity prices particularly in off grid and island communities. Ghana has the capacity to assemble technologies such as solar PV and its balance of system components. Since the market exists via government's special rooftop solar project, Ghana could partner with more foreign manufacturers to establish assembly plants in the country to drive down technology costs in the medium term and invest in research and development for technology independence in the long term.

2.4.2. Financing framework

2.4.2.1. Public investment, loan and financing

The level of renewable energy deployment is largely dependent on its attractiveness to commercial investors in that, private sector engagement is generally more efficient than public investment when markets are competitive (McGregor and James 2015). In Ghana, however the energy market is not fully liberalized. Bulk Supply Tariff (BST) is still highly susceptible to governmental influence and fuel prices are heavily subsidized (UNEP 2014; Norton Rose Fullbright LLP 2013; Ahlijah and Humphries 2013). Public financing and other fiscal incentives prove more effective at increasing renewable power generation in developing countries than other policies (Romano et al. 2017; Zhao, Ki, and Wang 2013). Majority of renewable energy projects particularly in rural and remote areas in Ghana are publicly financed through state institutions. Such projects as solar PV community lighting and solar home systems are off grid systems and therefore, do not contribute to realization of the 10% on grid renewable energy target (Togobo 2016).

The Renewable Energy Fund (RE Fund) was established in the RE Act through the support of the European Union to provide long term financial aid and resources for renewable energy development. (Parliament of the Republic of Ghana 2011). It's implementation however has been stalled by lack of funds (Affairs 2014). Climate Investment Funds (CIF) has endorsed Ghana's renewable energy investment plan and is expected to provide USD 40million funding as part of its Scaling-up Renewable Energy Program (SREP) in low income countries. Part of the amount is planned to be used in establishing a Renewable Energy Authority as well as resourcing the RE Fund (CIF Climate

Investment Fund 2015). Locally, a fraction of revenues accrued from the petroleum product levy and electricity charges are scheduled to be committed to the RE Fund (Chadha 2015).

2.4.2.2. Private funding, capital subsidies, grants and rebates

The Ministry of Energy has recently indicated its reluctance to provide government guarantees in support of renewable power projects and has thus directed investors/developers to the World Bank and African Development Bank for partial risk guarantees (PRGs) (Norton Rose Fullbright LLP 2013; CIF Climate Investment Fund 2015). Due to persistent load shedding across the country, the need for baseload power poses a challenge to prioritization of renewable energy. Government capacity to guarantee RE projects is limited although deliberations on issuance of governmental consent and support agreement (GCSA) with AfDB to provide partial risk insurance have commenced. Ghana's corporate bond market appears nonexistent and very few banks e.g. KfW (Kreditanstalt für Wiederaufbau) or national finance institutions (e.g. Ecobank, ARB Apex Bank) have infrastructure desks dedicated to renewable energy. Other banks provide mainly short-term debt financing. However, base rate is high (25%) and unstable due to measures for halting the ever rising inflation. Currently there are no reported grants for renewable energy financing either wholly or in-parts (G. Doe 2014). An effective strategy to address the lack of capital is a combination of reduced interest rate and longer payment period on loans that are offered by government. The government has much higher credit rating with which it can secure low cost funds on the capital market. Such funds could be transferred at a relatively lower cost to specific RE technology developers. This strategy has been found to be cost effective, allows subsidy recovery and therefore ensures long term sustainability (Shrimali et al. 2017).These type of loans have been used successfully for renewable energy and energy efficiency investment in the Yokohama Smart City Project of Japan (Y. Chang, Fang, and Li 2016).

2.4.2.3. Fiscal incentives (tax based)

Generation costs of renewable energy do not compete well with energy from conventional sources mainly because construction and development of most conventional power plants benefited from significant subsidies and have fully recovered their capital costs. Environmental costs (i.e. pollution from CO_2, SO_x, NO_x and other emissions) are not considered in pricing electricity that is generated from fossil fuels (Menanteau, Finon, and Lamy 2003). To increase competiveness, some governments provide tax exemptions/reductions to encourage investment in renewable energy. Others impose a carbon or energy tax on conventional power sources as part of environmental tax initiatives aimed at modifying energy prices (Abdmouleh, Alammari, and Gastli 2015; Liptow and Remler 2013; McGregor and James 2015). Tax based incentives can be in the form of investment subsidies, tax holidays, production-based incentives, indirect tax reductions and other tax reductions. Such approaches reduce tax liabilities and accelerate investor confidence which would otherwise take years to build (Ahlijah and Humphries 2013). Ghana offers investor friendly packages upon registration with the Ghana Investment Promotion Centre such as 100% exemption from payment of direct and indirect duties and levies on all imports such as plant machinery, equipment or parts thereof for renewable energy production. There is 100% exemption from payment of income tax on profits (tax holidays) for 10 years. Income tax may not exceed 8% thereafter. There is also, total exemption from payment of withholding taxes from dividends arising out of free zone investment. In addition, there are no import licensing requirements as well as restrictions on repatriation of net profit. The Ghana accelerated depreciation is in force and allows faster project writing off to maximize the tax benefit of depreciation by the equity provider (Kpekpena 2012; Ahlijah and Humphries 2013).

Although the environmental impacts of energy production have been captured in energy policy and strategy (EC Energy Commission 2006; Ministry of Energy and Petroleum Ghana 2010b), legislation on environmental taxes is yet to be developed. Financing support for renewable energy development in Ghana so far has been to a large extent via tax based incentives. This conclusion can be explained with the ineffectiveness of the FIT scheme which is in- force but lacks key support instruments such as the RE Fund. Tax based incentives are expected to boost RE deployment in the short-to-medium term by reducing the financial risks associated with investment in the industry.

2.5. Policy impacts

2.5.1. Development of renewable energy projects

Enactment of the Renewable Energy Act 2011 and related support frameworks (i.e. feed-in tariffs, quota obligations, grid access codes, renewable energy fund, market regulation etc.) have facilitated development of Ghana's renewable energy industry. The Energy Commission has issued licenses of two years validity to 66 renewable energy service providers in wholesale supply and generation since 2012. Figure 2.5 shows the distribution of proposed generation capacities and stages of development reached for the applicable renewable energy technologies.

In total, licenses of approximately 5000MW installed capacity have been issued for solar, wind, wave, biomass, mini-hydro and waste-to-energy projects. Of this proposed capacity, 54% have been issued construction and siting permits. Conversely, 16% of issued licenses have expired while 30% remain valid and provisional.

Approximately 7.0GWh (1.95MW installed capacity) is generated annually from biomass cogeneration plants in the major oil palm processing plants (EC Energy Commission 2012). However, these plants do not make any financial gain from the feed-in tariff scheme since the power produced is consumed on site. Perhaps as bulk power consumers, this could satisfy their quota obligations when the RPS policy is implemented. The share of biomass-based cogenerated electricity in the national power mix could increase appreciably if cocoa waste, agro-processing and sawmill wastes from timber processing are used for power generation (CIF Climate Investment Fund 2015).

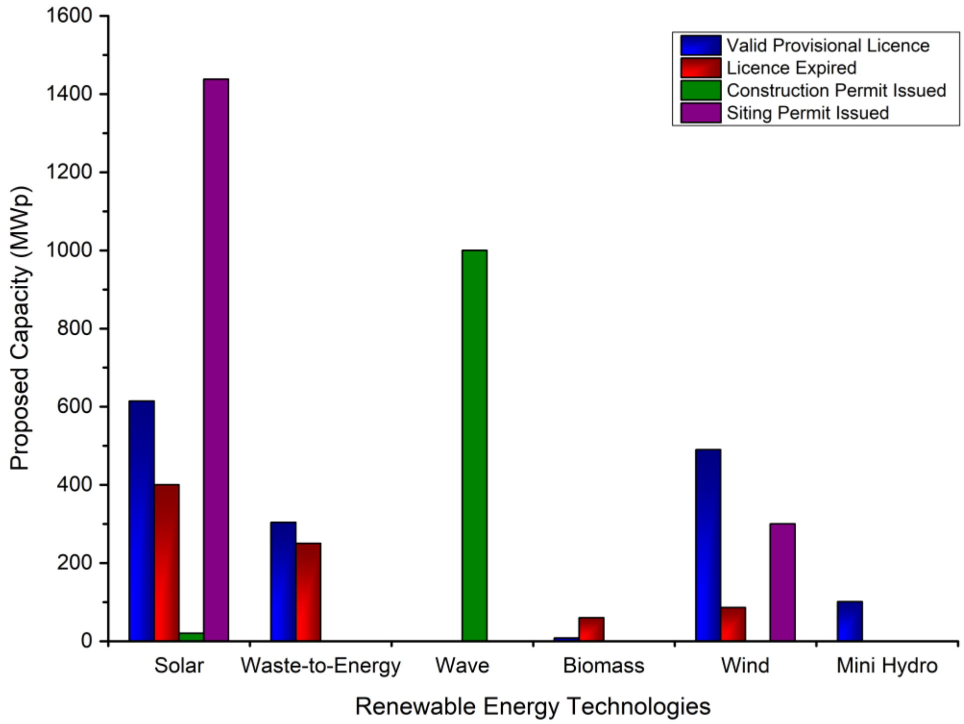

Figure 2.5: Status of RE projects development as at July 2015 (EC Energy Commission 2015d).

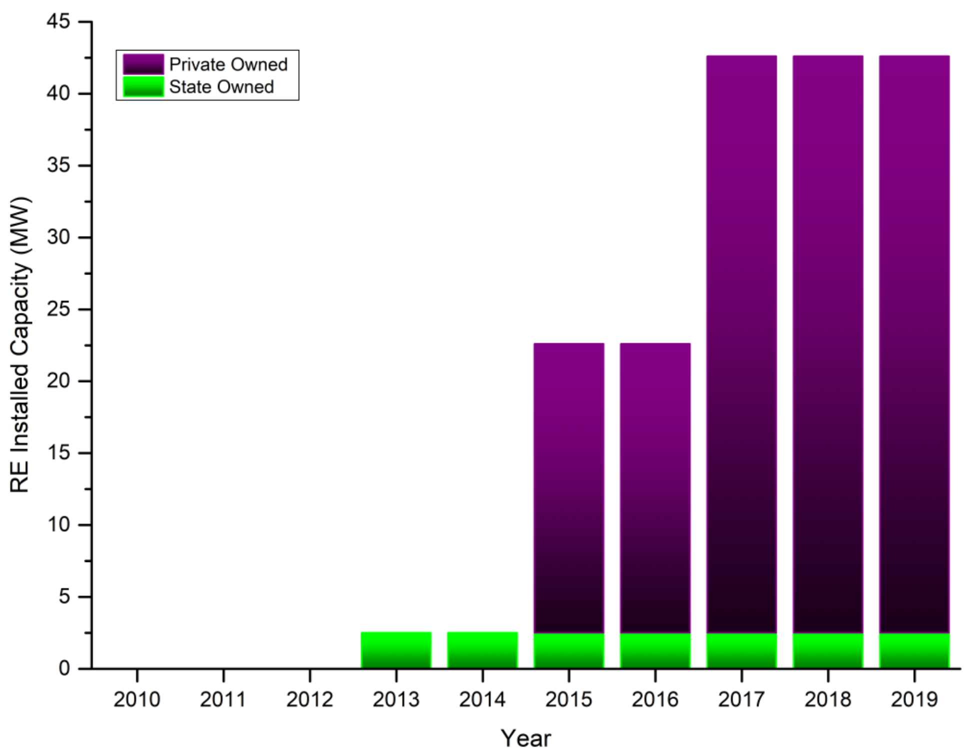

Figure 2.6: Evolution of grid-tied renewable energy (Energy Commission 2020b).

Energy Commission has developed three sub-codes proposing minimum technical connection and performance requirements for connecting variable renewable power to transmission and distribution networks for utility services and new IPPs. The codes propose technical connection conditions such as frequency range of operation, power quality (rapid voltage changes, flicker, voltage unbalance, and harmonics), and reactive power capability and control requirements, active power control, frequency response, abnormal voltage conditions, and automatic resynchronization, protection and fault levels. Compliance with the sub-codes is expected to ensure safe, reliable and secure operations of all variable renewable energy generation facilities (EC Energy Commission 2015c).

2.5.2. Increased share of renewables in national grid

The share of renewables (excluding large hydro) in grid tied national electricity mix was zero until 2013, when VRA commissioned its 2.5MW solar plant in Navrongo. Though the project was part of VRA's Renewable Development Program Phase 1 (REDP1), its commencement in 2012 was motivated by the Renewable Energy Act, 2011. Power from the plant represented approximately 0.1% of total grid capacity in 2013 and 2014, see Figure 2.6. The share of renewables in grid capacity increased to 42.6MW in 2019 representing 1.3%, with two private-owned (BXC Solar, Meinergy) 20MW solar power plants commissioned in 2015 and 2018 and a smaller 100kW waste-to-energy plant commissioned in 2015 (Safisana Biogas). The share of grid tied power generation from renewable sources is expected to increase as government implements the full provisions of the Renewable Energy Act.

Table 2.7: Construction-phase RE Projects and Progress since passage of RE Law (World Bank 2015; VRA Volta River Authority 2015b).

S/N	Project Name	Type of Ownership	Capacity (MW)	Technology	Start Year	Development Stage
1	Nzema Solar PV	Private	155	Solar	2012	Pipeline
2	Clenergen Gasification Biomass Plant	Private	2	Bioenergy	2012	Pipeline
3	Volta River Authority	State	160	Solar, Wind	2010-2015	Pipeline
4	TC´s Energy	Private	1000	Wave	2013	Pipeline
5	BXC Company Gh Ltd	Private	20	Solar	2013	Completed
6	Meinergy	Private	20	Solar	2015	Completed

2.6. Comparative analysis

Many countries are looking to renewable energy to meet their electricity supply needs. Following country pledges at the Paris Agreement, nearly 60% of all new power generation capacity to 2040 is projected to come from renewables (OECD/IEA 2016): China, United Kingdom, India, Germany, Brazil, South Africa, Mexico and Chile are among the top ten countries that have made significant investment in renewable energy development (FSUNEP/BNEF 2016). It is interesting to study which policies are in place in these countries that have created such an enabling environment for renewable energy investment for comparison with Ghana's policies. Table 2.8 shows this comparison.

Ghana compares very well with other African countries and stands out in the West Africa sub region in terms of laid down policies and support framework for renewable energy deployment. It is worth noting that there are no regulatory policies for off grid renewable energy systems which pose a major challenge for developers in island communities where there is limited access to electricity.

The coverage of policies under regulatory framework, fiscal incentives, public financing and other policy support features compares well with South Africa, Brazil, Chile and Mexico. The difference however is in the fundamental support scheme of the individual countries. Renewable energy development in South Africa, Brazil, Chile and Mexico are driven by market based instruments i.e. auctions and tradable RECs while Ghana's is driven by incentives i.e. FIT which is government dependent.

Many challenges have made Ghana unsuccessful in full implementation of its FIT, quota obligations and tradable RECs. There is no standardized production pricing for IPPs. Bulk supply tariffs are still susceptible to governmental influence in the form of subsidies so much so that, energy project developers (renewable and non-renewable) have had to force output prices into their PPAs for project based negotiation with governmental representatives. Ghana's grid network is congested and unbalanced. Depending on the location of the generating facility, many developers have to connect to weak medium voltage lines of distribution networks with high losses at about 25%. The renewable energy fund which is to provide incentives for RE development in Ghana including payment of FITs is not operational. Lack of funds among other factors has been indicated as the underlying reason. If these fundamental challenges are addressed, then together with the policies in place Ghana will be well poised for massive investment in renewable energy in the future.

Table 2.8: Comparison of renewable energy support policies in different countries (ECREEE 2014a; IRENA 2015; IRENA International Renewable Energy Agency 2017; IEA International Energy Agency 2016).

Countries	**Support Policies**		**Regulatory Policies**							**Fiscal Incentives and Public Financing**				
	RE act/ law	**RE target**	**Feed-in-tariff (incl. premium payment)**	**Utility quota obligation/ RPS**	**Tradable renewable/ green energy certificates**	**Auctions**	**Net metering**	**Heat obligation/ mandate**	**Biofuel obligation/ mandate**	**Capital subsidy, grant or rebate**	**Investment or production tax credits**	**Reduction in sales, energy, CO_2, VAT or other taxes**	**Production payment**	**Public Investment, loans or grants**
Cape Verde		✓				✓	✓					✓	✓	
Ivory Coast		✓										✓		
Ghana	✓	✓	✓	✓	✓			✓	✓	✓		✓		✓
Nigeria		✓	✓							✓		✓		✓
Algeria		✓	✓			✓					✓			
Kenya	✓	✓	✓			✓		✓				✓	✓	✓
South Africa	✓	✓		✓		✓	✓		✓	✓		✓		✓
UK	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		✓	✓
Germany	✓	✓	✓			✓	✓	✓	✓	✓	✓		✓	✓
China	✓	✓	✓	✓				✓	✓	✓	✓	✓	✓	✓
India	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓		✓
Brazil		✓	✓			✓	✓	✓	✓			✓		
Chile	✓	✓		✓	✓		✓	✓				✓		
Mexico	✓	✓			✓	✓		✓	✓	✓		✓		

2.7. Conclusions

This study provides a critical assessment of the effectiveness of Ghana's renewable energy policy in deploying renewable energy technologies. It identifies deficiencies in Ghana's policy design by direct comparison of policy features with unsuccessful implementation of such features in other countries and the underlying reasons for the failure. We extend the comparison to the top countries for renewable energy investment to identify which types of policy models have been successful in creating an enabling environment for renewable energy investment and development.

We find that although Ghana has developed policies and strategies to guide development and use of its renewable energy resources, the country has not succeeded in full implementation of the policies. The performance of Ghana's renewable energy policies on grid connected electricity has been poor compared to its target. The fundamental reasons for this unsatisfactory performance may be attributed to partial implementation of policies, lack of market driven support schemes, lack of pricing policy framework, weak grid network, limited access to funds and inconsistent development strategies. The ministry of energy has had difficulty liaising with other governmental agencies and stakeholders to overcome these barriers. This paper suggests the following strategies based on the analysis above.

- Regulation policies, incentives and market mechanisms need to be combined and implemented harmoniously to realize the complementary or substitution potential between policy instruments.

- Market driven support schemes should be prioritized for cost effectiveness and minimum governmental influence.

- Pricing policy framework should be established to assure developers of the profitability of renewable energy investment.

- The grid network should be upgraded to connect variable renewable energy. Smart grid and virtual power plants could be explored in future for off grid and island communities.

- Ghana could partner with more foreign manufacturers to establish assembly plants in the country to drive down technology costs in the medium term and invest in research and development for technology independence in the long term.

- Government could secure low cost funds on the capital market for transfer at relatively lower costs to specific renewable energy technology developers in addressing the lack of capital.

- Renewable energy plans, actions and strategies of current and previous governments could be consolidated into a master plan to guide technology deployment.

In conclusion, Ghana has put in place policies which can attract huge investment and accelerate renewable energy development in the country. Yet, there are a variety of problems that need to be solved. The countermeasures listed above will help improve the effectiveness of the policies and expedite the rate of deployment of renewable energy in the country.

Chapter 3

RESIDENTIAL ELECTRICITY SURVEY AND SOCIO-ECONOMIC DETERMINANTS OF ELECTRICITY USE

In order to establish a solid baseline for the study, firstly the electrical energy inventory for Tema city is developed. The inventory characterizes annual residential electricity consumption by end-use and appliance technology. It also investigates the influence of select socio-economic and building factors on household electricity use.

3.1 Residential electricity consumption

Many previous studies have been undertaken worldwide on electricity consumption of households to support policy design (Jones and Lomas 2015) and electricity supply infrastructure planning (Willis 2002). Data gathering in these studies is usually conducted either through household energy end-use surveys or end-use monitoring/logging (HEEPS 2010). This study combines the two approaches, supplementing measured appliance electricity use and household meter readings with the results of residential electricity consumption (REC) survey to enhance data accuracy and enable a more meaningful analysis of the results. Meter readings provide data on total electricity consumption which is used to obtain shares of the investigated appliances whereas survey results provide data for assessing the sensitivity of electricity use to selected socio-economic and building factors. The residential electricity end-use survey was designed by authors in close collaboration with the International Energy Studies group of Lawrence Berkeley National Laboratory and executed by research partners on the ground at the Regional Maritime University in Ghana. While isolated surveys have been conducted to collect data, to the authors' knowledge this is the first study on residential electricity use and appliance ownership that combines both survey results and end-use monitoring to yield a comprehensive analysis of city-scale electricity end-uses in Ghana.

3.1.1 Data collection

3.1.1.1 Survey design

An overview of the survey content and coverage area are shown in Figure 3.1 and Figure 3.2, respectively. The survey approach included the use of questionnaires and interviews with key informants (e.g. household heads). In households where illiteracy was encountered, a guided oral interview approach was adopted. The survey content was anchored on 6 thematic areas, consisting of characteristics of household members, electricity usage in buildings, electricity sources and costs, building characteristics, electricity use efficiency and assessment of electricity supply.

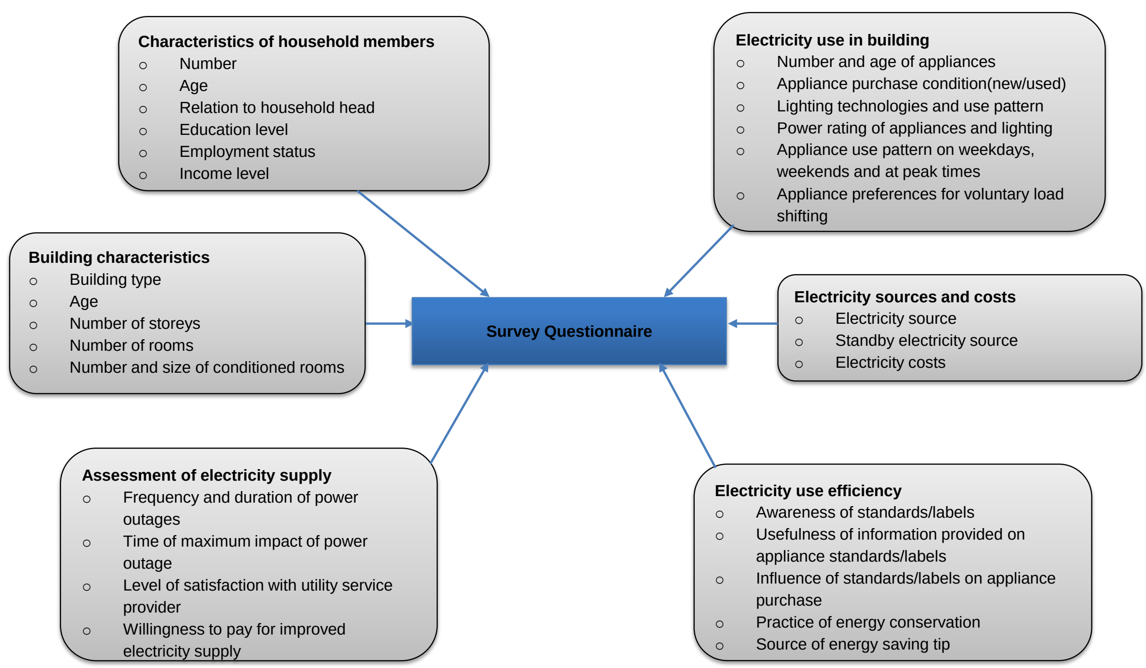

Figure 3.1: Framework of residential electricity consumption survey (RECS).

A sample size of 440 households was determined at a confidence interval of 95% in the study in accordance with the United Nations guidelines for households survey design in developing and transition economies (UN-Department of Economic and Social Affairs Statistics Division 2005) with the following equation:

$$\text{Sample size} = \frac{Z^2 \cdot r(1-r) \cdot f \cdot k}{p \cdot h \cdot e^2}$$

Where Z is the z-score, which is 1.96 at a 95% confidence level; r is an estimate of the key indicator to be measured by the survey; f is the sample design effect, assumed to be 2.0; k is a multiplier to account for the anticipated rate of non-response (value of 1.1); p is the proportion of the total population accounted for by the target population and upon which the estimate parameter, r, is based; h is the average household size; e is the margin of error (10% of r; thus e = r/10).

Initially, 440 households living in 21 communities of Tema metropolitan area were approached. Of these, 126 households participated in the survey which was conducted between June and August 2017. Individual households were selected randomly (Ahemen, Amah, and Agada 2016) following geographic stratification of household densities (ratio of number of households to land size/area). The communities were classified into three household densities: high density (more than 1250 households per square kilometer), medium density (between 250 and 1250 households per square kilometer) and low density (less than 250 households per square kilometer). The resulting sample size distribution was 23% for low density communities, 67% for medium density communities and 10% for high density communities. Household income/social class in Tema city is a function of household density. For instance, low density areas correspond to high income households and high density areas correspond to low income households (Tema Metropolitan Assembly 2014). The survey results are therefore a good stratified representation of the city in terms of geographic distribution and household income which can be directly related to appliance ownership and hence electricity consumption (Daioglou, Ruijven, and Vuuren 2012; Mensah, Marbuah, and Amoah 2016; Gyamfi et al. 2018).

The survey outcome provided data about appliance ownership and use pattern, household demographics, building characteristics and energy use, electricity sources and costs, appliances preferences for voluntary demand shifting, energy use efficiency and quality of power supply as shown in Figure 3.1. It should be noted that some of the information gathered in the survey were based on self-reported data. This could lead to inaccuracies in the results obtained due to recollection bias where participants are unable to accurately report data and/or social desirability bias where participants intentionally report incorrect information in order to conform to social norms or to please the interviewer (Jones and Lomas 2016).

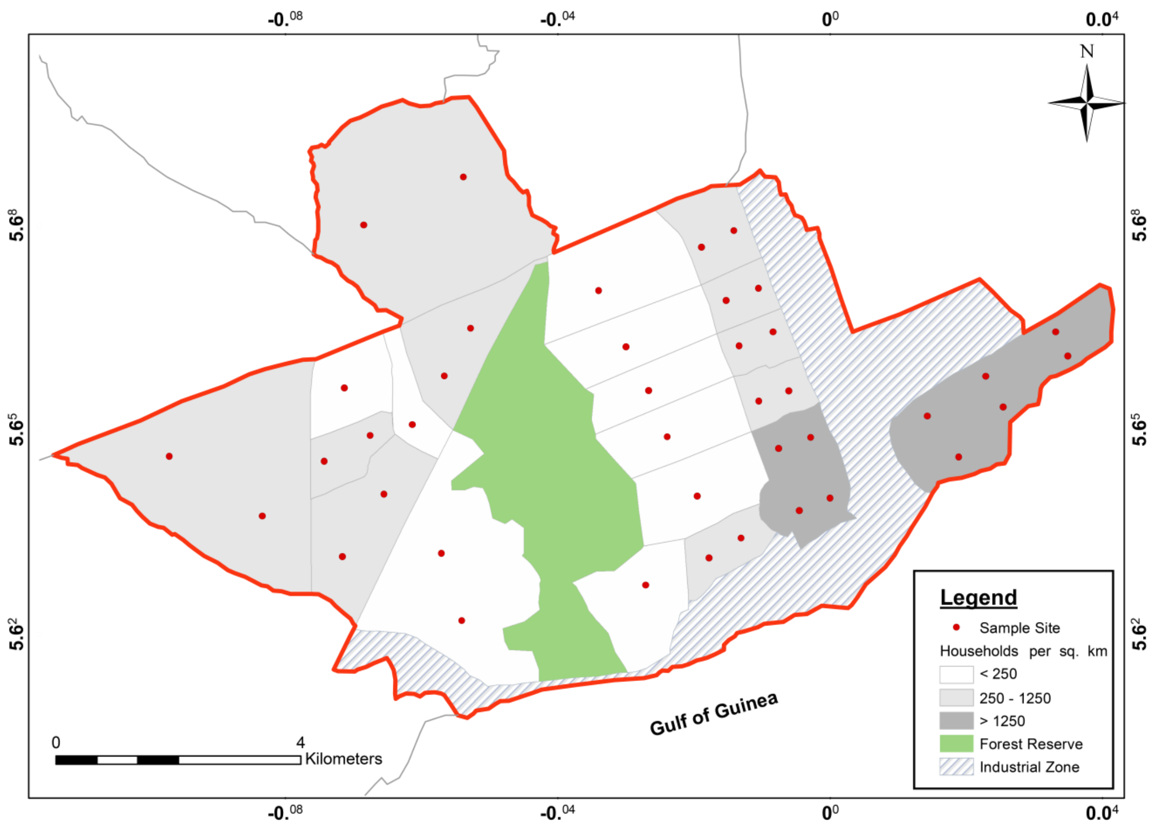

Figure 3.2: Tema metropolitan map showing distribution of sampled household locations and household densities.

3.1.1.2 End-use monitoring

In a second step, an energy audit was conducted in the selected households to supplement the survey information. Respondents were asked during the survey whether they would participate in follow-up activities which included regular electricity meter readings and appliance electricity use monitoring. A total of 80 households agreed to take part in the energy audit which was done between June and September 2017. This period is a conservative representation of the year with reference to climate-dependent electrical energy end-uses. The local climate does not vary much over the year (Nyarko 2014a).

The 11 most common electrical appliances and lighting in urban households were selected based on three key criteria: appliances with existing energy performance standards for assessing effects of the legislation (K. Agyarko 2015), appliance contribution to load curve (i.e. high-power ratings and long duration of use) and appliance viability for potential demand side management systems. The investigated appliances include; air conditioner, fan, refrigerator and freezer, television, satellite receiver, computer, washing machine, electric pressing iron, microwave oven, electric kettle, rice cooker, and electric water heaters.

For each household, the electricity consumptions of the selected appliances were monitored with data logging power analyzers at a time resolution of 30 minutes, over a 24-hour period for a typical weekday, Saturday and Sunday. Average hourly readings were recorded for all monitored appliances and used to obtain daily load profiles for a typical weekday, Saturday and Sunday. The hourly meter readings in the participating households were also monitored to enable accounting for non-investigated loads. The measurement of appliance electricity use counteracts social and reporting biases to which the survey results are subjected. For example, indicated duration of air conditioning use in some households would have resulted in an estimation that is 400% above the measured value. Household electrical energy consumption presented throughout this study is therefore limited to appliances owned and used as monitored. Furthermore, to understand the reasons for variations in appliance usage patterns over the monitored period, household activity patterns such as room occupancy and schedules for cooking, eating, showering, washing, etc. Were observed. Owing to incomplete responses by households to all components of the study, the overall sample size reduced as only 60 households produced a complete dataset for detailed analysis in line with the objectives of the study.

3.1.2 Data processing

Collected data from the survey and the energy audit were processed and analyzed with standard statistical methods as described below.

3.1.2.1 Data analysis

The multiple linear regression (MLR) method was used to analyze the data obtained. Regression is used to estimate the unknown effect of changing one variable over another. The MLR function shows the linear relationship between dependent variable (Y) and several independent variables or functions of independent variables (X). Technically, the linear regression estimates how much Y changes when X changes by one unit. The MLR function is calculated as follows:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + ... + \beta_n x_n + \varepsilon$$

Where y is the dependent variable, β_0 is the intercept (the value of y when all the variables are 0), $\beta_{1...n}$ are the regression coefficients, $x_{1\ldots n}$ represent the independent variables, and ε is the random error component which measures how far above or below the True Regression Line (i.e. the line of means) the actual observation of y lies. The mean of ε is zero. The ordinary least squares (OLS) method was used to estimate all model regression coefficients. The coefficient of determination (R^2) indicated measures the proportion of variance in the dependent variable that is predictable from the independent variables. It shows how well the values fit the data and is used as a guideline to measure the accuracy of the model (Kwame, Agbejule, and Yao 2016). In this study, the dependent variables used are appliance ownership and electricity consumption based on the context of analysis. The independent variables included socio-economic and building characteristic factors. The parametric data of the variables used were based on the survey information which is discussed in detail in the subsequent sections. Correlations between independent variables were initially examined to check possible multi-collinearity. The highest correlation coefficients between the independent variables were 0.402 (income and age of household head) and 0.357 (income and floor area). Consequently, there is no difficulty using the selected independent variables in the multiple regression analysis.

3.1.2.2 Estimation of annual electricity consumption

As the meter readings and appliance electricity use monitoring for each household were taken on different dates, the recorded daily electricity uses were normalized to annual consumption for the year 2017 using the below equation adapted from Paatero and Lund (Paatero and Lund 2006):

$$UEC_i = 52\,[5 \cdot EC_{wk,i} + EC_{sat,i} + EC_{sun,i}] - [14 \cdot EC_{sun,i}] + [14 \cdot EC_{sat,i}]$$

where UEC_i is the annual unit electricity consumption of appliance i (kWh/yr), $EC_{wk,i}$ is the electricity consumption measured on a typical weekday, $EC_{sat,i}$ is the electricity consumption measured on a typical Saturday, $EC_{sun,i}$ is the electricity consumption measured on a typical Sunday and the number 14, is the number of public holidays, which were treated as Saturdays.

Measured average daily electricity meter readings when normalized to monthly for the purpose of validating robustness of the estimates, produced an error margin of less than 5% in comparison with average monthly electricity use recorded on bills/prepaid receipts of the participating households for the investigated months. Results of UEC for investigated appliances during the energy audit provided the data on electricity consumption of appliances used for further analysis in this study.

3.1.3 Determinants of appliance ownership and electricity consumption

A multivariate linear regression analysis was applied to determine the variations in appliance ownership and electricity consumption due to socio-economic and building characteristics because of its data handling suitability (Mcloughlin, Duffy, and Conlon 2012) and its extensive use in literature for reasonable analysis of electricity consumption patterns.

3.1.3.1 Data description

3.1.3.1.1 Socio-economic and building characteristics of the sample population

Relationship of household electricity consumption to socio-economic and building factors defined in Table 3.1 such as income grade, number of occupants (household size) and age of household head were investigated with regression analysis. These factors were selected based on widely reported statistical significance to residential electricity use as reviewed by Jones et al (Jones, Fuertes, and Lomas 2015). To gain a better understanding of the data, descriptive statistics are shown in Table 3.2. Mean values were determined for each group of socio-economic and building factors as independent variables from the survey information. Floor area was used as proxy for building type in the regression analysis. The average electricity use per household is 3234 kWh/year, income is US$ 906/month, floor area is 132 m^2, household size is 4.2 and age of household head is 48 years. Figure 3.3 shows the histogram of the individual household characteristics and electricity consumption and is briefly discussed below.

Table 3.1: Definitions and numerical values assigned to socio-economic and building factors.

Dependent variable	Average value
Socio-economic factors	
Income Grade	
A	2300 USD/month*
B	1300 USD/month*
C	850 USD/month*
D	400 USD/month*
E	140 USD/month*
Age of household head	
19-34	26.5 years
35-44	39.5 years
45-54	49.5 years
55-64	59.5 years
65-74	69.5 years
75+	79.5 years
Building factors	
Building type	Floor area
Single family detached (SFD)	198 m^2
Apartment block (AB)	106 m^2
Single family semi-detached (SFSD)	78 m^2
Improvised homes (IM)	51 m^2
Multi-family house (MFH)	18 m^2
Household size (number of occupants)	
1	1 occupant
2	2 occupants
3	3 occupants
4	4 occupants
5	5 occupants
6+	6 occupants

Note 1: Income based on 1 USD to GHC 4.3959 conversion ratio

Table 3.2: Descriptive statistics for independent -socio-economic and building factors.

Variable	No. of records	Unit	Mean	Std. dev	Min.	Max	Mode
Dependent							
Electricity consumption	60	kWh/yr	3234	2653	364	12578	
Independent							
Income	60	USD/month	906	584	114	2844	569
Building type (floor area)	60	sq. meters	132	93	28	388	96
Household size	60	persons	4.2	1.4	1.0	8.0	4.0
Age of household head	60	years	48	14	20	78	56

Income: About 88% of the participants earn a monthly income ranging from US$ 500-1500 (see Figure 3.3 (a)). Close to 37% of households fall within the working-class group (D), 29% in lower middle class (C), 20% in upper middle class (B), 10% in high income class (A) and 4% in low class (E) category.

Household size: Majority of the survey participants, 92%, have a family size ranging between 2-6 persons (see Figure 3.3 (b)). Within the different classes of household composition, a family consisting of a couple and dependent children is dominant with a share of 37%, followed by family with dependent children, 32%, family with non-dependent children, 13%, couple with non-dependent children, 12% while couple only and single person accounted for 3% each.

Floor area: The survey outcome shows that about 78% of the participants live in building with floor area ranging between 50-200 m^2 (see Figure 3.3 (c)). The building type that the participants resides in vary, 45% live in SFD, 28% in AB, 13% in SFSD, 10% in IM while 3% live in MFH.

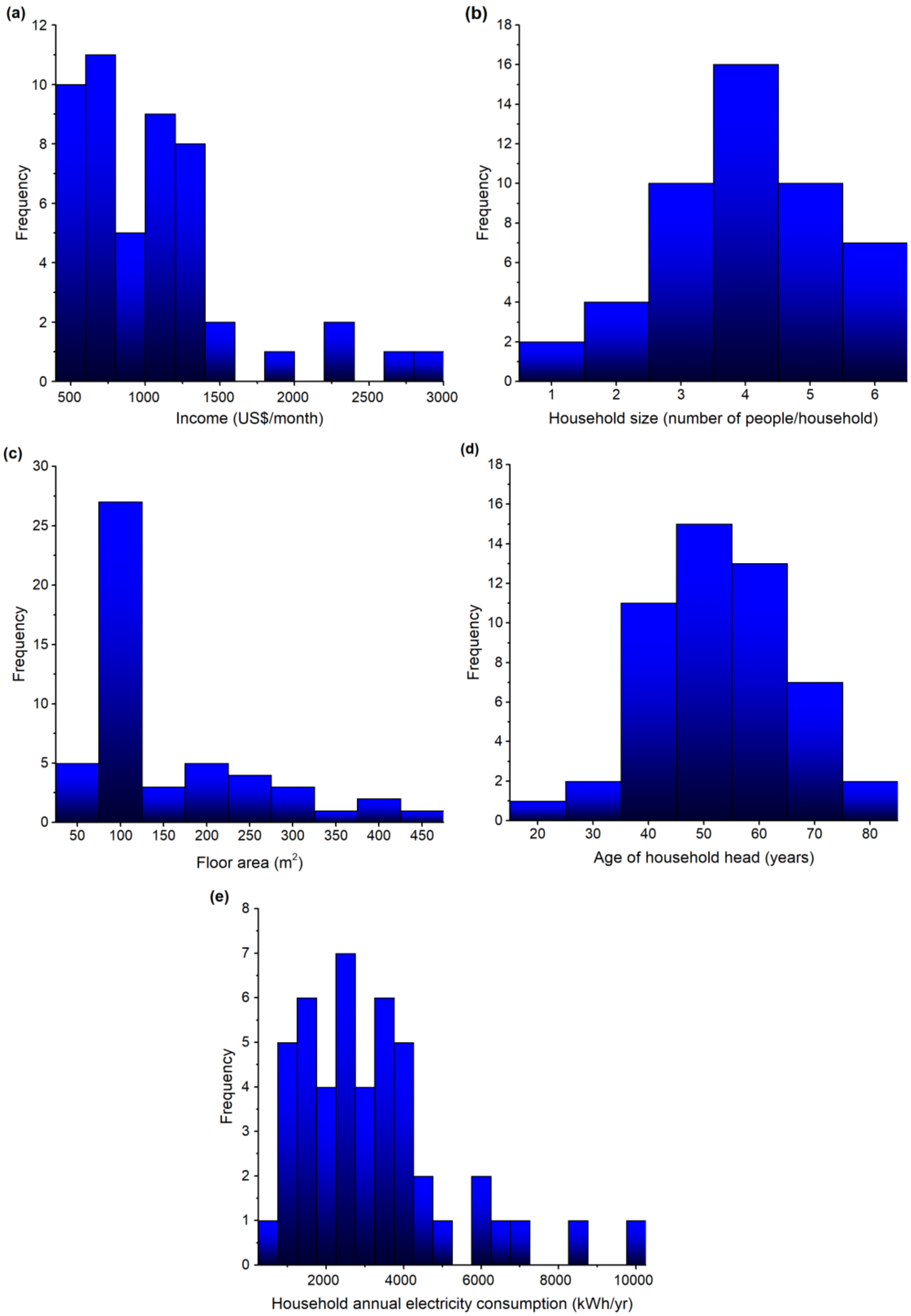

Figure 3.3: Distribution of household (a) income, (b) household size, (c) floor area, (d) age of household head and (e) electricity consumption (n = 60).

Age of household head: Sizeable number of the participants, about 76% indicated that the age of the household head ranges from 40-60 years (see Figure 3.3 (d)). Ages between 45-54 accounts for 28% of household heads, 27% for ages between 55-64, 18% for 19-34, 15% for 35-44, 8% for 65-74 and 3% for 75 years and above.

Electricity consumption: Different households own varying number of appliances based on the income level and lifestyle of a particular household. Majority of the participants, representing 73% consume electricity ranging from 1000-4000 kWh/year (see Figure 3.3 (e)).

3.1.3.1.2 Appliance ownership characteristics of the sample population

Figure 3.4 indicates that 82% of the participants have between 2-10 appliances while 84% have 3-21 lighting fixtures (both indoor and outdoor) in their homes. Collectively, every household owns an average of 8 appliances. Indoor and outdoor lighting have the highest household saturation of 11.00 and 3.14 respectively, followed by fans (1.76), T.V (1.43), refrigerators (1.02) while the lowest was electric water heater (boiler) with 0.04 as shown in Figure 3.4 (c). The ownership of indoor and outdoor lighting and television almost reached 100% while fans, electric iron and refrigerators reached between 80-84% (see Figure 3.4 (d)). The rest of the appliances have ownership rates of less than 50% with electric boiler having the lowest at 4%.

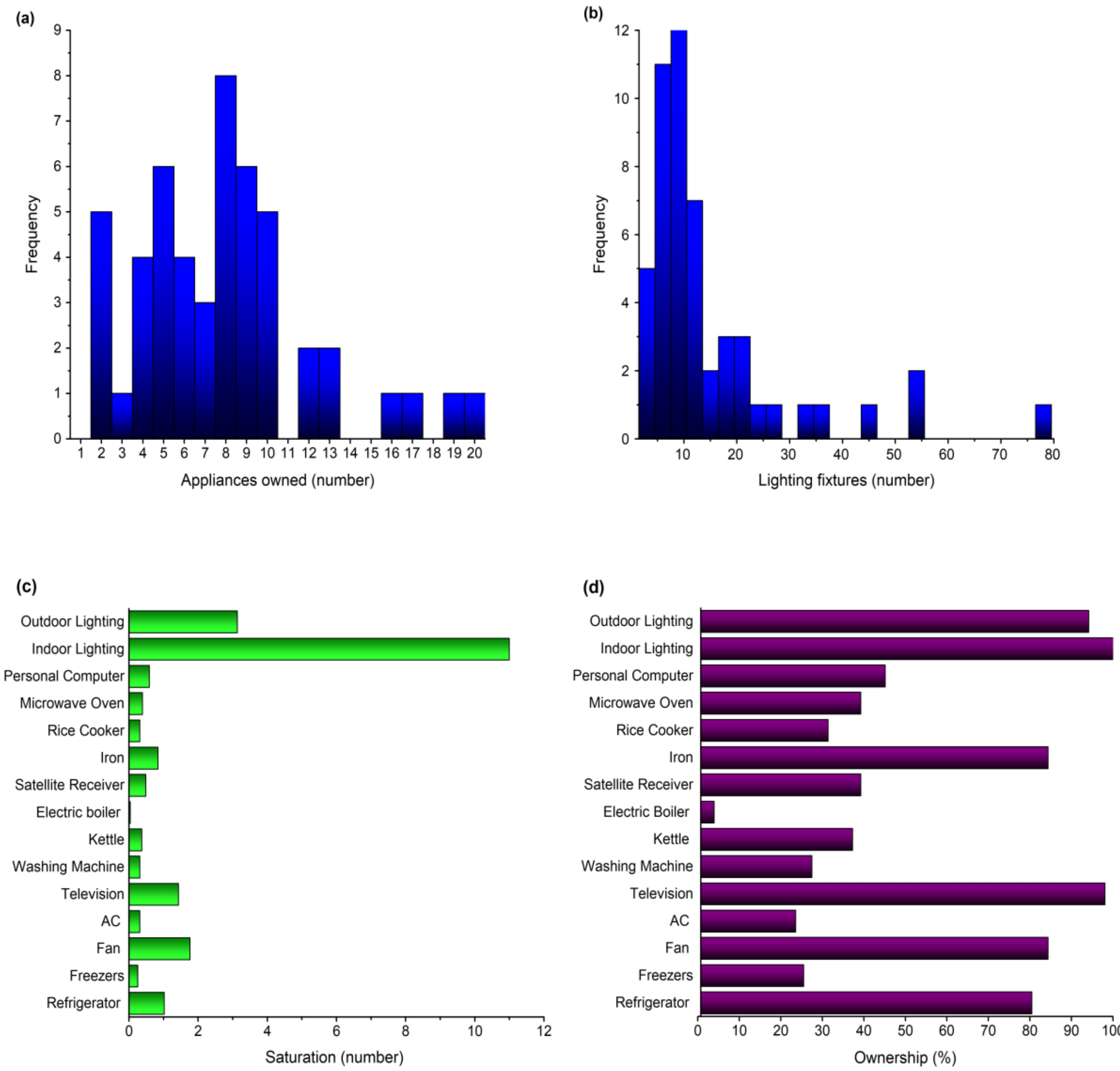

Figure 3.4: Distribution of household (a) number of appliances and (b) number of lighting fixtures (n = 60). Household appliance (c) saturation and (d) comparison of ownership (n = 60).

3.1.3.1.3 Analysis of the effects and reactions to MEPS and conservation campaigns

The REC survey provided data on energy efficiency awareness and practice from three categories of survey responses: (1) Building occupants' awareness of appliance MEPS, (2) Influence of MEPS labels on decision to purchase appliances and (3) Energy-conservative practices in the home. The responses on these 3 indicators were converted into a single factor by applying a weighting factor of 0.33 to each response. Occupants of houses that had checks for all three factors were classified as having "high" energy efficiency awareness and practice while occupants of houses that had zero checks were classified as having "lack" of energy efficiency awareness and practice as shown in Table 3.3.

Table 3.3: Weighting factors for energy efficiency awareness and practice levels of households.

Classification	Awareness of MEPS	Influence of MEPS on purchase	Energy conservation practice	Numerical value
	(0.33)	(0.33)	(0.33)	(sum)
High	√	√	√	0.99
Fair	Any two			0.66
Low	Any one			0.33
Lack	None			0
Did not answer				0

3.2 Results and discussion

3.2.1 Measurement of residential electricity consumption

The magnitude of a household's electricity demand is dependent on the number of appliances owned (Jones and Lomas 2016), and the duration of use which was found as explanation for 37% of the variance in residential electricity consumption (Bedir, Hasselaar, and Itard 2013). Results of the measured residential electricity consumption are presented and discussed below.

3.2.2 Variation of load curve per day of the week

Electricity demand profiles of the monitored households on a typical weekday, Saturday and Sunday are shown in Figure 3.5. There are two clear peaks on weekdays; morning peak which occurs between 05:00 and 08:00 hours, and evening peak which occurs between 18:00 and 22:00 hours. The morning peak generally occurs when people have breakfast and prepare for work and/or school. On Saturday and Sunday where there is no preparation for school or work in majority of homes, the morning peak reduces by about 50% while the evening peak stays almost same. High occupancy on weekends result in higher loads in the late morning and afternoon except for Sunday when electricity demand reduces significantly between 09:00 and 12:00 hours, as Christians who constitute 90% of the population (Nyarko 2014a), leave home for church service. The evening peak therefore represents the peak load of the residential sector. The average load factor on Weekday, Saturday and Sunday ranged between 36% and 39% over the 24 hours period, indicating potential and opportunity for demand side management strategies.

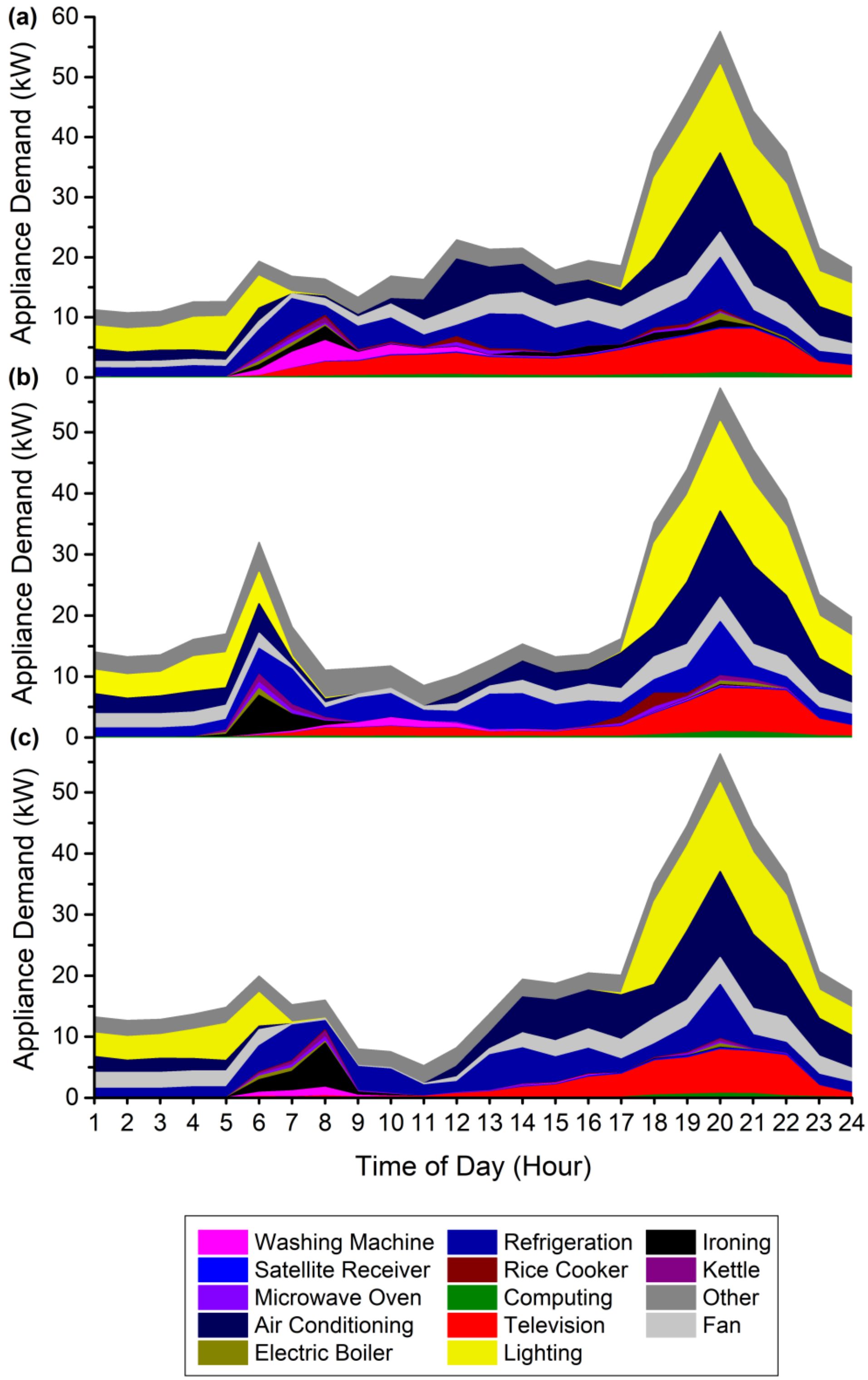

Figure 3.5: Hourly variation of appliance electricity consumption in 60 monitored households of Tema city for a typical a) Weekday, b) Saturday and c) Sunday.

3.2.3 Hourly variation of appliance use and contribution to daily residential peak

Lighting is clearly used in the late afternoon and evening when it is dark and throughout the night for outdoor lighting, with peaks at 05:00 and 20:00 hours as illustrated in Figure 3.5. Lighting contributes on average little over 25% of morning peak on weekends (Saturday and Sunday) and 16% on weekdays. The share of lighting in evening peak is about 26% for weekdays and weekends. Technological improvement in lighting fixtures will therefore yield maximum reduction in peak load. For example, a 50% improvement in energy efficiency of lighting technologies on average could translate to 13% reduction in overall daily peak load.

Air conditioners are mainly used in the late afternoons and evenings, with evening peaks at 20:00 hours for all days. Afternoon peaks are at 14:00 hours for weekdays and Sundays when children return from school and the family returns from church respectively, and at 12:00 hours on Saturdays when children and/adults are at home. Night time consumption is low. Air conditioners account for 25% of residential peak load, which makes it the second priority target for peak reduction.

Refrigeration is used throughout the 24-hour period with noticeable spikes at 20:00 and 14:00 hours due to increased frequency of use around dinner time and lunch time when children return from school. Refrigeration contributes 15% of peak load which makes it the third priority target for reducing peak electricity consumption.

Television is mostly used in the late afternoons and evenings, with peak between 18:00 and 22:00 hours when people are home. Morning consumption is highest on Saturdays when children are home and lowest on Sundays when the families attend church service. There is little "on" or "standby" electricity use at night. Television has 13% share of residential peak load, making it the fourth priority target for peak reduction. Satellite receivers are used jointly with television and contribute only 0.5% of peak load.

Fans are used throughout the 24-hour period at a relatively flat consumption rate. Morning use is significantly lower, between 05:00 and 11:00 hours, as some people prepare to leave home. Fan contributes 7% of peak load, making it the fifth priority target for demand reduction.

Ironing of clothes is mostly done in the mornings with peaks at 06:00 hours on weekdays and 08:00 hours on weekends in preparation for work, school, church service or stepping out in general. Ironing has notable 20% and 36% shares of morning peaks on weekdays and Sundays respectively. There is virtually no ironing in the evenings of these days which probably might be due to lifestyle activities and behavioral pattern of occupants. Electricity consumption of ironing on Saturdays on the other hand, is relatively flat through the morning and evening as people dress up in the morning and straighten clothes for Sunday's church service in the evening. The electricity use profile of pressing iron indicates lack of bulk ironing culture among residents. While ironing is a very significant contributor to morning peaks, its share of evening peak is only 0.3% on weekdays and Sundays, and 2% on Saturdays.

Computers are mostly used throughout the day and in the evenings, with peak between 18:00 and 22:00 hours when children/students do their assignments and adults work at home. Others who use computers for entertainment do not turn the equipment off but leave it in standby mode which consumes electricity at night. The contribution of computers to peak load is 2% on weekdays and 1% on weekends.

Washing machines are often used in the mornings with peak between 07:00 and 10:00 hours. Evening consumption is very low and there is no night time consumption. Majority of washing is done on Saturday mornings for accumulated clothes used during the weekdays. Washing machine contributes 0% of residential peak load.

Electric boiler and kettle are used in the morning between 05:00 and 09:00 hours, and in the evening between 18:00 and 22:00 hours to heat water for bathing in the case of the boiler, and for bathing and food preparation in the case of the kettle. The contribution of electric boiler to peak load is 1% on weekdays and Sundays, and 2% on Saturdays due to increased frequency of warm showers at peak hour. The impact of kettle use on peak load on the other hand is 1% on weekdays and Sundays, and 0.2% on Saturdays due to reduced use in food preparation at peak hour.

Microwave oven and rice cooker are mostly used around breakfast, lunch and dinner times. Rice cooker has noticeable higher consumption on weekdays between 16:00 and 19:00 hours due to increased use in "packaged food" preparation for school children. Rice cooker has only 0.15% share of peak load on weekdays and Sundays, and 1% share on Saturdays due to its use in dinner preparation. Microwave oven contributes, on average about 0.5% of peak load on all days.

Other than refrigerators that have a steady use, the operating schedules of other appliances are dependent on the activity patterns of household occupants.

3.2.4 Distribution of average annual electricity consumption per end-use

The lowest household, in terms of electricity use intensity, consumed 364 kWh/yr and the highest household consumed 12578 kWh/yr, while the average household consumed 3234 kWh/yr as shown in Table 3.2. The distribution of annual electricity consumption in the participating households by end-use is shown in Figure 3.6.

Lighting, i.e. indoor and outdoor lighting, is shown to be the largest end-use application of electricity, accounting for 23% of the total electricity consumption. Air conditioning ranks second, accounting for 21% of annual electricity consumption, and is followed by refrigeration (16%), fan (12%) and television (11%). While lighting, air conditioning and refrigeration maintain their ranks for peak load contribution in share of annual electricity use, fan displaces television for the fourth rank due to higher electricity use of fan at off-peak hours as illustrated in Figure 3.6.

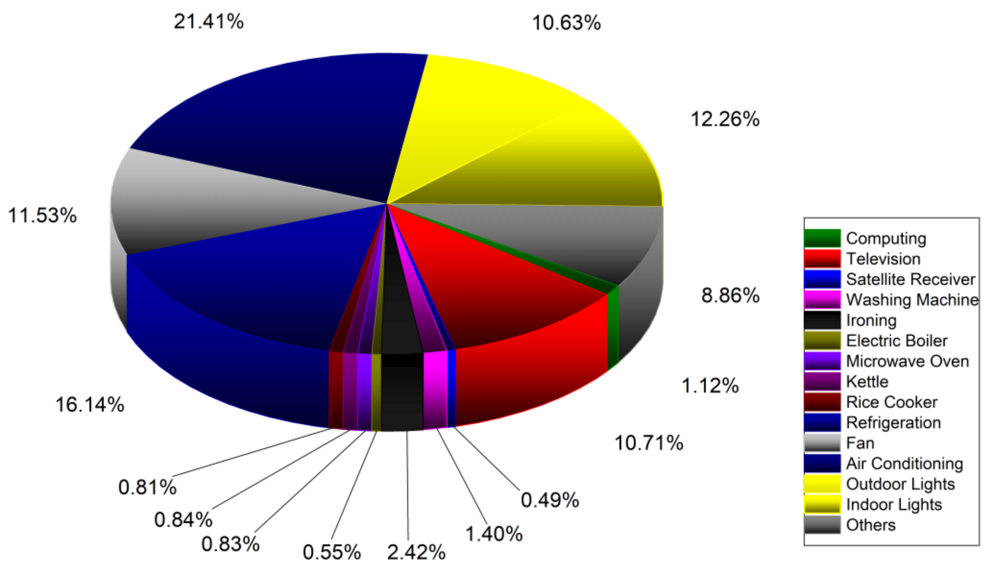

Figure 3.6: Annual electricity consumption breakdown in the participating households.

3.2.5 Flexibility of appliance use at peak load

There is flexibility in the use of priority appliances (i.e. major peak contributors) during peak hours as shown in Figure 3.7. Lighting was not considered due to its necessity for vision. Electricity demands of appliances that are not in use "always" are considered flexible.

Appliances for space cooling i.e. air conditioner and fan have the highest flexibility of use during peak hours with 44% and 31% respective shares of households indicating that these appliances are not always on. Television is the third most flexible peak load at 10% and refrigeration is the least flexible peak load as expected at 2%. These results suggest space cooling as the most significant electricity end-use that residents can comfortably do without

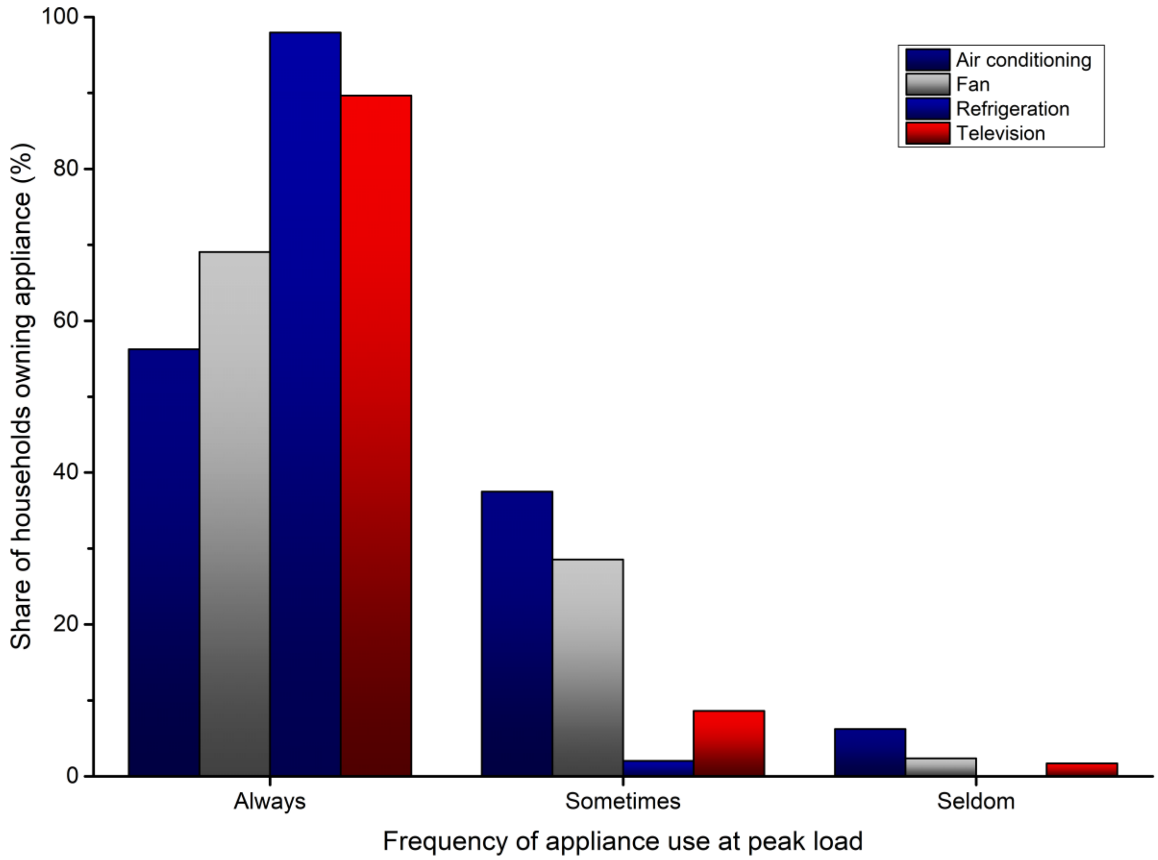

Figure 3.7: Flexibility of priority appliance use at peak load.

during peak hours. Air conditioning alone could reduce residential peak load by 11% (via combination of 44% flexibility and 25% share of peak load).

3.2.6 Appliance preferences for DSM initiatives

More than 40% of owners of air conditioners, refrigerators and televisions indicated preference for turning off the appliance or shifting their use, to prevent temporary curtailing of power supply at critical load of the utility service provider as shown in Figure 3.8. Management of the use of these appliances could collectively reduce residential peak demand by 28% or yield desired changes in the load profile of power suppliers.

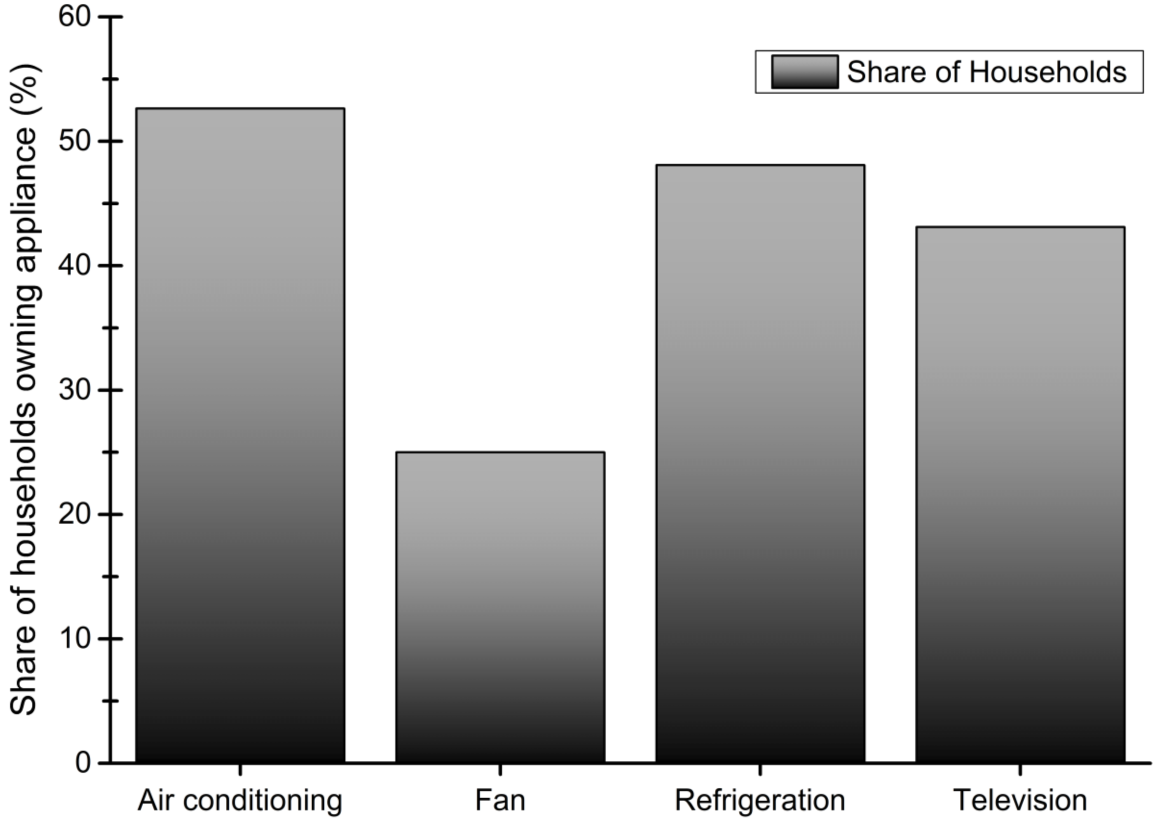

Figure 3.8: Appliance preferences for voluntary demand response management.

Two pathways exist for demand reduction. Firstly, energy conservation measures with increased energy efficiency (EE) via minimum energy performance standards (MEPS) could reduce both baseline and peak electricity demand. Although MEPS already exist for some appliances (i.e. refrigerator, air conditioner, lighting) (Gyamfi et al. 2018), a number of identified high electricity consuming appliances and major contributors to residential peak load (i.e. television, fan, iron) are currently not included in this policy. The range of appliances for which MEPS are required could be extended in addition to continuous revision of existing MEPS requirements in consistency with technological advancement. Secondly, economic means of induced use behavior via increased electricity tariffs or time-based pricing could reduce residential electricity consumption. In December 2015 for example, residents responded to a 59% rise in electricity tariffs with changes in electrical energy consumption patterns, resulting in significant reduction in power demand (Ghana Grid Company Limited 2017). This report is in line with many studies (Bartusch et al. 2011; Thakur and Chakraborty 2016; Bradley, Coke, and Leach 2016; Cosmo and O'Hora 2017) that found demand response management has potential to be used as standby power resource and is feasible for application in several parts of the world.

3.2.7 Characteristics of appliance ownership

The survey results on appliance ownership are presented in groups of socio-economic and building factors as illustrated in Appendix A.2. Electric boiler was excluded from this section of results analysis because only two households owned the appliance. Refrigerators and freezers were combined in this section to represent refrigeration end-use mainly because there were few freezers and their owners were also owners of refrigerators. In this study, appliance ownership refers to the share of households owning one or more type of appliance while saturation refers to the quantity of a given appliance per household (Rosas-flores, Rosas-flores, and Morillón 2011; McNeil and Letschert 2010). Often, the total number of households across socio-economic and building factors is 60. Though 126 households provided responses to appliance ownership, electricity uses of the owned appliances were monitored in 60 homes due to high costs and unwillingness of some household participants. Observations from the analysis are presented below.

The share of lamp technologies used for indoor lighting are 62%, 35%, 3% and 0% for compact fluorescent lamps (CFL), light emitting diodes (LED), ballast fluorescent tubes (FL) and incandescent bulbs (INC) respectively, while that for outdoor lighting are 62%, 17%, 20% and 1% for CFL, LED, FL and INC respectively. Single family detached (SFD) houses have the highest saturation of lamps at 22, while multi-family houses and improvised homes have the lowest at 3. SFD houses have larger floor area which demands higher lighting needs. The average household uses 11 lamps for indoor lighting and 3 lamps for outdoor lighting.

Over 80% of ownership of air conditioners is amongst household heads aged between 19 and 54 years and in full-time paid employment. Households with dependent children account for 75% of air conditioner ownership. This result is consistent with that of Matsumoto (Matsumoto 2016) who finds that younger people use air conditioners more intensely because they prefer cooler temperatures at home although electricity use per capita was higher for household heads above 65 years.

Refrigeration is owned in every category for all socio-economic and building factors, showing that refrigeration is widely owned, and a major driver of growth in residential electricity demand.

Ownership of television is highest amongst households with dependent children at 67% and in line with previous study by Matsumoto (Matsumoto 2016), who found that the presence of teenagers increases use of television. Satellite receivers were used jointly with televisions in monitored households. Similar to television, its ownership is mostly by homes with dependent children.

Ownership of fans is highest in homes comprising of a couple and non-dependent children. The average of such households owns 4.14 fans.

Households whose heads are in full time employment dominate ownership of pressing iron as expected at 76% because it is often used in straightening clothes for work as discussed in section 4.1.2. Computer ownership in homes is about 81% for full-time employed household heads and about 70% for household heads aged between 19 and 54 years, suggesting a "home-working" culture amongst employed residents.

Homes with dependent children dominate ownership of washing machine at 78% due to increased workload that is associated with looking after children, who generally use more clothes than adults.

Households with dependent children top ownership of electric kettle at 59% because children are more inclined to have warm shower which is made possible with kettle in most homes. About 53% of ownership of rice cookers is amongst households with dependent children probably because children generally prefer rice as a packaged lunch for school.

Similarly, about 67% of ownership of microwave oven is amongst households with dependent children.

3.2.8 Determinants of appliance ownership

A regression model was developed by looking at the effect of socio-economic and building characteristics on each independent appliance separately. The results of the regression analysis are presented in terms of the regression coefficients which reflect the magnitude and direction of change in the number of a given appliance in a household, when the degree of a given socio-economic or building factor increases by one, while holding all other variables constant. Negative coefficient indicates reduction in number of appliances while positive coefficient indicates increase in the number of appliances. The results are presented in Table 3.4.

Table 3.4: Regression results for determinants of appliance ownership.

	Household size		**Energy efficiency awareness**		**Age of household head**		**Floor area**		**Income**	
	Co-eff	Std.err.	Co-eff	Std.err.	Co-eff	Std.err.	Co-eff	Std.err.	Co-eff	Std.err.
Lighting	-	-	-	-	-	-	0.092***	0.017	0.0084***	0.0032
Air conditioner	-	-	0.309*	0.187	-0.016**	0.006	0.002***	0.001	0.0003*	0.0001
Refrigerator	-	-	0.426*	0.229	-	-	0.003***	0.001	0.0006***	0.0002
Television	-	-	-	-	-	-	0.004***	0.001	0.0005***	0.0002
Fan	-	-	-	-	-	-	-	-	0.0009**	0.0004
Computer	-	-	0.478*	0.253	-	-	0.003**	0.001	0.0004**	0.0002
Satellite receiver	-0.123**	0.066	-	-	-	-	0.002*	0.001	0.0006***	0.0002
Iron	-	-	-	-	-0.010**	0.004	-	-	0.0002**	0.0001
Washing machine	0.079*	0.044	-	-	-0.014***	0.005	0.002***	0.001	0.0002*	0.0001
Kettle	-	-	-	-	-	-	0.001*	0.001	0.0003**	0.0001
Microwave	-	-	-	-	-	-	-	-	0.0003**	0.0001
Rice cooker	-	-	-	-	-	-	0.001**	0.001	0.0003**	0.0001

-	*Not significant*
*	*Significant at the 10% level*
**	*Significant at the 5% level*
***	*Significant at the 1% level*

A unit rise in household size reduces the number of satellite receivers in a home by 0.123 because household members tend to share the appliance in a common living room. Household size positively influences the number of washing machines at 10% significance level, and is supported by higher tendency to generate more dirty laundry as reported in (Jones and Lomas 2015).

Age of household head has a negative influence on the saturation of air conditioner, iron and washing machine such that, the number of these appliances in a home reduces by 0.013 on average when the age of the household head increases by one. This finding is supported by concentration of ownership of these appliances within 19-64 year groups of household heads, see Appendix A.2. Previous studies in other parts of the world have had similar findings. Leahy and Lyons (E. Leahy and Lyons Sean 2010) found that in Ireland household heads above 75 years and retired are less likely to have a washing machine. Jones and Lomas (Jones and Lomas 2015) report that in the United Kingdom, homes with household heads older than 65 years likely have fewer occupants who generally own less appliances. A lower number of air conditioners in homes headed by over 65 year-olds in Ghana may be because such households have less income and cannot afford the electricity costs associated with the energy intensive appliance. Compared to working families, retired residents change clothes less often and thus need less use of iron and washing machine.

Floor area significantly influences the number of lighting fixtures, air conditioners, refrigerators, televisions, computers, washing machines and rice cookers positively. A 10 m^2 rise is floor area would increase the number of lamps by 0.9. These findings are supported by (Bedir, Hasselaar, and Itard 2013; Jones and Lomas 2015) who find that larger floor areas mean additional rooms which demand additional cooling and lighting. Bigger houses in Ghana are mostly owned by the wealthy who can afford domestic workers such as cooks, gardeners, drivers, gate keepers, baby sitters etc., whose presence increases need for additional appliances.

Income had the expected effect on all appliances. When income increases by US$100, each appliance increases by an average of 0.04 and lighting by 0.8. This result is in line with findings in (O'Doherty, Lyons, and Tol 2008) that as income increases by £100 in Irish homes, the weighted number of appliances increased by 0.6%.

It can be inferred from the results that economic development in Ghana and associated rise in income levels will not only enable households purchase "new entrant appliances" but will also increase the saturation of existing appliances in homes. While section 3.2.3 identifies the highest electricity consumers and major contributors to peak load, this section identifies the specific groups of households that own majority of these priority appliances and provides the basis for developing demand side management initiatives that would guide targeted households to reduce their electricity consumption over time.

3.2.9 Determinants of household electricity consumption

The electricity consumption of households were regressed against appliance ownership and socio-economic/building variables i.e. income, household size, age of household head, building type and energy efficiency awareness & practice. The derived regression coefficients of the variables are presented in Table 3.5. The statistical significance of the main variables is described in the following.

Table 3.5: Statistic for the variables found to be best indicators of a household's electricity consumption.

Variable	**Co-eff (standard error)**
Socioeconomic and building characteristics	
Income	1.942 (0.912)**
Building type (floor area)	7.151 (5.924)**
Household size	580.433 (318.695)***
Age of household head	-
Energy efficiency awareness and practice	-1277.196 (1230.964)*
Appliance ownership	
Air conditioner	1990.497 (1189.932)**
Refrigerator	226.155 (685.451)*
Freezer	886.322 (1003.405)**
Television	126.715 (836.403)*
Fan	649.459 (307.903)***
Personal computer	-
Satellite receiver	-
Iron	-
Washing machine	-
Electric kettle	-
Electric boiler	-
Microwave	-
Rice cooker	-
Lighting	87.488 (47.488)***

$R^2 = 0.568$

- *Not significant*
* *Significant at the 10% level*
** *Significant at the 5% level*
*** *Significant at the 1% level*

3.2.9.1 Building type

The size of the floor positively affects electricity consumption because the larger the house, the more the requirement for lighting and cooling needs to maintain visual and thermal comfort. Single family detached houses have larger floor areas and use an average of 80% more electricity than other building types because majority of single family detached houses in the city are owned by the high-income earners who prefer larger homes to accommodate domestic workers. Table 3.5 shows that a 1 m^2 rise in floor area increases a household's annual electricity use by 7 kWh. This result agrees with the findings of Zhou and Teng (S. Zhou and Teng 2013) in China who found that 10 percentage point increase in the size of a building increases electricity consumption by 1 percentage point. Other studies (S. Zhou and Teng 2013; Jones and Lomas 2015; Carlson, Matthews, and Bergés 2013) also found buildings with larger floor area consumed more electricity and attributed the rise in electricity use to larger heating and cooling needs.

3.2.9.2 Income

Household income is statistically significant with positive coefficient and has varying effect in electricity consumption. A unit rise in the income of a household in this study results in almost 2 kWh increase in electricity consumption. This means that electricity use in a home increases with rising income mainly because the number of appliances, which offer opportunity for electricity use in a home, is proxy to wealth. The more households purchase appliances, and use it frequently, the more the electricity consumption, *ceteris paribus*. This finding is consistent with previous studies (S. Zhou and Teng 2013; Jones and Lomas 2015; Louw et al. 2008; Carlson, Matthews, and Bergés 2013; Wiesmann et al. 2011). For instance, Louw et al. (Louw et al. 2008) found that income had a positive relationship with electricity demand in all tested models and suggested that electricity use is a cost-based decision.

3.2.9.3 Household size and age of household head

Household size has a strong influence on the variance of electricity consumption. For every addition to the number of occupants in a home, annual electricity consumption of the household increases by 580 kWh as shown in Table 3.5. The increased consumption is due to increased floor area, appliance ownership, appliance saturation and frequency of appliance use to meet the needs and comfort of the many occupants. Typically, with relatively similar lifestyle, more household occupants result in increased consumption. For instance, single family households in detached houses with domestic workers such as drivers, cooks, and gardeners in this study had very high electricity consumption.

Other studies in different parts of the world have reported varying findings on the influence of household size on electricity consumption. A study conducted in Japan by Genjo et al. (Genjo, Tanabe, and Matsumoto 2005) found that household size (Beta = 0.23, $p < 0.05$) in addition to income and appliance ownership has a significant influence on electricity consumption. Wiesmann et al. (Wiesmann et al. 2011) found that occupants of single family houses in Portugal consume more electricity than occupants of multifamily houses, depicting the concept of economies of scale. The model 4 developed by Louw et al. (Louw et al. 2008) on another hand indicated that household size was insignificant (t-value = 0.57) and explained that household size does not affect electricity use since end-use demands of household occupants can be met simultaneously. The differences in the influence of household size on electricity use could therefore be attributed to the different lifestyle and socio-cultural dynamics of the particular environment. Age of household head had no significant influence on electricity use, which suggests occupant behavior as a more relating energy-use driving factor than age.

3.2.9.4 Appliance ownership, lighting and EE awareness and practice

Lighting and some appliances show statistical significance in the variance of electricity use with positive coefficient while EE awareness and practice show strong significance but with a negative coefficient. Air conditioner, refrigerator, freezer, television and fan were all significant at various levels (99%, 95% and 90%). Air conditioner shows the highest influence and accounts for 24-68% of total consumption in homes that own the appliance. Freezer has the second highest influence followed by fan, refrigerator and television. These impacts are linked to the high shares of end-uses such as cooling, refrigeration and entertainment which collectively account for about 48% of the annual electricity consumption. Appliances such as personal computer, satellite receiver, iron, washing machine, electric kettle, electric boiler, microwave oven and rice cooker show no significance at all. This can be explained by their negligible running power and/or relatively low frequencies of use. The holding of appliance may reflect partially the effect of home appliances on electricity use but its power and rate of use is essential. Lighting is very significant in the variance of electricity use because various homes have high number of lighting fixtures and long hours of use. Some few households leave lights on in unoccupied rooms.

Table 3.5 shows that a unit increase in the number of lighting fixtures increases household electricity consumption by 87 kWh annually. Lighting is a major factor, and this is supported by Genjo et al. (Genjo, Tanabe, and Matsumoto 2005) who found that lighting and household appliances contributed 3 MWh and 60% of the variance in the yearly electricity consumption of 505 Japanese households. The results for the EE practice and awareness is expected because as households purchase efficient appliances and use them cautiously, the energy required for meeting the same specific end-use service is curtailed. This means households with large consumption who effectively partake in EE activities save and minimize waste in electricity use. Collectively, these factors, i.e. income, household size, age of household head, building type and energy efficiency awareness & practice account for 57% of variance in residential electricity consumption.

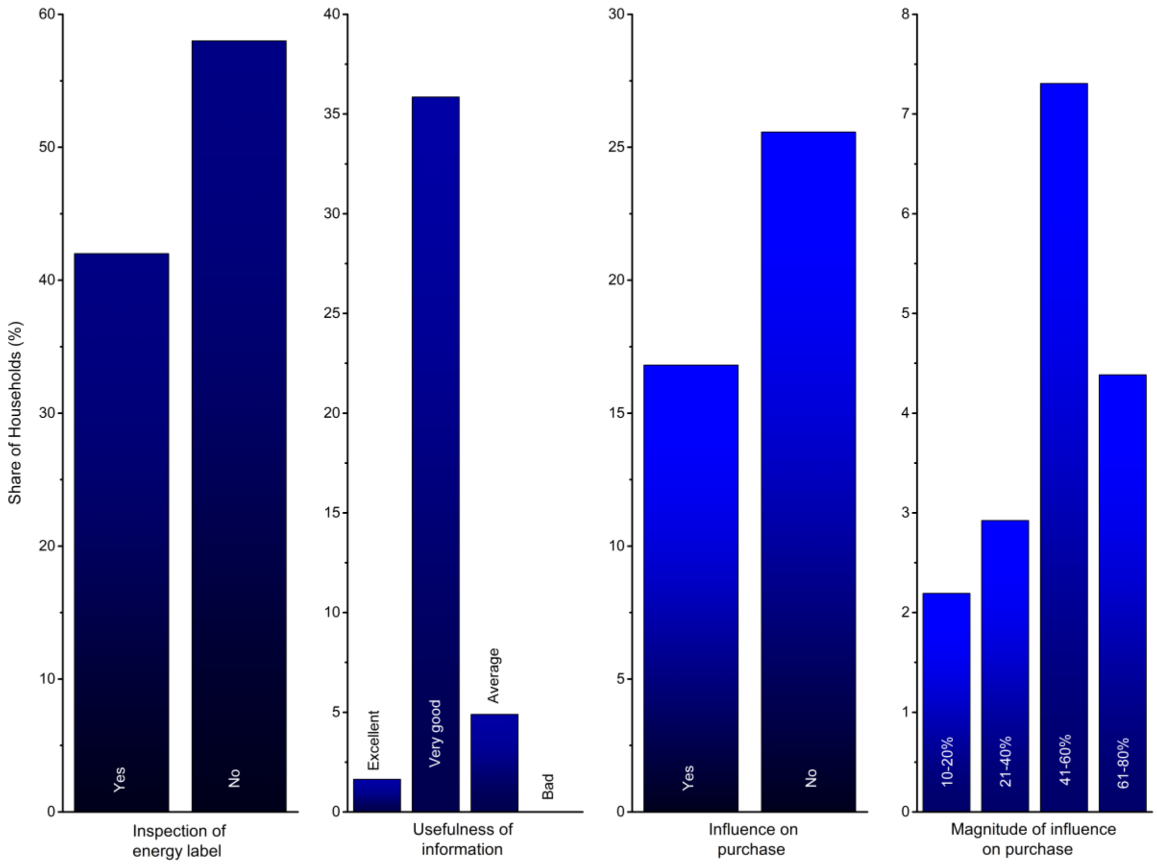

Figure 3.9: Reaction to minimum energy efficiency standards (MEPS).

3.3 Policy implications

3.3.1 Effects and reactions to energy efficiency initiatives

3.3.1.1 Minimum energy performance standards and labelling (MEPS)

Lighting fixtures, air conditioners and refrigerators in Ghana have energy efficiency labels. Figure 3.9 shows that about 42% of the respondents claim they would pay attention to energy efficiency label when buying an appliance, and 38% of the respondents claim they found information on the label extremely useful, indicating that the promotion of Ghana's MEPS had positive impact. However, only 17% of the respondents claim their decision to purchase a particular appliance would be influenced by its energy label. Preference for trusted brands and high costs were identified as the key barriers to purchase of highly efficient appliances, with 31% and 28% of the respondents specifying these reasons for not buying an energy-efficient appliance respectively as shown in Figure 3.10. Explanations for the remaining respondents were split mainly between ignorance and lack of interest, indicating that though some successes have been achieved in promoting Ghana's MEPS, there is still considerable room for improvement.

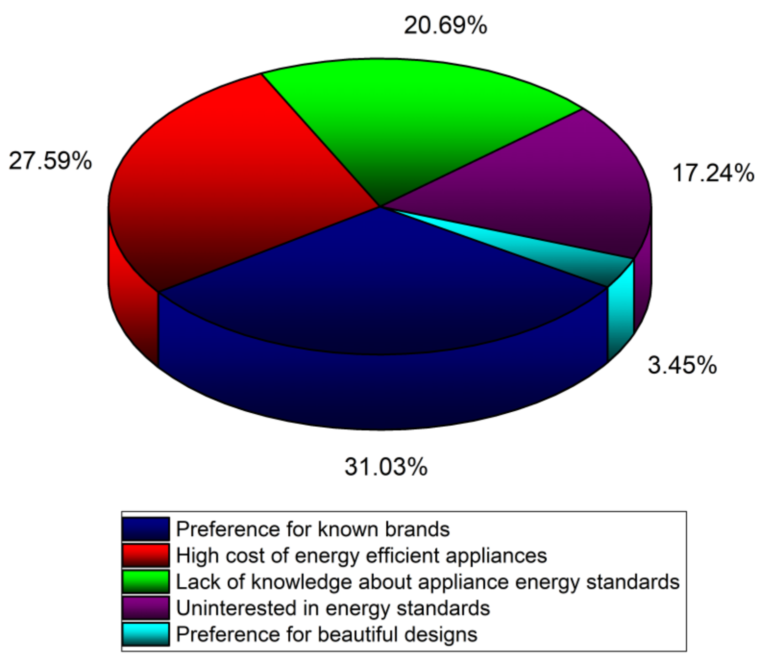

Figure 3.10: Key barriers to purchasing energy efficient appliances.

Ghana and China have similarities in the type and timing of government sponsored energy efficiency initiatives. China sought to rid its homes of incandescent bulbs through the Green Lighting Project in 2004 while Ghana did same with legislation in 2005 and with the Efficient Lighting Project in 2007 (Hu et al. 2017). Both countries invested in public education to promote awareness of the legislation, and to encourage efficient electricity use behavior (Hu et al. 2017; Gyamfi et al. 2018). After a decade of EE implementation, 44% of urban Chinese households claim they would pay attention to energy efficiency labels when

buying an appliance (Hu et al. 2017), this is comparable to Ghana's 42%. High costs was identified as key barrier to the purchase of highly efficient appliances in China (Hu et al. 2017) as it was in Ghana. The share of incandescent bulbs in lighting was only 0.2% (2 out of 817), indicating a highly successful implementation of Ghana's Efficient Lighting Project. This result is in line with the findings of previous studies (Diawuo et al. 2018; Gyamfi et al. 2018). In comparison, (Hu et al. 2017) found incandescent bulbs represent 4% of lighting fixtures in urban Chinese homes.

Table 3.6: Label classification of the average electricity consumption for monitored appliances.

Appliances	**A+++***	**A++***	**A+***	**A***	**B***	**C***	**D***	**Outdated***
Air conditioner						✓		
Refrigerator							✓	
Freezer						✓		
Television[a]								✓
Washing machine[a]				✓				

**Appliance standards and label classification based on Ghana's MEPS and energy efficiency index (EEI) in* (Diawuo et al. 2018)
[a] *MEPS not in-force*

Table 3.6 shows how the average electricity consumption of appliances measured in this study conform to Ghana's MEPS. The average electricity consumption of refrigerator and freezer were found to be 375 kWh/yr and 417 kWh/yr respectively, both of which meet their respective MEPS. This result could be explained by the use of the city as pilot for Ghana's Refrigerator Energy Efficiency project, and is consistent with (Gyamfi et al. 2018) who found that households who participated in the project had the electricity consumption of their refrigerators reduced to 385 kWh/yr. The average television in the city was found to consume 225 kWh/yr and outdated. Television is very widely owned, second to refrigeration (see Appendix A.2) and as such, is a major driver for growth in residential electricity consumption. Similarly, the average air conditioner was found to consume 2221 kWh/yr and outdated though this consumption meets the MEPS. Air conditioner was found to contribute 25% of peak load (section 3.2.3). These results show great potential for energy savings and emphasize the need for revision of existing MEPS, as well as expansion of

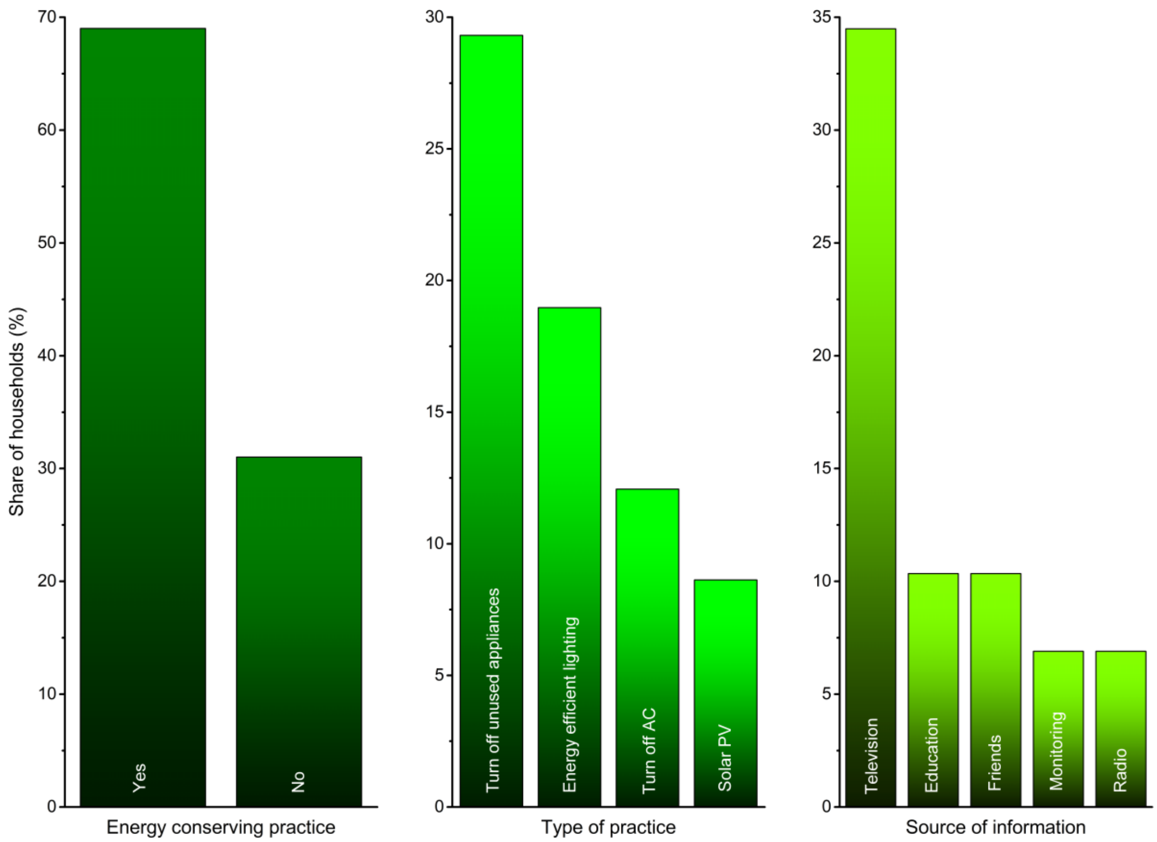

Figure 3.11: Reaction to energy saving behavioral campaigns.

coverage of appliances for which MEPS are required. Regulatory policies should be supported by financing incentives to overcome the barriers to penetration of highly efficient appliances in Ghanaian homes.

3.3.2 Energy conservation awareness and practice

About 70% of the respondents claim awareness and practice of energy conservation at home, indicating that Ghana's energy-conservative behavioral campaigns have had some success as shown in Figure 3.11. Switching off unused appliances and use of energy-efficient lighting were identified as the most known and accepted energy conservation measures, with 29% and 19% of the respondents specifying these as their energy-saving practice respectively. Another 12% of respondents claim they would switch off air conditioning to conserve energy, supporting the argument that this appliance could be a priority target for residential load management. Television was identified as the most effective medium for launching energy-efficient behavioral campaigns, with 35% of respondents indicating it as their main source of information. Education on energy-use efficiency in schools and friends were the second most successful means with 10% of the respondents choosing each channel as their source of information. Broad energy conservation and energy efficiency advocacy on major television channels as well as intensified teaching of energy-saving behavior in schools should be given priority in educating the public on the efficient use of electricity at home.

3.4 Limitations of the study

Though this study has provided significant insight, the results obtained are limited by three main restrictions; the sample size available for analysis, time period for electricity end-use monitoring and proclivity of socio-economic and building factors to reporting biases. While a total of 440 households in a single Ghanaian city were targeted in the whole survey, the eventual sample size used in the analysis reduced to 60 households because many respondents did not provide a complete set of data, and high cost of end-use monitoring limited coverage to a smaller fraction of households. This resulted in small group sizes for some socio-economic and building factors. The distribution nonetheless, was able to capture all groups under consideration.

Electricity end-use monitoring was conducted for selected households over a 24-hour period of time on a weekday as well as Saturday and Sunday. The weekday measurements were assumed to be representative of all other weekdays during the year, as were Saturdays and Sundays. A year-long end-use monitoring study would be beneficial to accurately capture seasonal variations in household electricity consumption and the usage patterns of the various appliances but would also entail significant cost implications.

Aside floor area/building type which could be verified, information on other socio-economic and building factors used in this study were derived from self-reported data and are subjected to reporting biases of the respondents.

Future study on the functions of appliances and the activity patterns of household occupants could further provide substantial insight into electricity consumption in residential buildings. A follow-up study on assessing the potential of balancing and trimming the peak of the load curve through voluntary demand response strategies is presented in (Diawuo et al. 2020).

3.5 Conclusions

This study combines a residential electricity consumption survey (RECS) with electricity end-use monitoring of 60 households conducted between June and September 2017 in Tema, Ghana, to yield a comprehensive investigation of city-scale electricity consumption in Ghanaian homes. To the authors' knowledge, this is the first electricity end-use monitoring study carried out in Ghana. Meter readings provide data on total household electricity consumption which is used to obtain shares of measured appliances' electricity consumption whereas survey results provide data for assessing the sensitivity of electricity uses to selected socio-economic and building factors.

Lighting, air conditioning, refrigeration, television and fan are found to collectively contribute 85% of residential peak load. The results suggest space cooling i.e. air conditioning and fan, as the most significant end-use with flexibility in operating schedule during peak period. Management of the use of air conditioning alone could reduce residential peak load by 11%.

This study identifies the vast majority of ownership and electricity use of air conditioners is amongst household heads, aged between 19 and 54 years and in full-time paid employment. Refrigeration is widely owned, and high-income earners own twice as many refrigerators as low-income earners. Ownership of fans increases with increasing levels of income, and highest in homes with non-dependent children. The presence of dependent children in a home is found to increase ownership of television, iron, washing machine and small kitchen appliances. The presence of retirees as household heads on the other hand, is found to decrease ownership of air conditioners, washing machines and irons in a home.

The results show that income, household size, floor area and ownership of some appliances such as air conditioner, freezer, fan, refrigerator and television are significant determinants of household electricity demand. This study reveals the importance of socioeconomic and household factors with regards to electricity consumption in Ghanaian homes and enables development of policies that go beyond the usual consideration of income to reducing the impact of such social and building characteristic influences on residential load growth. Residential building energy standards that require optimization of lighting and cooling energy intensity could be implemented for instance, to curb load growth due to increasing building floor area and air conditioning.

Although Ghana's minimum energy performance standards (MEPS) have had successful promotion, this study finds that the energy label influences only 17% of residents' decision to purchase an appliance due to high cost of efficient ones and preference for trusted brands. Switching off unused appliances and use of energy-efficient lighting are identified as the most known and accepted energy conservation measures, and television as the most effective medium for launching energy-efficient behavioral campaigns. The range of appliances for which MEPS are required should be extended in addition to continuous revision of existing MEPS requirements in consistency with technological advancement, to counteract electricity demand of appliances from "trusted brands" that may otherwise be energy-inefficient. Introduction of fiscal incentives, subsidies, soft loans and other credit facilities could be effective in eliminating the high cost barrier to purchase of highly efficient appliances. As price sensitivity exist for appliance ownership amongst income groups, effective discrimination of these incentives is necessary to avoid excessive appliance ownership and saturation which can thwart the purpose of such schemes. Overall, the results of this study increase understanding of the patterns of appliance ownership and residential electricity consumption associated with social and economic variation in Ghana's urban homes and provide a foundation for developing more tailored energy-saving policy interventions.

C h a p t e r   4

ASSESSMENT OF MEASURES TO REDUCE RESIDENTIAL COOLING ELECTRICITY DEMAND

While no previous records exist for ownership of air conditioners in Tema city, the share of households that own one or more of the appliance in the Greater Accra Metropolitan Area (GAMA) to which Tema city belongs, sextupled between 2000 and 2014 from 0.8 percent to 3.6 percent (Nyarko 2014b; Bediako 2008; Asenso-Okyere 2000). The rising ownership of air conditioners together with the rising temperatures resulting from climate change (ECREEE 2014a) is creating a rising temperature-sensitive peak load that could prove problematic given the persistent challenges surrounding power generation and spinning reserve capacities (Sakah et al. 2017). This development should serve as caution to the planning of generation systems and distribution networks in Ghana, particularly for middle income and high income communities where installation of air conditioners and other appliances have increased the most in recent years (Gyamfi et al. 2018).

Several studies have been conducted around the world to investigate opportunities for reducing the energy use of buildings and to explore the possibility of net zero energy homes (Sadineni and Boehm 2012). Reports suggest that for residential renewable energy systems to be cost effective, energy use of the building must first be reduced to the barest minimum through energy efficiency measures (Sadineni and Boehm 2012). Building energy codes and standards is one of the most frequently used instruments for energy efficiency improvements of buildings in several parts of the world due to its mandatory nature which guarantees significant levels of relative energy use reduction (Jank 2013). However, no building energy standards are in place in Ghana and this is aggravated by lack of data for building energy consumption (Nii, Emmanuel, and Joshua 2017). Tema had roughly 4.2 million m^2 of residential building stock in 2010 (Nyarko 2014a) , and grew at an average annual new construction rate of 0.1 million m^2 between 2001 and 2010 (Nyarko 2014a; Acquah 2001). Trends indicate preference for detached and semi-detached houses in addition to large floor areas for all building types (Acquah 2001). Following such trajectory in new construction, the total floor space of residential buildings in Tema in 2010 could double by 2050. In the face of challenges related to electricity supply insufficiency, the main objective is to improve thermal comfort in homes without increasing the demand for electricity which is the basic source of mechanical air conditioning systems (Kuczyński and Staszczuk 2020).

For building engineers and policy makers, there is scarcity of validated micro data on the physical and operational characteristics of homes to reliably estimate baseline energy consumption, and quantify efficiency saving opportunities to cost-effectively reduce the cooling energy consumption of residential buildings in Ghana. Therefore, this research has collected cooling energy related data and information, including statistics, large-scale questionnaire surveys, monitoring and case study data in EnergyPlus building simulation tool to establish an engineering-based bottom-up model. The study assesses the key influencers of residential cooling energy intensity with focus on three main sections of the building model: wall and roof composition, efficiency of air conditioning equipment and fenestration (i.e. window-to-wall ratio and window material for solar heat gains). The air conditioner is treated as a building component rather than an electronic appliance. As-built materials and performance details gathered from the survey and energy use monitoring are used to calibrate the simulation model due to climate dependency of some of these parameters. The objective is to identify key drivers, primary barriers of energy-efficiency technology, and make policy recommendation for effective reduction in cooling energy consumption of Ghana's residential sector.

4.1 Methodology

Building on previously identified energy efficiency opportunities in residential cooling, this section investigates the energy savings potential in terms of kWh/m^2 reduction in energy demand of conditioned spaces for current and future residential buildings. In this investigation, the energy use of reference buildings are modelled with EnergyPlus software using measured data from the energy audit and REC survey.

Figure 4.1: Characteristic building types of apartment building, semi-detached home and single-family detached home (from top to bottom).

4.1.1 Cooling load simulation

EnergyPlus is a simulation engine whose space load calculation is based on temperature differences between spaces and materials and constructions of the involved space boundaries. The heat and thermal balance simulation is integrated with the building systems simulation such that, results are always accurate and independent of space loads being met or not (Maile, Fischer, and Bazjanac 2007). EnergyPlus is the official building energy simulation tool for the United States' Department of Energy, and has been examined and used extensively by the international research community to model heating, cooling, ventilation, lighting and water consumption of buildings (Royapoor and Roskilly 2015). DesignBuilder is the most comprehensive interface for EnergyPlus. Its integrated CAD interface enables creation of specific thermal building model geometry using templates of country or region specific materials and construction, and supports import of data collected from existing buildings including information about building use schedule, HVAC equipment on space level, openings (window to wall ratio) and lighting. Therefore, DesignBuilder version 4.5.0.148 was used as graphical interface (front-ending EnergyPlus version 8.3). The conduction transfer function state space method as described in (NREL et al. 2015), was selected as the heat balance algorithm in EnergyPlus to simulate the thermal performance of the building envelope.

A four-story apartment building, a semi-detached house, and a single family detached home were selected as reference buildings to represent low income, middle income and high income housing units. Figure 4.1 shows an example for each building type. The simulated cooling capacities or AC system sizes of the cooled rooms include a safety factor of 15% to cater to cooling needs that exceed that of the design day/week. The study seeks also to quantify possible cooling energy use reduction due to interaction between the thermostat operation schedules and electricity use of the air conditioner. The operation schedules of the ACs used in the simulations are taken from the monitoring survey. Cooling behavior varies significantly with income class, especially for thermostat settings. Overall, part-time cooling

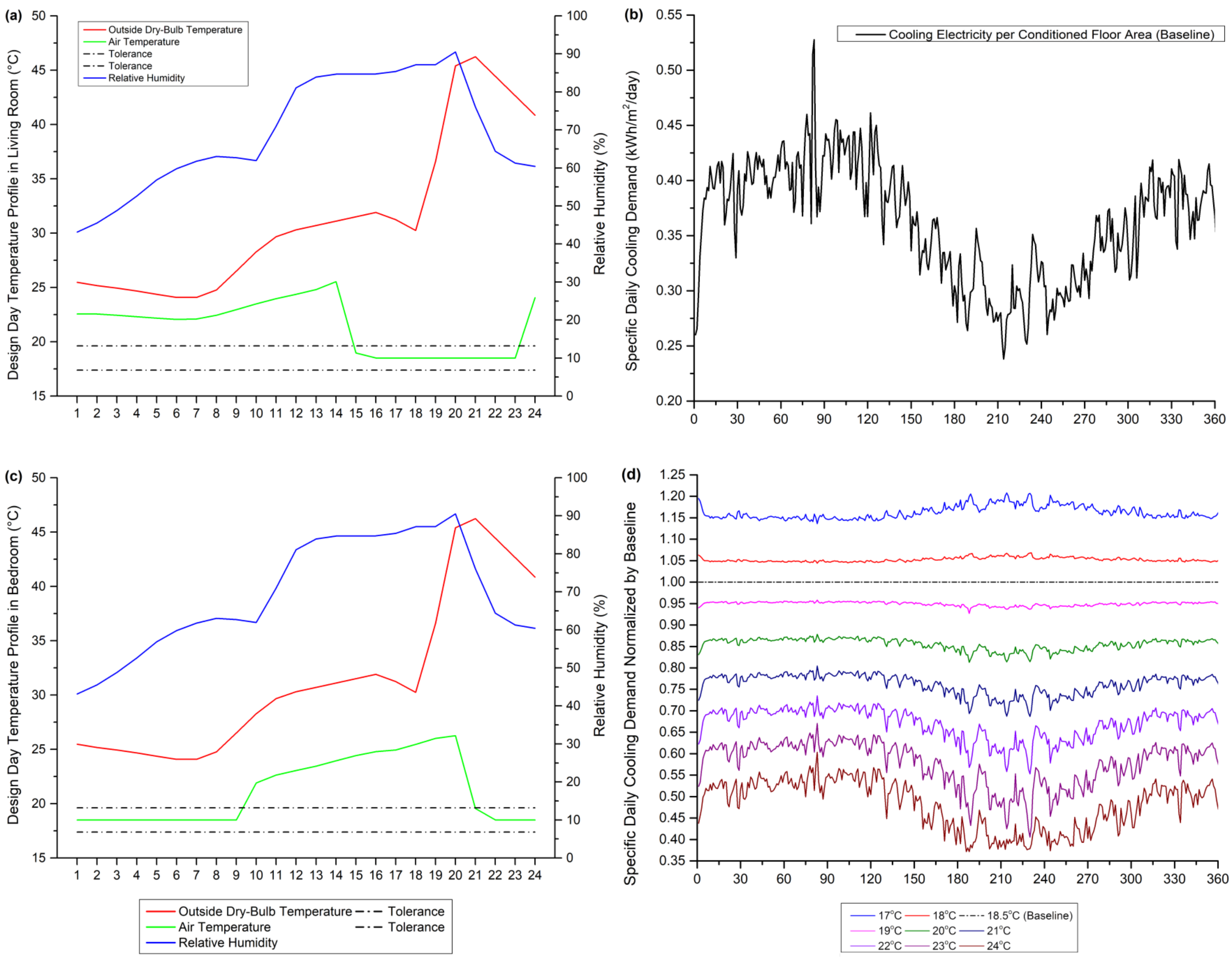

Figure 4.2: Daily cooling schedule living room/bedroom (a/c), Annual variation of cooling intensity baseline/per temperature setpoint (b/d).

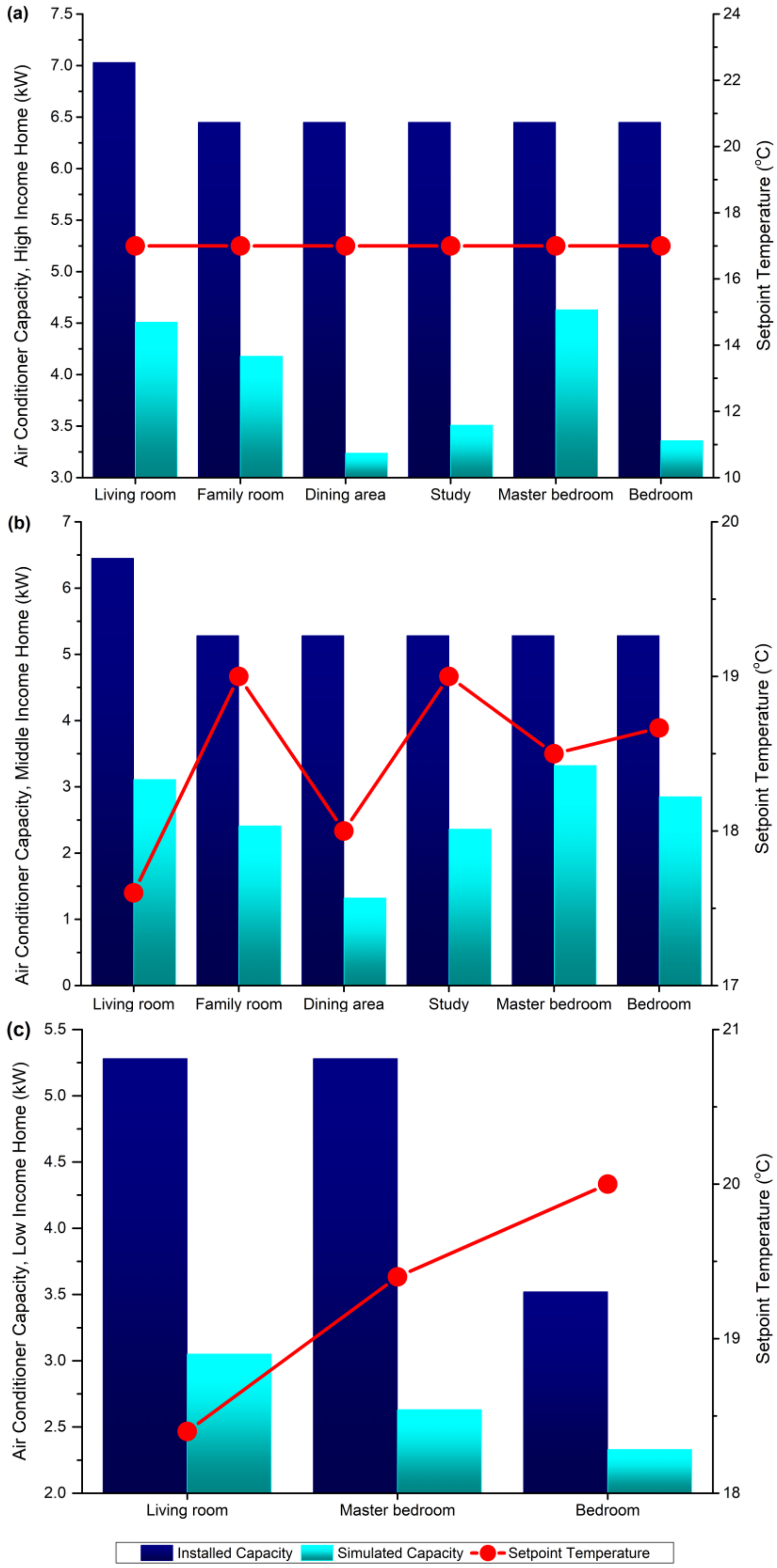

Figure 4.3: Installed capacity of air conditioners by income level.

with off mode during unoccupied periods is the most common cooling mode amongst the residents. The ACs are therefore assumed to be switched off during non-occupied and/or non-cooling periods in the simulations. Cooling period for living rooms is taken as between hours 15 and 23, and hours 21 through to 07 for bedrooms as shown in Figure 4.2 for the baseline setpoint temperature on the design day. The living room schedule is used where the dining area and living room spaces are combined as is the case for low income homes. The study room in high income homes was found to double as guest room. The AC operation schedule for bedroom was therefore assumed for the study room. Figure 4.3 shows that most high income homes maintain the same comparatively lower setpoint temperature of about 17°C on average in all rooms. For middle and low income homes however, thermostat setting varies per room function. Living rooms have lower setpoint temperatures than bedrooms, and master bedrooms have lower setpoint temperatures than other bedrooms. However, thermostat setting for each room in the middle income home is higher than that of the corresponding room in the high income home, and lower than that of the low income home. Overall, living rooms were set between 17°C and 18.5°C, master bedrooms between 17°C and 19.4°C, and other bedrooms between 17°C and 20°C for the three representative homes.

The approach used in this section involves two stages of simulations. In the first stage, control parameter input and screening is used to populate the model with as-built fabric, air conditioning parameters, lighting and occupancy schedules. A summary of input thermal properties for building materials in DesignBuilder is given in Appendix A.3. The input variables are further refined by identifying the most influential input parameters using measurement data in a reiterative process of adjustment until a final validated model is established. The model is validated by comparing simulated and measured cooling energy results using cumulative variation of root mean square error (CVRMSE):

$$\mathrm{CVRMSE} = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(M_i - S_i)^2}}{\frac{1}{n}\sum_{i=1}^{n} M_i}$$

where M_i is measured cooling energy, S_i is corresponding simulation result, i is running index, and n is the total number of measurements. CVRMSE indices were constructed over weekly intervals to obtain 16 period points over the study period. This index measures accumulated error normalized to the mean of the measured values and is therefore a good indicator of the overall prediction accuracy of the model.

In a second step, the validated model is used in the subsequent section to simulate variations in cooling energy intensity due to improvements in efficiency of air conditioner, changes in thermostat setting for cooling, orientation of the building with respect to geographic north, composition of building's wall, type of window, slope of roof as well as roofing, ceiling and flooring materials using the representative building as described below.

The validated three bedroom semi-detached model house was selected as the representative building for Tema city due to the following reasons:

- Semi-detached houses have historically had the highest share of building stock for both existing buildings and new developments in Tema city (Acquah 2001).
- There is biggest variety in this building type. It provides housing for all income classes i.e. low, middle and high income residents of the city. Its occupancy rate (i.e. number of residents per house) range from low, through moderate, to high based on income level.
- The low to middle income class, who reside historically in semi-detached houses in Tema city, is expected to be the highest driver of growth in new buildings and associated energy use (UN-Habitat 2011). This class will likely also undertake refurbishment to meet any future building energy standards.
- The simulation results for cooling energy consumption in this building type show very good (95 %) agreement with measured results of the electricity use monitoring survey. There is a high degree of confidence that the results of investigated parameters and developed recommendations are valid and closely align with the real Tema city. Energy savings estimated are thus 95% realistic.

4.1.1.1 Data and assumptions

Parameters such as glazing type, WWR, EER, cooling setpoint temperature and building occupancy were collected through surveys of both existing buildings and design drawings of new construction from Tema Development Cooperation. The low income semi-detached house has a living room and two bedrooms. The middle income apartment building has in addition, a third bedroom and designated dining area while the high income detached house has a fourth bedroom as well as designated family room. Living rooms and bedrooms represent conditioned spaces in all building types. Where present, dining and family rooms add to the amount of conditioned spaces. The ratio of conditioned area to total floor area per building is between 58% and 65% as shown in Figure 4.4. Floor area, conditioned area as well as simulated cooling energy intensity/cooling energy consumption are assumed to represent averages of such building types in the city. The representative building shown in Figure 4.5 houses a family of four, which is the average household size

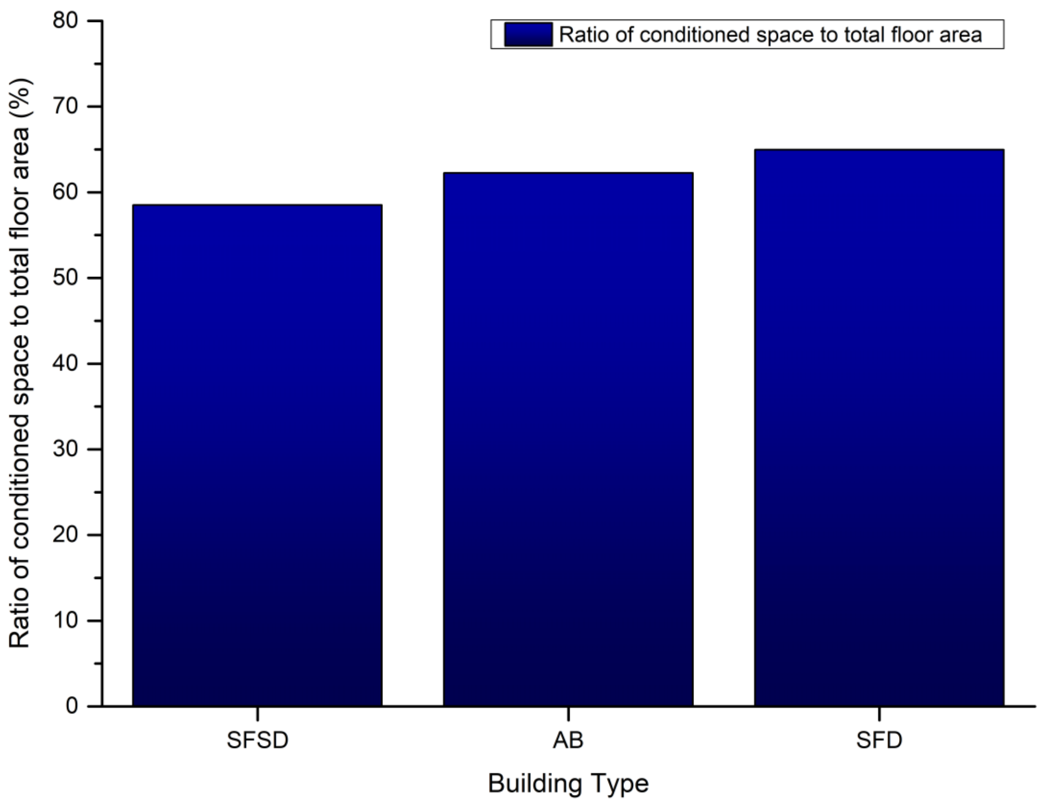

Figure 4.4: Share of air-conditioned floor area by building type.

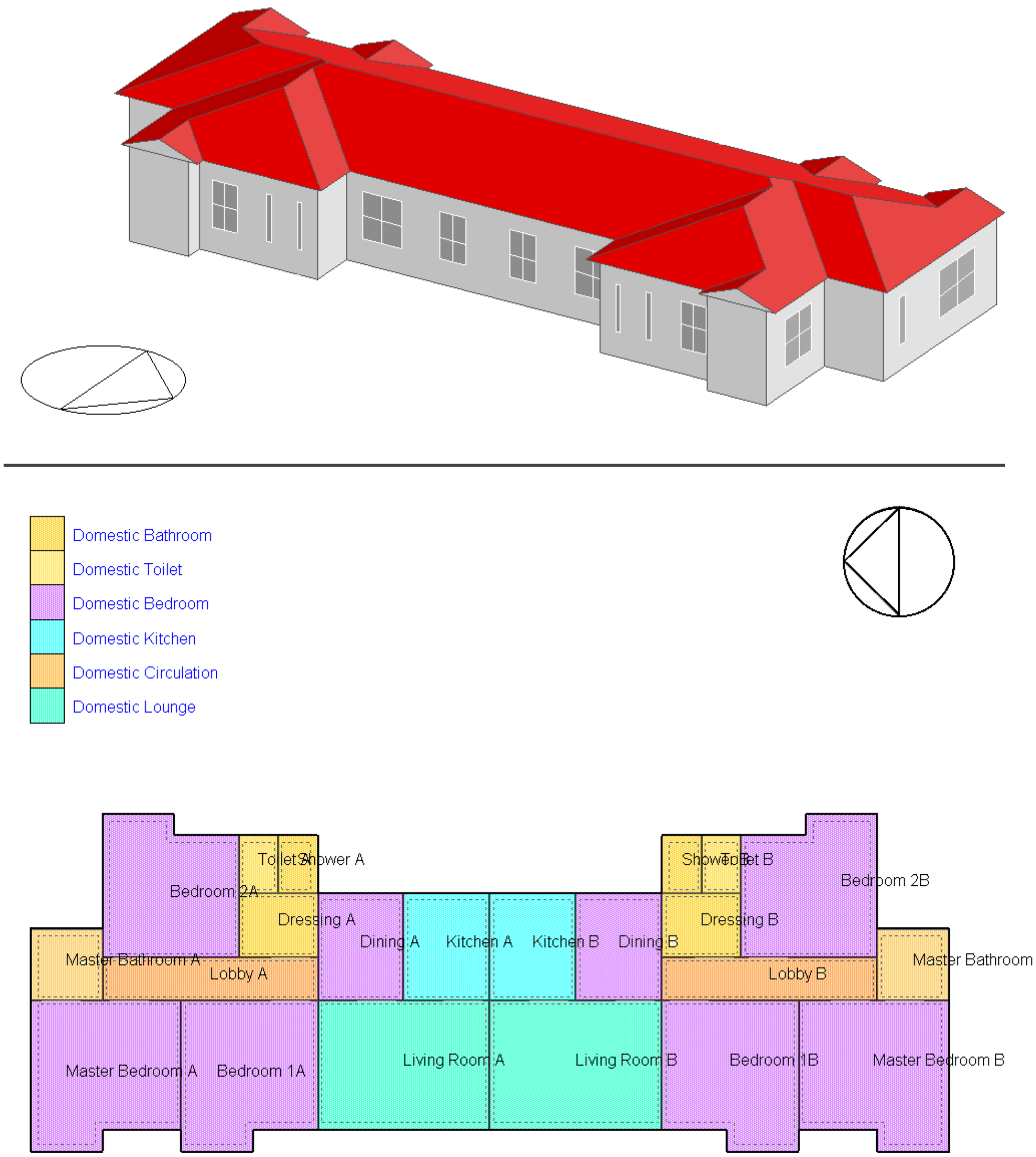

Figure 4.5: Representative building modelled in DesignBuilder, 3D view and room plan.

in Tema city (Nyarko 2014a). The conditioned section of the building is approximately $60m^2$ and comprises a living room with dining area combined, a study and two bedrooms based on occupancy level of two people per bedroom as found in the survey. Room sizes are averages adapted from Tema Development Cooperation's house type and plan (TDC Development Company Limited 2017).

4.1.1.2 Local climate consideration

Changes to the annual cooling energy use in residential buildings depend on climate, wall construction, building orientation, air conditioner efficiency and operating schedule (Rosado and Levinson 2019). Therefore the first and foremost task required in modelling the cooling energy demand of future buildings in Ghana for the purposes of establishing energy efficient retrofit solutions, is to understand the climate zone difference between Ghana and other parts of the world vis-à-vis retrofit solutions that have yielded significant energy savings. Based on surface observations of climate zone change variability between 1981 and 2005, ASHRAE in partnership the US Department of Energy have developed climate zone maps for development of building energy codes (Stackhouse Jr. et al. 2015).

Figure 4.6 compares Ghana's climate zones to global climate zones of ASHRAE Standard 169-2013. About 20% of northern Ghana experiences extremely hot humid climate which falls within ASHRAE zone OA while the rest of the country is categorized in zone 1A with very hot humid climate. The case study, Tema city, is located in the very hot and humid zone 1A with comparable cooling degree days (i.e. $5000 < CDD10^oC \leq 6000$) as Hawaii, Guarft, Puerto Rico and the Virgin Islands of the United States. California which has been the subject of several studies, is categorized into seven zones namely 2B, 3B, 3C, 4B, 4C, 5B and 6B which have hot dry, warm dry, warm marine, mixed dry, mixed marine, cool dry and cold dry climates respectively, with a range of $1000 \leq CDD10^oC \leq 5000$ cooling degree days for the first five zones and heating degree days range of $4000 < HDD18^oC \leq 5000$ for climate zone 6B (Stackhouse Jr. et al. 2015).

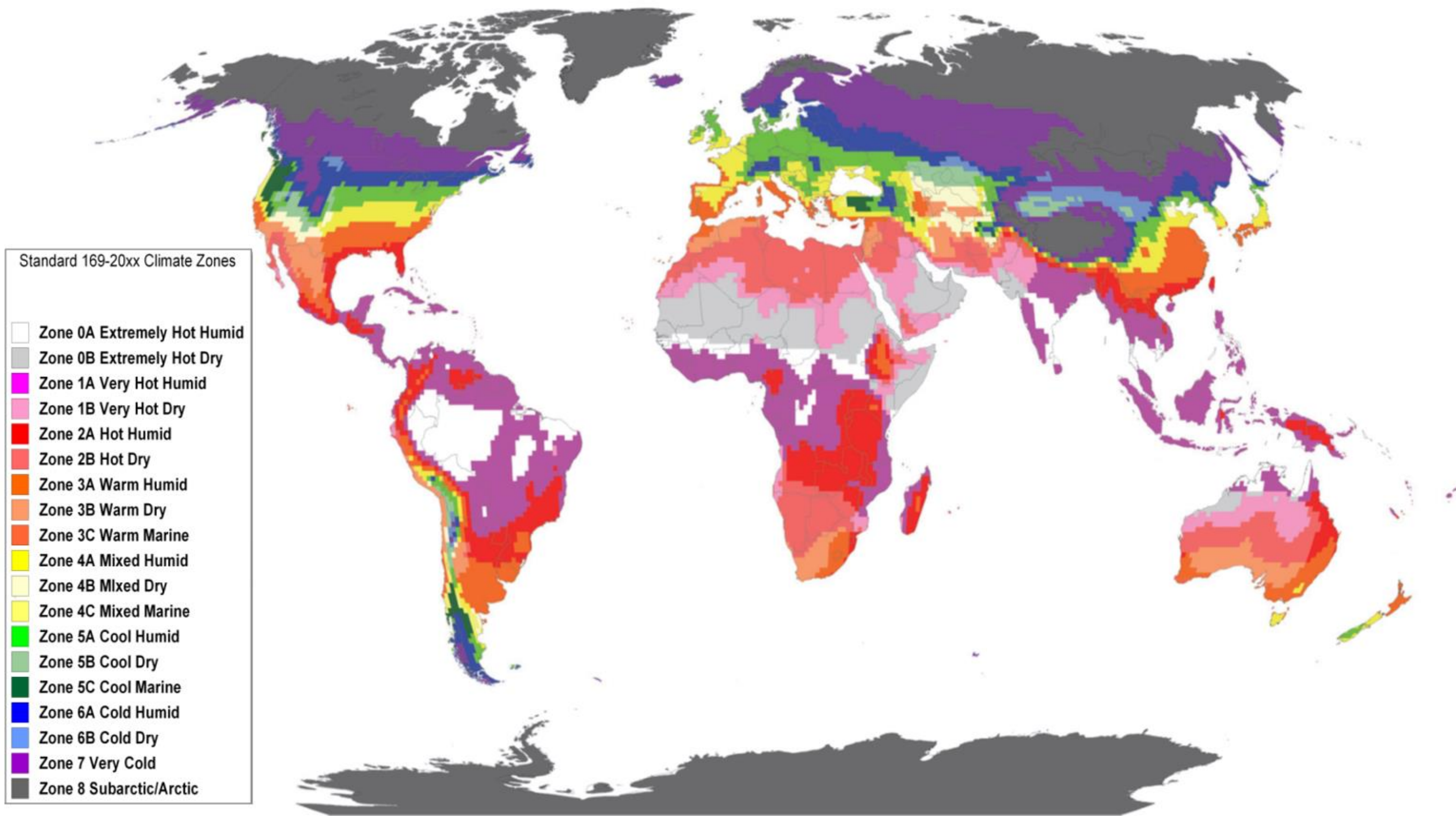

Figure 4.6: Global climate zone map according to ASHRAE Standard 169-2013 (Stackhouse Jr. et al. 2015).

Ghana's climate differs from that of California in two main ways. Firstly, Ghana is humid while California is dry and marine. Practically this means that at the same temperature, it will feel warmer in Ghana than in California because the high moisture content in Ghana's air significantly reduces the cooling effect of perspiration. Secondly Ghana is hotter, and homes require cooling for longer duration than the hottest climate zone 2B of California with a difference of 1000 CDD. This is why it is fundamentally important for Ghana to determine the indoor comfort threshold and boundary conditions for simulation calculations based on its own cooling energy needs, so that standards and regulations for residential building energy efficiency can be based on its local national conditions, climate and building characteristics, living habits and building energy consumption. Due to lack of relevant data and experience, the energy efficiency and sustainability section of Ghana's Building Code provides no information on acceptable efficiency levels or acceptable energy intensity levels for the building envelope or installed equipment. Instead it states that the Efficiency Standards for Residential and Non-Residential buildings (2008) by the California Energy Commission are relevant. This adoption of California's standards, whose core technical indicators are based on California's climatic conditions, leads to grave inaccuracies in analysis results of the energy performance of Ghana's residential buildings. Cooling equipment that are sized based on this standard stand the risk of being undersized due to neglect of the effect of high humidity on cooling in Ghana.

To address this issue, a 25-year historic hourly real weather data that captures extreme weather conditions for Accra Ghana was downloaded from WMO region one Station 654720 and installed in DesignBuilder as an EnergyPlus Weather (EPW) file, which is then used for the simulations (Solar and Wind Energy Resource Assessment SWERA 2017). The year 2002 exhibited the most extreme weather conditions. Based on that year's data, the coldest month is June and the hottest month is March. The maximum dry bulb temperature of 47.6°C occurs on March 23 while the minimum dry bulb temperature of 18.0°C occurs on June 20. The extreme hot week period (i.e. the design week) was March 19 - March 25 while the extreme cold week period was July 30 – August 5. Basing on the hourly weather data in this file, the annual CDD was reported as 6161 at 10°C baseline, and 3241 at 18.0°C baseline. There is no heating requirement with zero annual heating degree days at both baselines.

4.1.2 Simulation of cooling energy efficiency levels for the representative building

The most influential building fabric parameters identified in section x are used to generate possible building cooling energy efficiency levels based on the stage of building development as shown in Table 4.1. Two efficiency levels were developed in addition to the baseline (i.e. business as usual, BAU). The BAT efficiency level uses the most energy-efficient (best available technology) options of the seven considered parameters for new construction, and the most energy-efficient windows and air conditioners for retrofit in completed buildings. The medium efficiency level uses options with median energy efficiency performance under all seven parameters for new construction, and median energy-efficient windows and air conditioners for retrofit in completed buildings.

4.1.2.1 Scenario definition

The scenarios created are based on building cooling energy efficiency level and retrofit rate of base year buildings to the year 2050. The choice of retrofit rate as a scenario indicator is related to the fact that not all existing buildings in the base year will be retrofitted by 2050, and the amount of potential energy savings due to energy efficiency retrofit in the short, medium and long term is linked with the rate at which existing homes undergo such retrofit. Three scenarios were created for building energy efficiency retrofit rates. The specific definition of scenario parameters is shown in Table 4.1.

Table 4.1: Definition of building efficiency levels.

Building Parameter	Baseline	Moderate efficiency retrofit	BAT[1] retrofit	Moderate efficiency, new build	BAT[1] new build
Setpoint Temperature (°C)	18.5	18.5	18.5	18.5	18.5
Retrofit Rate (%)	2.5	5	10	-	-
EER of AC (W/W)	2.8	3.8	5.8	3.8	5.8
Window Type	Sgl clr 6mm	Sgl clr 6mm, louvre 0.5m	Dbl clr 6mm/6mm, air, louvre 0.5m	Sgl clr 6mm, louvre 0.5m	Dbl clr 6mm/6mm, air, louvre 0.5m
Wall Type[2]	Solid Block, 125mm	Solid Block, 125mm	Solid Block, 125mm	Hollow Block, 150mm	Hollow Block, 225mm
Building Orientation	South	South	South	South east	East
Roof Slope (°)	20	20	20	25	30
Roof Material	Roof tile	Roof tile	Roof tile	Aluzinc sheet	Aluminum sheet
Ceiling Material	Plywood, lightweight	Plywood, lightweight	Plywood, lightweight	Plywood, heavyweight	Wood panel

[1] *Best available technology currently on the Ghanaian market*
[2] *Refers to type and thickness of block units, all internal and exterior walls have 25mm cement mortar plastering on both sides of the wall*

4.1.2.2 Data and assumptions

Transition to energy efficient residential cooling is assumed to take place over a 30 year period beginning in 2020 as the base year. The population of Tema city is assumed to maintain an average annual growth rate of 2.6 percent within this time (Arup 2016). The average household size of four is assumed for the transition period (Nyarko 2014a). For each year the quotient of projected population growth and average household size gives the projected number of newly added households. The population of Tema city is projected as 369805 in the base year 2020, and 806720 in the year 2050 as shown in Figure 4.7. Based on these population figures, the total number of households in the city is shown as 91447 in the base year, and doubled in 2050 to 198012 households. The projected number of households by 2050 represents a growth of about 280% in the number of households reported in the district analytical report of the 2010 population and housing census for Tema metropolitan area. Newly constructed buildings and corresponding floor area to accommodate the projected growth in households is assumed to have a net conditioned area of $60m^2$ per household. Since one building can be occupied by several families with shared walls, floor/ceiling as is the case in apartment buildings, duplexes, semi-detached houses etc., a home is used in this section to represent a household that occupies a floor space in a residential building which may or may not be shared with other households.

The established energy efficiency-based scenarios are assigned retrofit rates for existing buildings in the base year. The shares are based on direct comparison of Ghana and Europe's building construction sectors. The annual construction rates in the EU residential sector is about 1% and energy efficiency retrofit activities average around 0.4 – 1.2% each year, echoing the impact of the financial crisis in the construction sector as well as the EU focus on refurbishment (Camarasa et al. 2019). Ghana's construction sector on the other hand was the largest subsector of industry in 2015, with a growth rate of 30.6% and a 14.8% share of GDP. It has grown consistently over the past five years, up more than 70% since

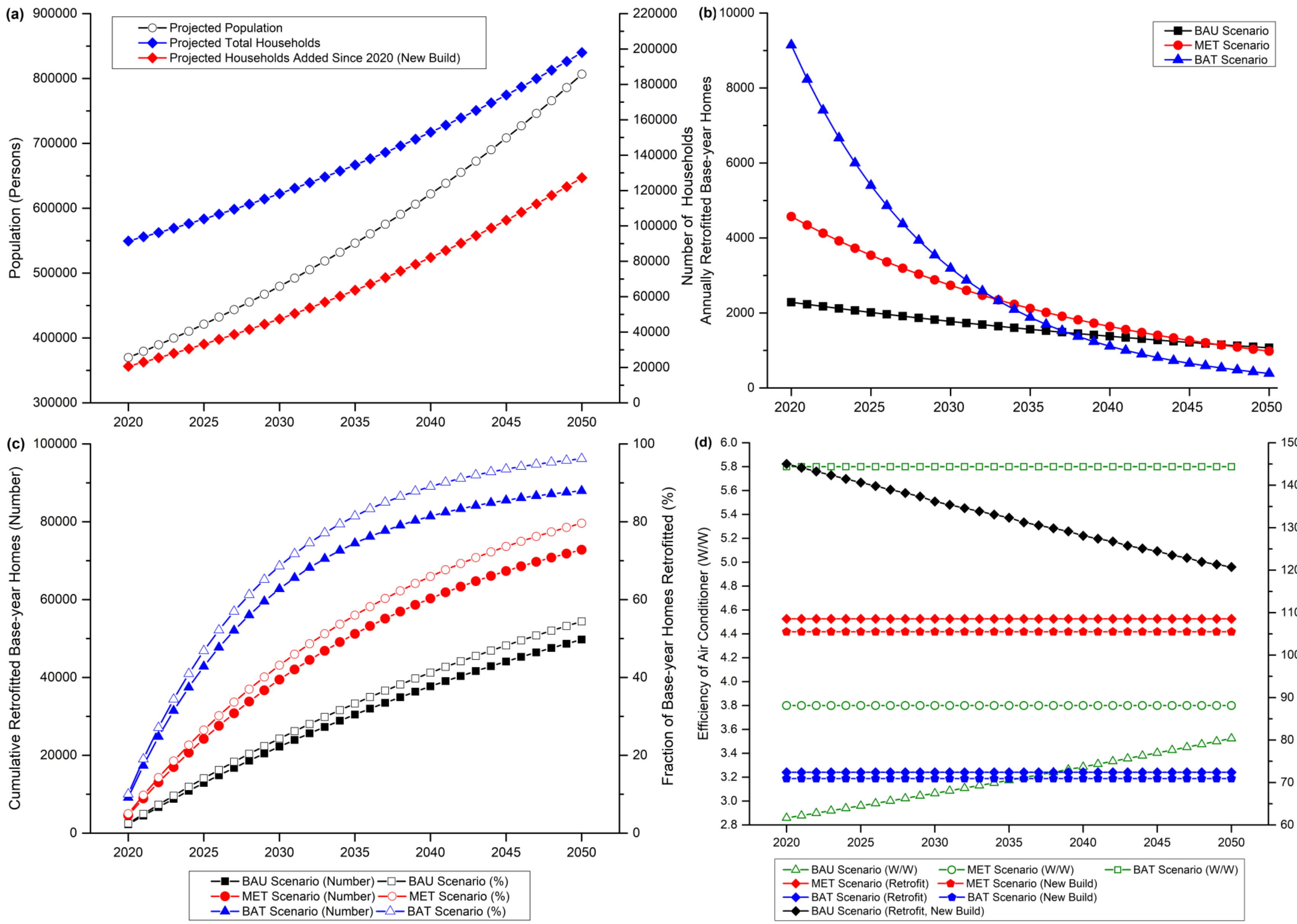

Figure 4.7: Definition of cooling efficiency scenarios: Population growth, Annual Retrofits, Cumulative Retrofits, AC efficiency (top left to bottom right).

2010 (Oxford Business Group 2020). Retrofit rates in Ghana follow trends in new construction to achieve competitive pricing on the real estate market. Owing to a robust economy and the government's reform program, various segments, from high-end residential real estate to industrial and logistics property, are performing strongly. Growth is set to continue (Oxford Business Group 2019). Construction is used as proxy for renovation/retrofit to reflect booming housing development. The business-as-usual (BAU) scenario assumes retrofitting of existing base year buildings at an annual rate of 2.5 percent, while the MET and BAT scenarios assume 5% and 10% respectively. The city has 91447 homes at the beginning of 2020 out of which 2286, 4572 and 9145 homes are retrofitted respectively for the BAU, MET and BAT scenarios by the end of 2020 as shown in Figure 4.7.

All three scenarios show fall in the number of homes retrofitted per year, which is expected because the number of remaining energy inefficient base year buildings in any given year is reduced by the number of retrofitted buildings in the previous year. However, the BAT scenario indicates propensity to yield the highest short to medium term energy savings due to its fast conversion rate. This is evident in 2038 when BAT retrofits begin dropping below that of the other two scenarios and continues till 2050 where retrofitted BAT homes are 63% less of BAU and 60% less of MET despite having the highest conversion rate. The MET and BAU scenarios on the other hand show lower initial conversions but decrease slowly and steadily over the years, indicating propensity to yield higher medium to long term energy savings. By the end of 2050, about 96%, 80% and 54% of the base year buildings would be retrofitted respectively for the BAT, MET and BAU scenarios.

Figure 4.7 shows the simulated cooling energy intensity and efficiency of air conditioners (EER) for each scenario. The BAU scenario maintains baseline building fabric parameters and follows historical trend of 0.7% year on year improvement in air conditioner efficiency starting at 2.86 in 2020 (Agency 2007). The cooling energy intensity of the BAU scenario therefore reduces with increasing air conditioner efficiency from 145 kWh/m^2/year in 2020, to 121 kWh/m^2/year in 2050. BAU retrofit is assumed to be limited to replacement of retired air conditioners only. The medium efficiency technology (MET) scenario uses medium efficiency parameters described in Table 4.1 with cooling energy intensity of 105 kWh/m^2/year for new construction and 108 kWh/m^2/year for MET retrofit of base year buildings. Due to lack of resources such as testing laboratory with adequately trained staff and modern equipment, there is lax in enforcement of energy efficiency labelling programs particularly by customs officials, wholesalers and retailers (Agency 2007). Resultantly the efficiency of air conditioners on the Ghanaian market remains low with the prospect of only a small improvement in the future (Agency 2007; Gyamfi et al. 2018). Therefore a constant EER of 3.8, which is the higher average of surveyed energy efficiency compliant air conditioners, is assumed for the MET scenario. Figure 4.7 shows that by 2050 this constant 3.8 EER for the MET scenario is still higher than the 3.52 EER for the BAU scenario after applying the 0.7% year on year efficiency improvement. The BAT efficiency scenario uses BAT efficiency parameters described in Table 4.1 with cooling energy intensity of 71 kWh/m^2/year for new construction and 72 kWh/m^2/year for BAT retrofit of base year buildings. Similar to the scenario, the BAT scenario maintains a constant EER of 5.8 which is the highest of surveyed energy efficiency compliant air conditioners, available on the Ghanaian market.

Potential energy savings estimated in following sections assume that living rooms and bedrooms in all projected homes will be cooled. This assumption overestimates air conditioner penetration in the short term but becomes increasingly accurate in the medium-term to long-term view, as new buildings mostly come with air conditioners and greater shares of the residential population are able to afford conditioned cooling.

4.2 Results

4.2.1 Model validation

Figure 4.8 presents microscopic validation of the model at the building level. It gives a visual overview of the measured and simulated cooling energy consumption for investigated buildings and their statistical variations over the study period by arranging paired data points in weekly interval. The total electricity consumed for cooling by air conditioning within the study period is respectively 991 kWh, 2469 kWh and 1881 kWh for the three bedroom apartment, four bedroom detached house and three bedroom semi-detached house. The final validated model produced a sum of 953 kWh, 2366 kWh and 1844 kWh to yield corresponding deviation of 4.06%, 4.31% and 2.01% respectively for the three bedroom apartment, four bedroom detached house and three bedroom semi-detached house. The measured cooling energy consumption in all three building types quite clearly surpasses the corresponding simulated energy use. The degree to which measured and simulated energy consumption profiles match have can be quantified by the coefficient of variation of the root mean square error (CVRMSE). This metric is defined in ASHRAE Guideline 14 and considers a model calibrated if its hourly CVRMSE values fall below 30% and monthly values are below 15% (Royapoor and Roskilly 2015; Shin and Lok 2016; Glasgo, Khan, and Azevedo 2020). The four bedroom detached house carries the largest cumulative error with CVRSME at 9.8% followed by the apartment building at 7.02% and least by the semi-detached house at 5.27%. The differences could be attributed to individual occupant activity pattern that deviates more randomly from the average values used in the EnergyPlus model. Another explanation could be the model's use of design temperature from a 30 year historic local weather data and static setpoint room temperature as opposed to actual temperature during the study period in 2017 as well as varying setpoint room temperature in response to occupants' thermal comfort level. Available data indicates that Ghana's average daily temperature has increased by 1°C over the past 40 years (C. Dela Doe 2018).

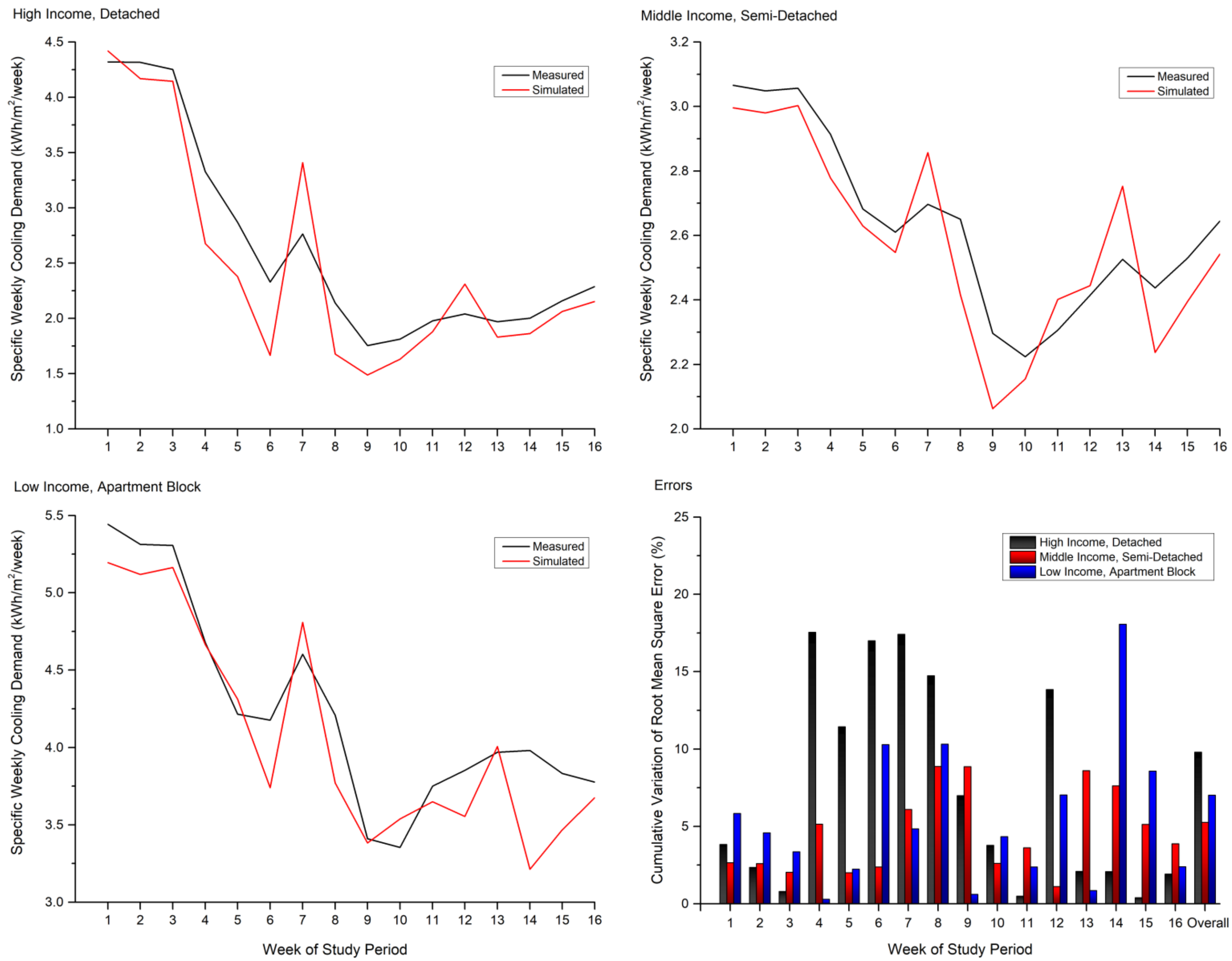

Figure 4.8: Cooling energy demand for detached house, semi-detached house and apartment block: Simulation and measurement.

There is no city-level data on actual residential cooling energy use or the broader residential electricity consumption for direct comparison with simulation results. Nonetheless, the accuracy of the baseline modelling was checked against the sum of measured cooling energy use in all monitored homes. Figure 4.9 presents the macroscopic validation of the model. The simulated energy use for cooling is 35 MWh as compared to the measured 37 MWh. The model underestimates the cooling energy consumption of the monitored homes for the June to September 2017 study period with a relative error of 5.42%. Based on this validation; it is assumed that the developed simulation model can be used for extrapolation of cooling energy demand to the entire year, January to December. It can be concluded that the model in this study is validated and well suited for accurate prediction of electricity use for cooling in urban Ghanaian homes.

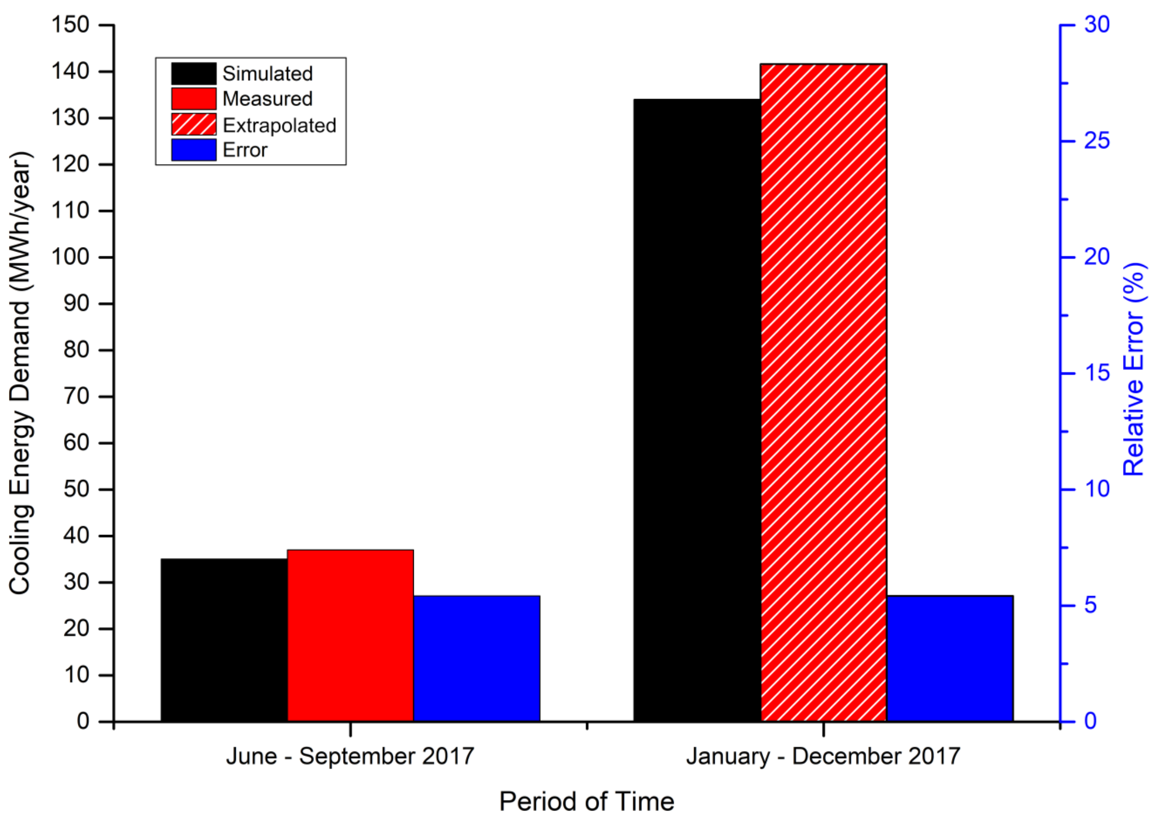

Figure 4.9: Cooling energy demand of monitored household sample: Simulation, measurement and annual extrapolation.

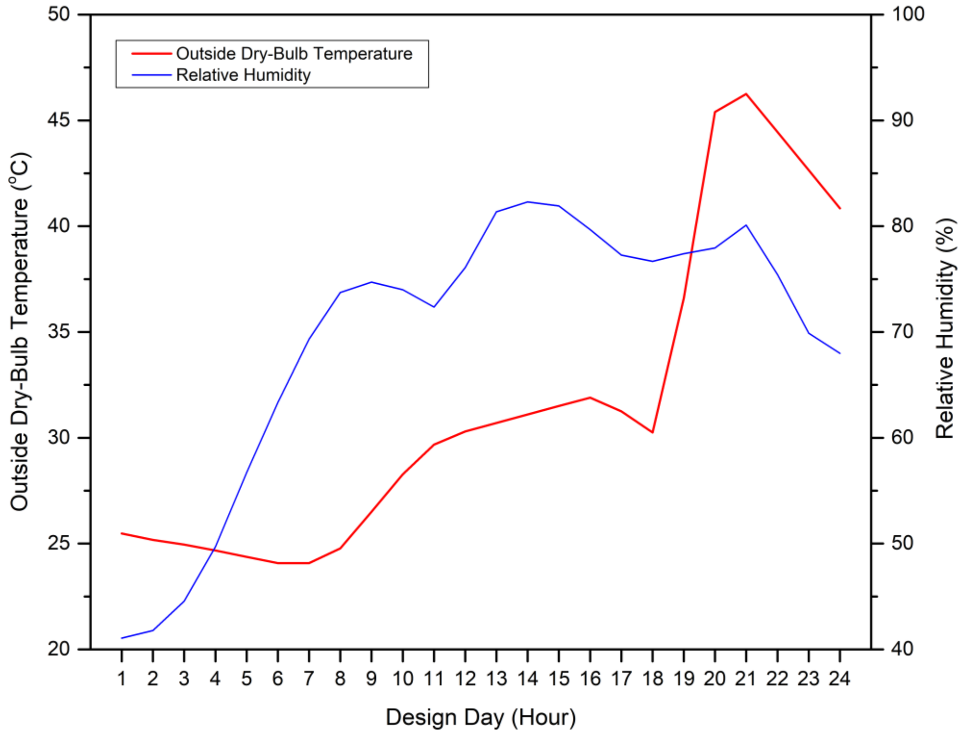

Figure 4.10: Ambient conditions of the design day used for AC sizing.

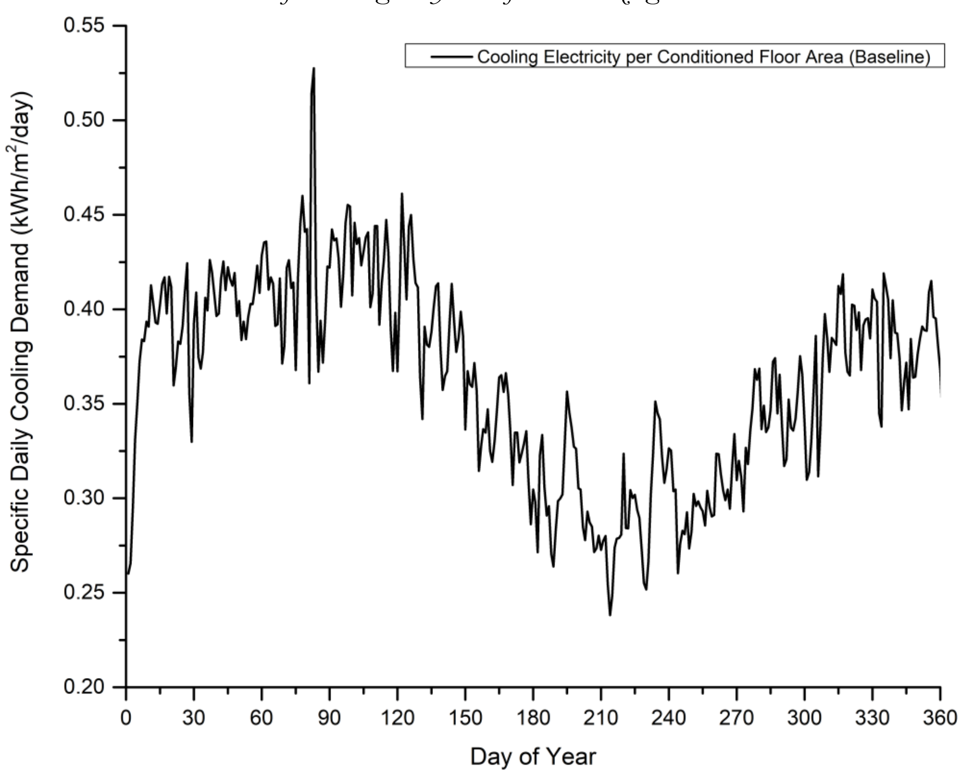

Figure 4.11: Baseline variation of daily cooling intensity over the year.

4.2.2 Efficiency of air conditioner

The minimum energy performance standard for air conditioners in Ghana is an energy efficiency ratio of 2.8 watts of cooling per watt of electricity input (Commission 2016), and is reported in the simulation interface as coefficient of performance (EER) of the cooling system. It was found during the monitoring study that pack terminal air conditioners and unitary split air conditioners respectively represent 29% and 71% of cooling systems of residential buildings in Tema city. About 85% of these had readable energy efficiency labelling which met the minimum standard. Centralized or multi-split cooling systems were not encountered. Therefore, unitary split air conditioner was selected as the representative cooling system based on this observation. The EER of an air conditioner by definition directly affects the amount of electricity used in cooling the building. The EER of the representative building's cooling system was varied between 2.8 and 7.8 W/W at an incremental value of one, with 2.8 as the baseline. Figure 4.10 shows temperature and humidity profile on the design day. Variation of the specific daily cooling energy demand over the year is shown in Figure 4.11 and totaled 148kWh/m^2/year for the conditioned building area. January to April have the highest cooling energy demand averaging about 400Wh/m^2/day, followed by October to November with an average of about 350Wh/m^2/day, and May to August at the lowest with an average of about 300Wh/m^2/day.

Figure 4.12 (a) shows the building's daily cooling energy intensities for all the investigated efficiency levels. As expected, the amount of electricity used in cooling the building reduces very significantly as the efficiency of the cooling system increases. The specific daily cooling demand normalized by baseline in Figure 4.12 (b) shows that about 25% of electricity is saved when the efficiency of the cooling system increases from 2.8 to 3.8 W/W, and a little over 50% of electricity is saved when EER increases further to 5.8 W/W. These highly significant energy savings are 95% realistically achievable given 5% model error, and considering that air conditioners with EER between 3.8 and 5.8 are currently available locally on the Ghanaian market (Commission 2016; Daikin Europe N.V. 2012; Gyamfi et al. 2018). There would still be room currently for further improvement due to availability of air

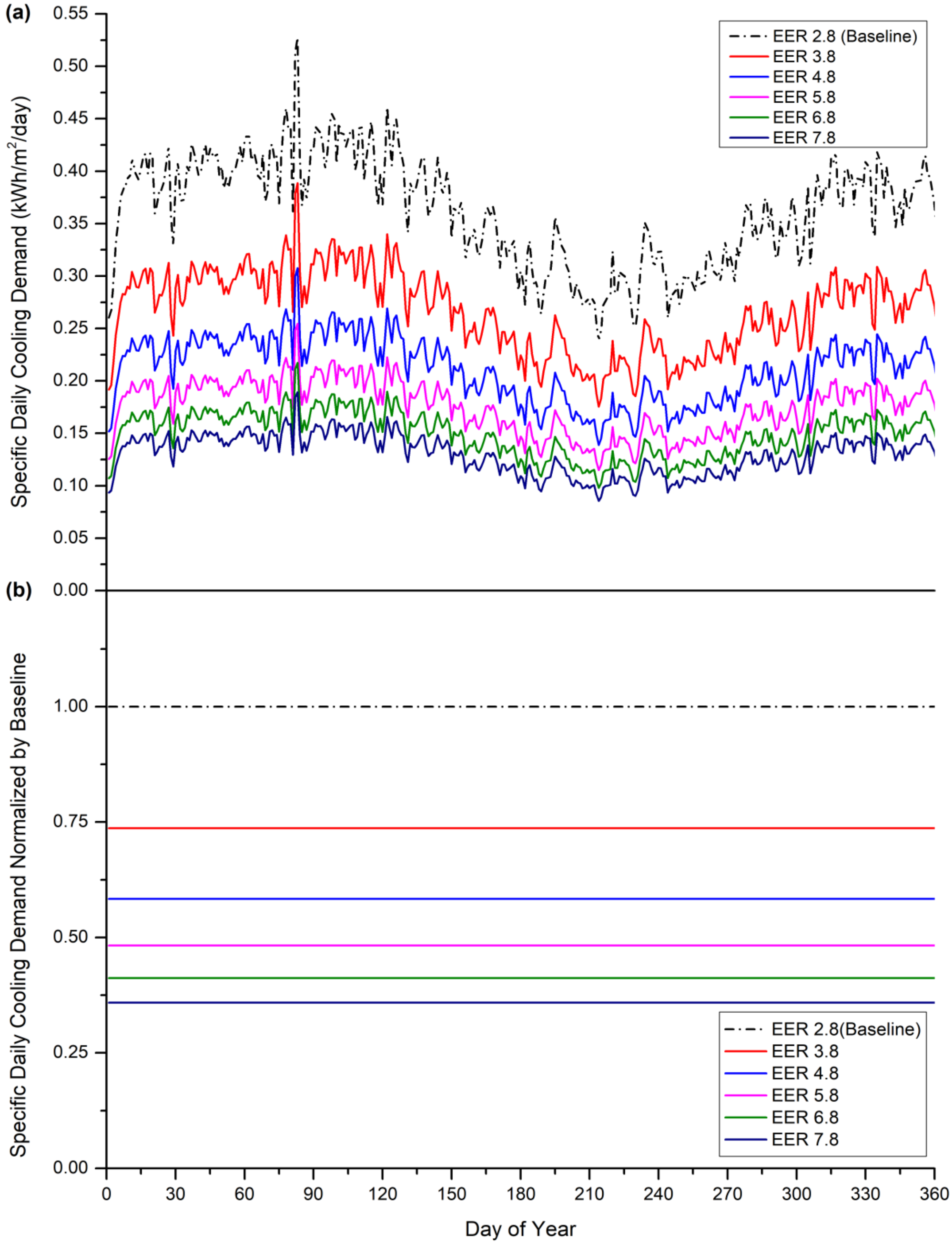

Figure 4.12: Cooling intensity as function of EER, absolute (a) and normalized by baseline curve (b).

conditioners with even higher efficiencies (i.e. EER 7.8 and above) for sale on the international market (Top-Ten 2019).

In light of these findings, it is recommended that building designers and architects in Ghana consider the cooling system, which is conventionally not considered currently when optimizing the energy performance of the building form and envelope in the early building design stages. The use of an efficient cooling system has the potential to achieve better trade-offs between two conflicting objectives of achieving optimized cooling and daylighting performance of the glazing (K. W. Chen, Janssen, and Schlueter 2018).

4.2.3 Thermostat setting (setpoint temperature)

Nine thermostat settings were chosen for simulations based on the most common setpoints found in the monitoring study and REC survey for Tema city as a whole. Setpoints for the monitored households ranged between 17°C and 24°C. About 62% of households set their AC to 18.5°C. Based on these observations, setpoints between 17°C and 24°C were chosen, with 18.5°C as baseline and tolerance level of plus or minus 1.1°C. It appears that the thermal comfort levels of residents in Tema, Ghana are at lower temperatures in comparison with residents of other cities around the world. For example setpoint temperature ranging between 21°C and 26°C has been reported for eight hot summer cities of the Yangtze River Basin in China (Guo et al. 2019), and ASHRAE 55-2013 specifies between 23°C and 27°C for summer months in the United States (Standard 2013). The apparent lower temperature requirement for thermal comfort in Tema, Ghana could be explained by the relatively higher humidity levels which render the cooling effect of perspiration less effective. Mean monthly humidity is over 75% and reaches over 80% June through September (World Weather & Climate Information 2020).

It can be seen that it takes about an hour to cool the rooms to the desired temperature. While the living room cooled, a 15°C spike in outside dry bulb temperature that lasted an hour had no impact on the air temperature of the room. This confirms adequate AC sizing by the model. Comfort level is defined in this section as the number of hours that the setpoint temperature is unmet during occupied cooling for a year. This value was zero hours per year for setpoints between 17ºC and 21ºC, and 0.5 hours per year for setpoints between 22ºC and 24ºC.

The specific daily cooling demand normalized by baseline in Figure 4.2 (d) shows that, cooling energy intensity of the building increases with decreasing setpoint temperature and vice versa. Electricity use for cooling increases by about 10% for every 1ºC decrease in the setpoint temperature. Therefore a 3ºC increase in setpoint temperature could effectively lower the amount of electricity required to cool the same room by about 30%. These results compare well with a similar study of a residential building in the hot summer of Xiamen, China which found that the annual cooling power consumption was linear with the cooling setpoint temperature, and the energy consumption could be decreased by 6% with 1ºC increase in setpoint temperature from 26 ºC.

4.2.4 Orientation

The increase or decrease in the cooling load yielded by a building facet is directly proportional to the sunlight intercepted by its walls and windows. Building facets that receive more sunlight throughout the year and belong to a cooled room are therefore expected to contribute more to changes in cooling load. Consider a square building with walls facing east, west, north and south at the southern end of the northern hemisphere, in the so-called tropics where Ghana is located. The noon sun appears in the northern sky for a considerable period of time. At the equinoxes in March and September, the sun's path follows the celestial equator and rises directly east and sets directly west. The east and west walls of the building are expected to receive similar daily solar radiation due to the east–west symmetry of the solar path. Beam solar radiation strikes the east wall in the morning and the west wall in the afternoon. After the March equinox, the sun's path gradually drifts northward. By the June solstice, the sun rises in the northeast and sets in the northwest with peaks in the northern sky close to the zenith. The north wall will therefore only receive solar beam radiation during this period which is typically between early April and September.

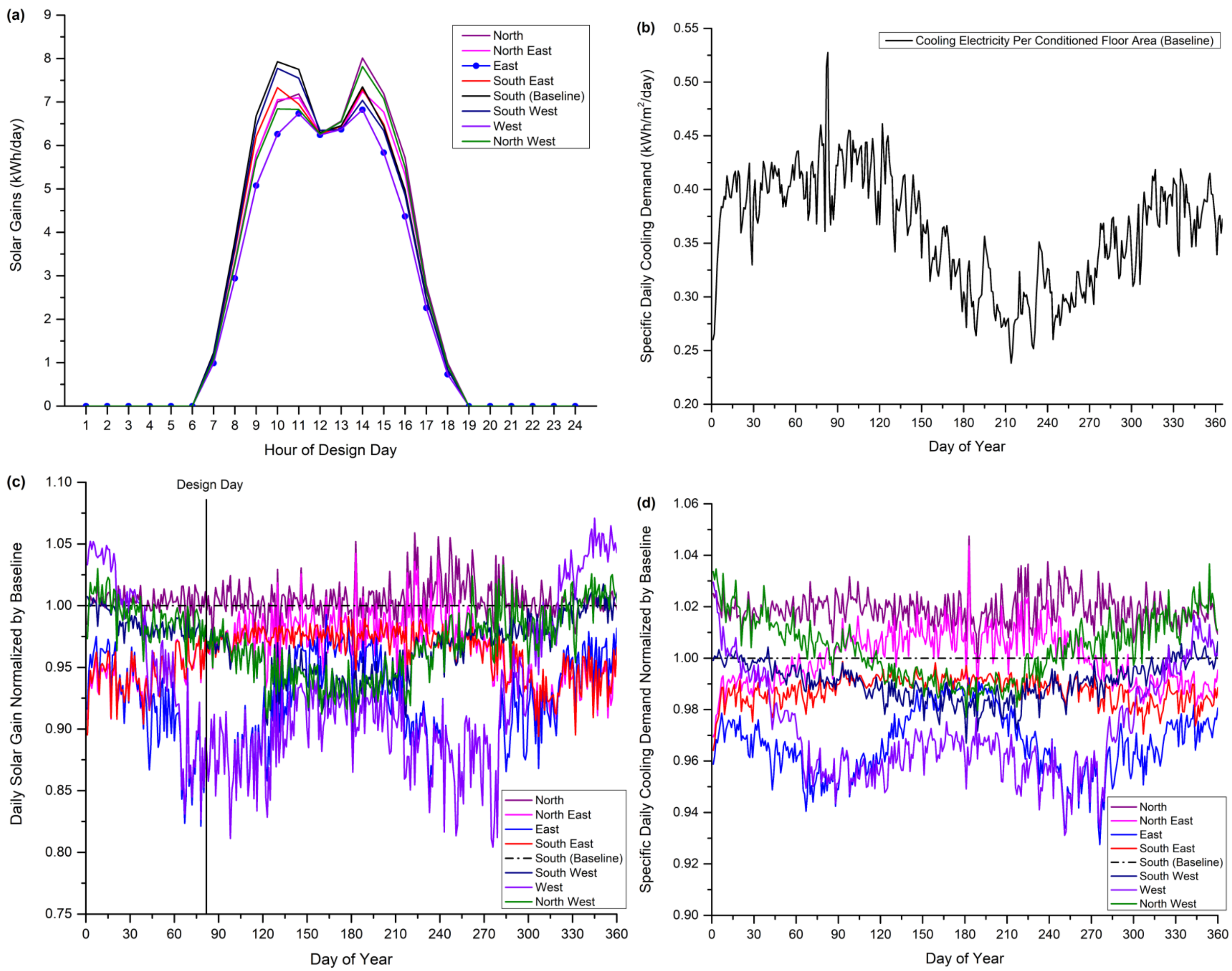

Figure 4.13: Variation of solar gain over orientation: daily (a), annual (c). Annual cooling intensity: baseline (b), over orientation (d).

These months are predominantly within the rainy season in Ghana and comparatively colder (Meteoblue 2018). After the June solstice, the sun's path gradually drifts southward. By the September equinox, its path is again along the celestial equator. The southward drift then continues until the December solstice, when the sun rises in the southeast and sets in the southwest with peaks in the southern sky at a smaller elevation angle. The south wall will therefore only receive solar beam radiation during this period which is typically between late September and late March. These months predominantly belong to the dry season in Ghana and are comparatively warmer (Meteoblue 2018). After the December solstice, the sun's path drifts northward again, returning to the celestial equator by the March equinox (Schroeder 2011). Given the differences in exposure to daily solar radiation based on orientation, the north wall will have the lowest annual cooling energy intensity, followed by the south wall. The east and west walls will have the highest annual cooling energy intensities. Applying this to the representative building, it is expected that aligning the building east-west so that majority of the cooled rooms is oriented north, will yield the lowest annual cooling energy demand among all other directions.

The orientation of the representative building was varied between 0 degrees and 360 degrees at 45 degrees interval to capture the four main cardinal directions and their corresponding ordinal directions. Orientation at 180 degrees represented as south, was used as baseline. Results of simulated daily solar heat gains over the year for considered orientations are shown in Figure 4.13 (c). All directions have similar minimum solar heat gains in the rainy and relatively colder months of June and July (i.e. day 150 – 210). The pattern of solar gains from January to June has close resemblance to that of July to December. Orienting the building east or west resulted in the lowest annual heat gains as expected, similar to the design day gains but with interesting monthly dynamics. West receives about 10% more solar heat than east for January, November and December while east receives about 5% more heat in June and July due to the relative positioning of the sun as described earlier. Solar heat gains for east in March, April, May, August, September and October are almost the same as west as evident on the design day which was on March 23rd.

The normalized specific daily cooling energy demand in Figure 4.13 (d) shows that, orienting a residential building in Tema city east (i.e. 90 degrees to the north), so that external walls of the conditioned spaces align north, results in the lowest (96%) electricity use for cooling due to lower solar heat gains within the day and throughout the year. On the other hand, orienting the building north so that external walls of the conditioned spaces align east-west, results in the highest (102%) electricity use for cooling. These results are consistent with findings of a similar study on California and the United States that used simulations of a single-family home to represent residential buildings. (Rosado and Levinson 2019) compared solar-reflective "cool" wall energy savings to those provided by roofs, and explored variations of the cool-wall savings by building facet. It was found that the east or west wall received the most daily solar radiation in summer for all US climate zones, and therefore yielded the greatest cooling energy savings intensity for most locations. It is however worth noting that in the United States' summer months, i.e. June, July and August, the sun peaks in the southern sky while it peaks in the northern sky in Ghana. This means that all other things being equal, the north wall of a home in Ghana will receive considerably more solar radiation to generate significantly higher cooling energy demand than the north wall in most US homes.

4.2.5 Wall types

The building block material for the representative building was varied to investigate the impact of the wall's thermal properties on cooling energy efficiency of the building. Only the most commonly used building units were considered in this study comprising of 100mm brick and varying hollow and solid block sizes ranging from 125mm to 225mm at 25mm interval. All wall units are assumed to have 25mm cement mortar plastering for both external and partition walls except the 100mm brick which had no external wall plastering. The 125mm solid block was selected as baseline. It can be seen from Figure 4.14 (c) that heat gain in the building through the walls, decreases with increasing block thickness for

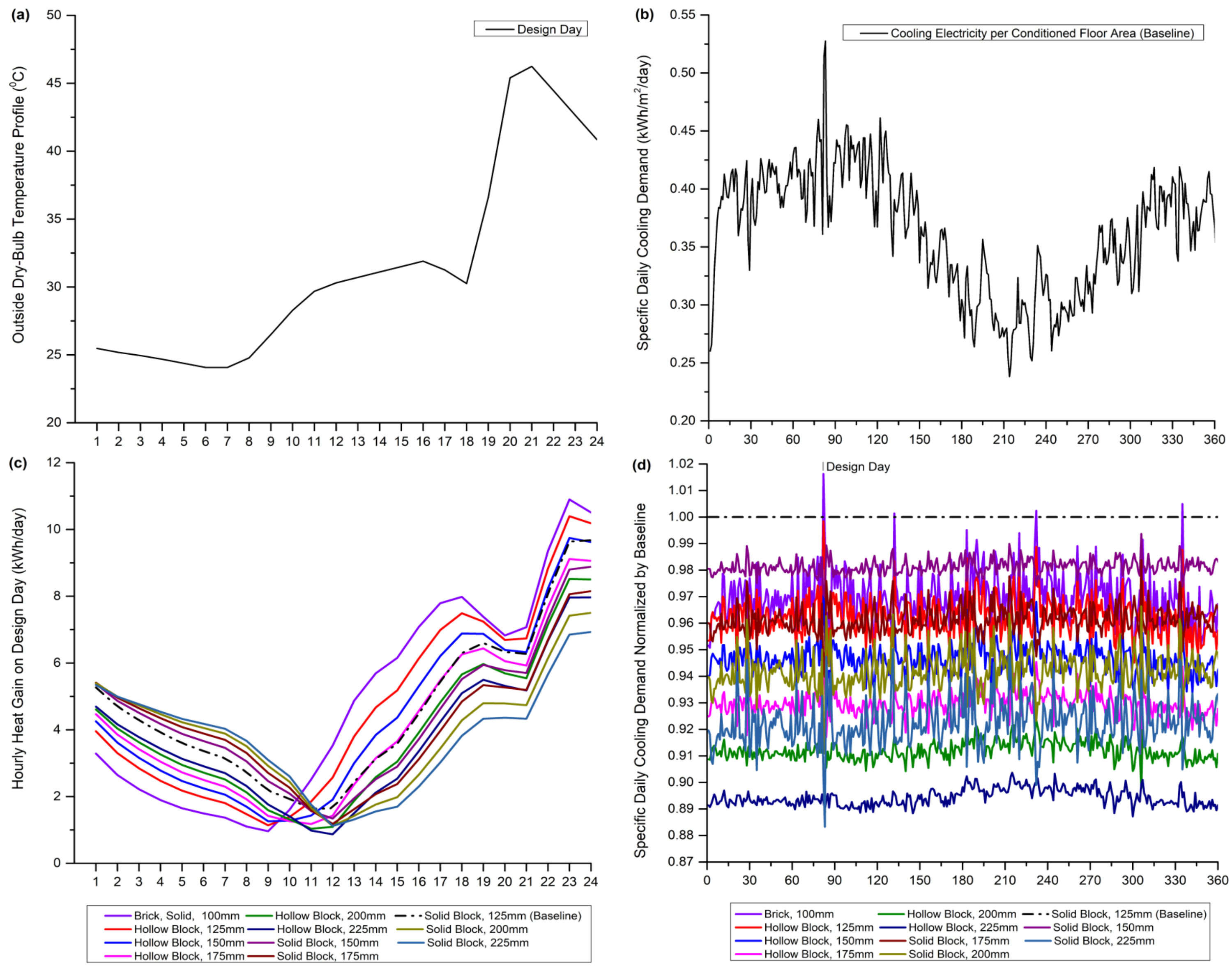

Figure 4.14: Design day temperature (a), Baseline cooling intensity (b), Hourly heat gain over wall types (c), Cooling intensity over wall types (d).

both solid and hollow blocks as outside dry-bulb temperature rises. The solid blocks however have lower heat gains in comparison with hollow blocks. On the contrary as outside dry-bulb temperature falls, heat gain increases with increasing block thickness for both solid and hollow blocks, and hollow blocks have lower heat gains in comparison with solid blocks. These observations could be explained by the thermal capacity and thermal resistivity of the varying units of the composite wall, see Appendix A.3. Thicker blocks have higher resistivity to conductive heat transfer and result in lower heat gain in the building during the day as outside dry-bulb temperature rises. However, thicker blocks also mean larger thermal capacity and more heat transfer into the building in the evening and night times as outside dry-bulb temperature falls. Optimization of total daily heat received in the building therefore requires trade-offs between heat storage ability and heat transfer resistance of the construction blocks. This "sweet spot" appears to be the 225mm hollow block which has similar heat gains as the 175mm solid block during the day but lower night gains than all the solid blocks.

The normalized specific daily cooling energy demand in Figure 4.14 (d) shows that the 225mm hollow block reduces the specific daily cooling energy demand by about 11% to become the most energy efficient as expected. The second place is the 200mm hollow block with about 9% cooling energy savings. The 125mm solid block has the highest cooling energy intensity. The importance of a trade-off between thermal capacity and thermal resistance of the blocks is more evident when a comparison is made between the daily cooling intensities of the solid blocks and that of their same-sized hollow blocks over the year. Unlike the design day which had a spike in outside dry-bulb temperature at 19:00 hours and higher evening temperatures than during the day, majority of days in a year typically have lower temperatures after sunset and through the night till around 06:00 hours when the sun rises again. The hollow blocks due to their lower thermal capacity, store and transfer less heat energy into the building to be cooled. It can be concluded that for all block sizes, hollow blocks have lower cooling energy intensity and are therefore more energy efficient than their corresponding solid blocks in residential building applications. The impact of energy-efficient walls on cooling energy savings has been studied by (Rosado and Levinson 2019) who found that in warm US climate zones 1A (Miami, Florida) through 4B (Albuquerque, New Mexico), "cool" walls in all vintages reduced building annual HVAC source energy use by 2 – 8.5%, which is comparable with the up to 11% energy savings found in this study for Ghana.

4.2.6 Window types

The effect of different window glazing types on the building's cooling energy intensity was investigated in this study as the glazing influences the total heat flow into the building. Single clear 6mm glazing, double clear 6mm/6mm with air gap glazing, single clear 6mm glazing with 500mm louvre shading, and double clear 6mm/6mm air gap with 500mm louvre shading were considered as alternative materials for the windows of the representative building. The louvre shading is made of wood that is assumed to be 100% opaque. Its positioning on the external surface of the glazing is expected to reduce the solar gains received by the building. Two window-to-wall ratios were chosen based on the most common window to wall ratios measured in the monitoring survey. A window-to-wall ratio of 30% and 25% for living room/family room/lounge and bedroom/office/all other conditioned spaces respectively, represented 84% of surveyed houses. Based on these observations, 30% window-to-wall ratio was selected for living room and 25% for all other conditioned spaces. The single clear 6mm glazing was selected as baseline, and gained the highest average daily solar heat of about 60kWh/day. The double clear 6mm/6mm with air gap glazing reduces solar heat gains by about 25% while the single clear 6mm glazing with 500mm louvre shading and double clear 6mm/6mm air gap with 500mm louvre shading reduce solar heat gains by about 33% and 58% respectively. The presence of the louvre shading on the windows had negligible impact on lighting energy use.

The normalized specific daily cooling energy demand in Figure 4.15 (c) shows that, addition of an air gap and a second layer of glazing provides good insulation and reduced

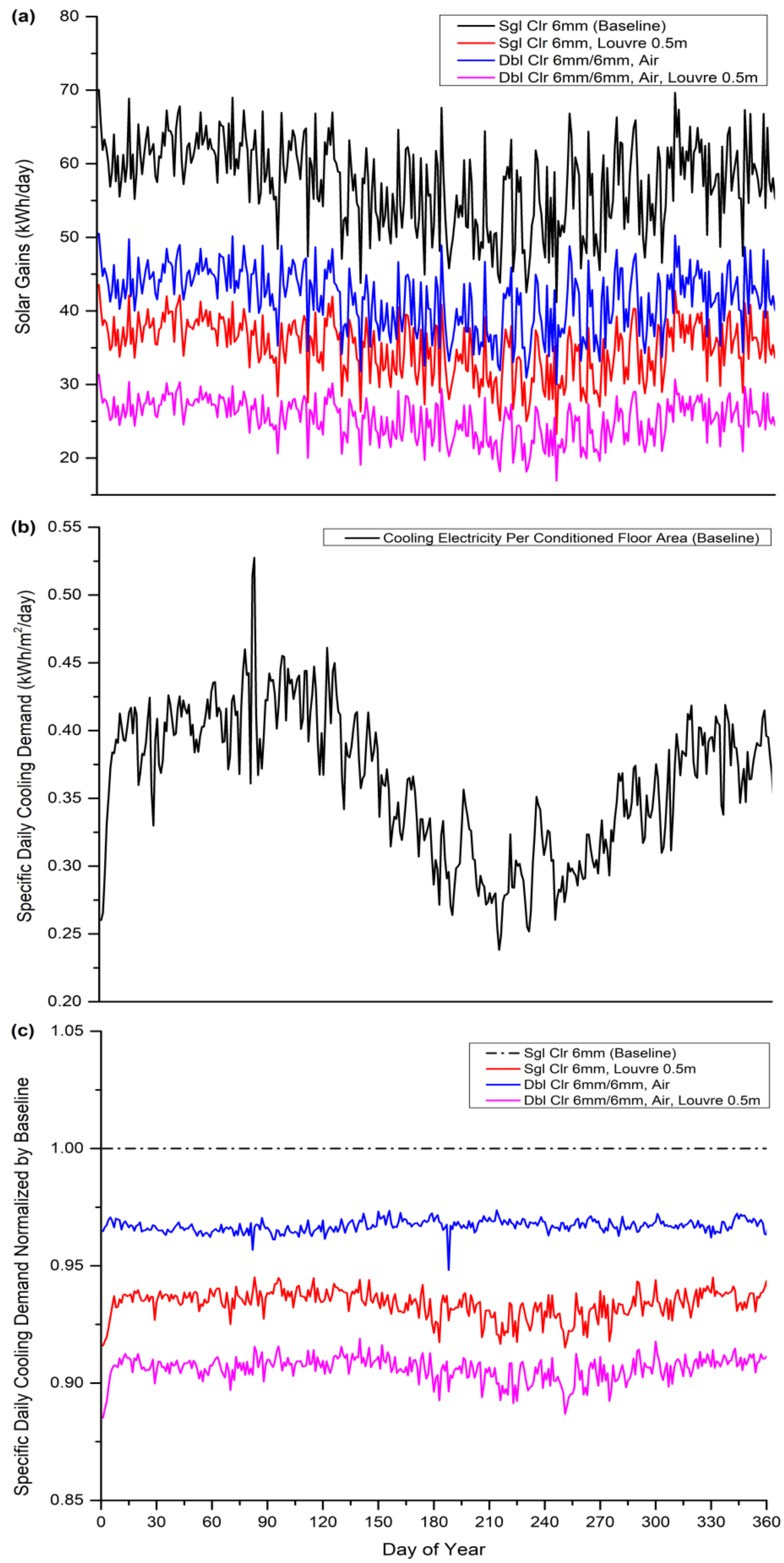

Figure 4.15: Solar gains over window types (a), Baseline cooling intensity (b), Cooling intensity over window types (c).

convective solar heat transfer into the cooled room to reduce the daily cooling energy intensity of the building by about 4%. Addition of 500mm louvre shading effectively reduces the building's daily cooling energy intensity as expected by about 7% and 10% respectively for the single clear 6mm glazing and the double clear 6mm/6mm with air gap glazing. While the much promoted double glazed window in Ghana provides some (4%) reduction in daily cooling energy intensity, this study finds that addition of 500mm shading louvres on the external surface of a single glazed window provides nearly double (7%) savings in daily electricity use for cooling.

These findings are consistent with simulation results of similar studies in other parts of the world. van Hooff et al. (2016) analyzed the effect of passive climate adaptation measures applied at building component level, on the cooling and heating energy demand of a terraced house using building energy simulations in the mild sea climate of the Netherlands. Results show that the required total cooling energy can be limited to a large extent (59–74%) when external solar shading or additional natural ventilation is applied. Harkouss et al. (2018) simulated a building in twenty-five different climates following the Koeppen-Geiger climate classification, with the aim of producing best practices to reduce building energy demand including passive cooling strategies such as blinds and natural ventilation. An optimal passive solution of the studied building indicates the potential to save up to 54% of the cooling demand in cities of the representative climates including Dakar in Senegal, West Africa. These results reinforce the established effectiveness of shading in reducing the cooling energy demand of residential buildings.

4.2.7 Roofing slope

The effects of the slope of the building's roof on heat gains and cooling energy intensity were investigated by varying the roofing slope between 15 degrees and 45 degrees at five degrees interval, with 20 degrees as baseline. The results show that the amount of heat received in the building reduces as the angle of the roof increases. A roof slope of 20 degrees

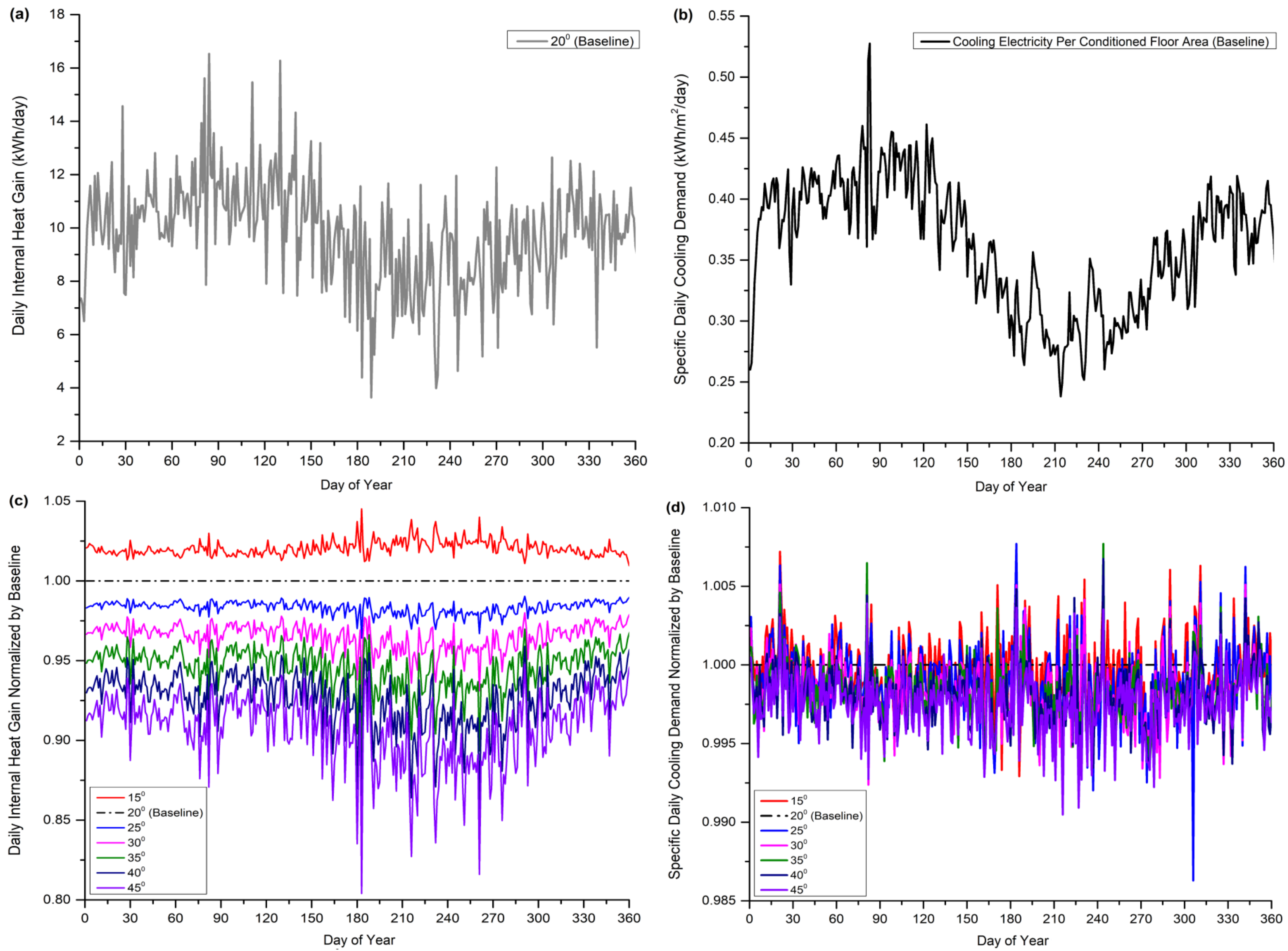

Figure 4.16: Daily heat gain baseline / for different roof slopes (a/c), Cooling intensity baseline / for different roof slopes (b/d).

(Baseline) receives an average of about 10kWh/day of heat energy through the year as shown in Figure 4.16 (a). A slope of 15 degrees receives about 2% more heat each day, while a 45 degrees slope receives about 8% less heat each day as shown in Figure 4.16 (c). The savings in heat gains earned by raising the slope of the roof are translated to savings in the building's cooling energy intensity in Figure 4.16 (d), but are not as significant. The differences between the daily cooling energy uses by the building for all considered roof slopes are less than 0.5 percent. It can be concluded therefore that while high roof slopes provide significant savings (up to about 8%) on the amount of heat energy received in the building, their reduction on the amount of electricity used to cool the building daily is almost negligible.

4.2.8 Roofing material

The building's roofing material (outermost) was varied to investigate their effects on heat gain and cooling energy intensity. Roof tile, concrete roof slab, asbestos cement sheet, Aluzinc sheet and aluminum sheet which are the most common roofing materials used for residential buildings in Tema city were selected, with roof tile as baseline. It can be seen from Figure 4.17 (c) that with roofing tile and asbestos cement sheet, the building gained the highest heat energy and the least with aluminum sheet which saved about 25% heat energy comparatively. Concrete roofing and Aluzinc sheets provided the building with savings in heat gains of about 13% comparatively. These savings are translated into savings in cooling energy intensity but not nearly as significant. Figure 4.17 (d) shows that the building uses comparatively more electricity for cooling when it is roofed with asbestos cement sheet or roof tile than it does with concrete roof or aluminum sheet. These differences however, are less than 0.5 percent. It can be concluded that while roofing materials provide very significant savings (up to about 25%) on heat gains into the building, similar to the roofing slope, their impact on the daily cooling energy intensity is almost negligible.

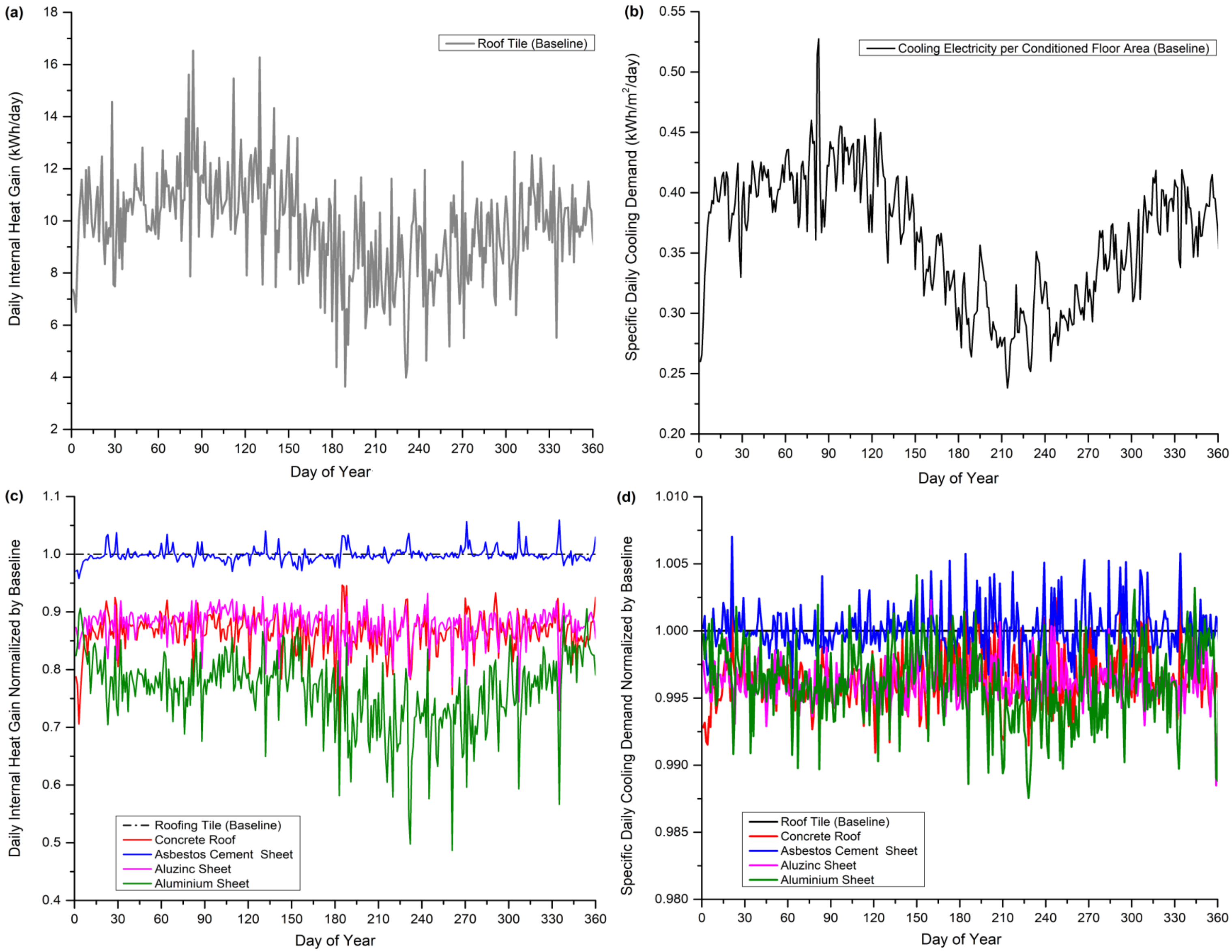

Figure 4.17: Daily heat gain baseline / for different roofing materials (a/c), Cooling intensity baseline / for different roofing materials (b/d).

4.2.9 Ceiling material

The building's ceiling material was varied to investigate their effects on heat gain and cooling energy intensity. Wood panels, PVC ceiling tiles, gypsum plastering, heavyweight plywood and lightweight plywood which are the most common ceiling materials used for residential buildings in Tema city were selected, with lightweight plywood as baseline. The building's baseline heat gain is about 10kWh/day. Figure 4.18 (c) shows that use of the much trendy gypsum plastering and PVC ceiling tiles in Ghana results in about three percent higher heat gains than plywood, and about four percent higher heat gains than wood panels. The magnitude of savings provided by the ceiling materials diminishes in cooling energy intensity to less than 0.5 percent as shown in Figure 4.18 (d). Similar to roofing slope and roofing material, ceiling material is found to have negligible impact on the daily cooling energy intensity of the building.

4.2.10 Floor material

Residential buildings in Tema city, Ghana have at least 300mm of compacted gravel sand as subgrade, followed by 100mm of concrete and 70mm of cement mortar screeding as standard practice (Tettey et al. 2012). The innermost material (floor finishes) however varies, and include smooth cement finish, terrazzo finish, carpet or textile flooring, wood flooring and porcelain tiles. These floor finishes were investigated to evaluate their likely effect on heat loss and cooling energy intensity of the building. It was found that variations in the material for the floor finishing had zero impact on both heat loss and cooling energy intensity of the building.

Generally the magnitude of influence of the building envelope was significantly higher for heat gain than cooling energy intensity of the building primarily because while heat gain

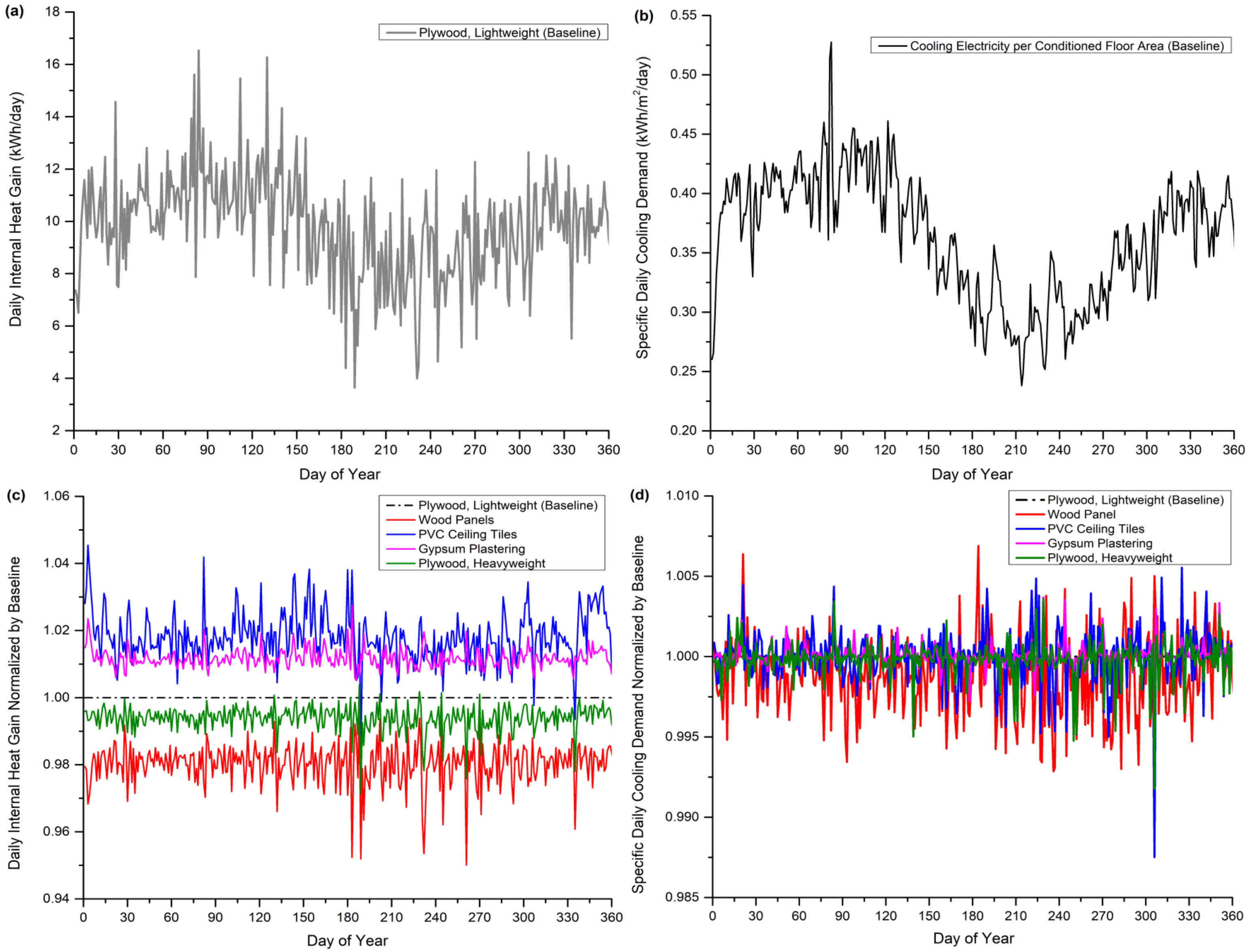

Figure 4.18: Daily heat gain baseline / for different ceiling materials (a/c), Cooling intensity baseline / for different ceiling materials (b/d).

captured the entire building envelope, only the conditioned rooms representing about 58% of the building's total floor area contributed to the cooling energy intensity. Therefore, while building components such as ceiling material, roofing material and roofing slope yield little to negligible (less than 0.5 percent) reduction in cooling energy intensity, their effects on reducing heat gains are significant and could be very useful in improving the thermal comfort in non-conditioned spaces such as kitchen, storeroom, garage, laundry room etc. or an entire unconditioned home.

4.2.11 Cooling energy efficiency levels for the representative building

Figure 4.19 shows the building's daily cooling energy intensity at the five efficiency levels based on the stage of building development. The BAT efficiency level provides the highest savings with averages of about 60% and 56% respectively for new construction and retrofit. The medium efficiency level provides lesser but very significant savings with averages of about 31% and 30% respectively for new construction and retrofit. The amount of savings from the retrofits and their corresponding new constructions at both efficiency levels do not vary much due to already established near negligible impact of differentiating parameters such as roof slope, roof material and ceiling material. Wall type on the other hand has significant influence on energy savings and is evident at both efficiency levels. The difference in energy savings between the new build and retrofit of the BAT efficiency level is higher (4%) than the 1% of the moderate efficiency level due to similarly higher difference between the wall types of the new build and retrofit of the BAT as compared to that of the medium efficiency level in Table 4.1. Direct comparison of the baseline with both medium and BAT retrofits highlight the overarching influence of air conditioner efficiency and window type. While all other parameters remain the same, improvement in the efficiency of the air conditioner and window type yield 30% and 56% savings for the moderate and BAT efficiency levels respectively.

Comfort levels were found in the monitoring survey to be subjective to the building occupant and dependent on the indoor air temperature. Thermostat setting which regulates the indoor air temperature was already established as very significant impact factor of the building's cooling energy intensity. The thermostat setting for the representative building was increased from 18.5^{o}C to 22^{o}C to evaluate the combined effect of building fabric, technology and occupant comfort level adjustments. Figure 4.20 shows the representative building's annual cooling energy intensity for the baseline, moderate and BAT efficiency levels. An upward adjustment of 3.5^{o}C in temperature setting yields an additional 35% savings for all efficiency levels. The combined effect of building fabric, technology improvement and occupant comfort level adjustments in comparison with the baseline therefore amounts to 52%, 54%, 68%, and 72% savings in cooling energy demand respectively for the medium efficiency retrofit, medium efficiency new build, BAT retrofit and BAT new build. These results compare well with findings of similar studies around the world. Sadineni and Boehm (2012) found that a switch to energy efficient building envelope, HVAC system and lighting in the average Villa Trieste home in Las Vegas resulted in approximately 31%, 72% and 23% less electrical energy cooling, lighting and total annual energies respectively based on energy efficiency improvements alone.

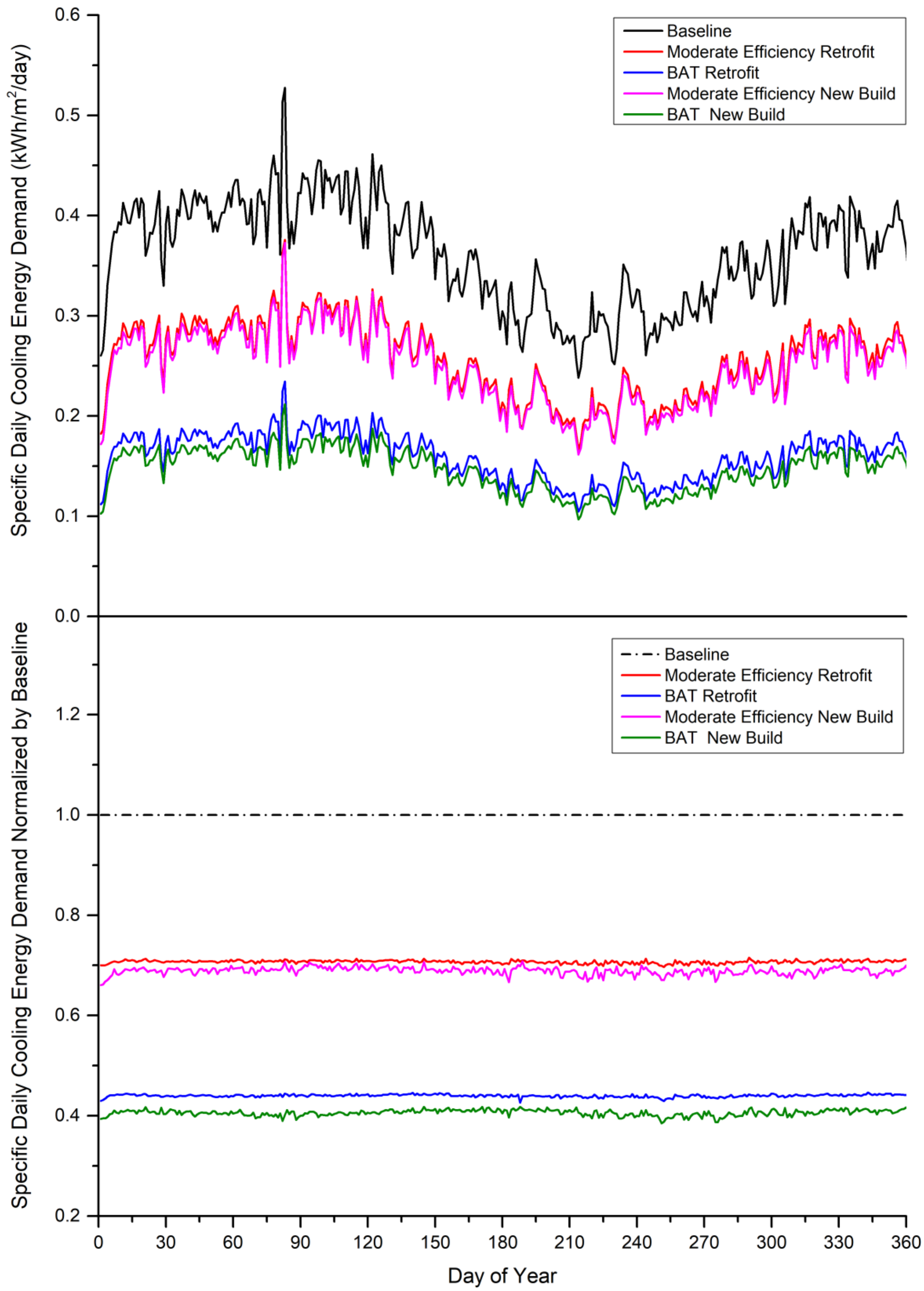

Figure 4.19: Variation of cooling energy intensity over the calendar year for different building efficiency levels.

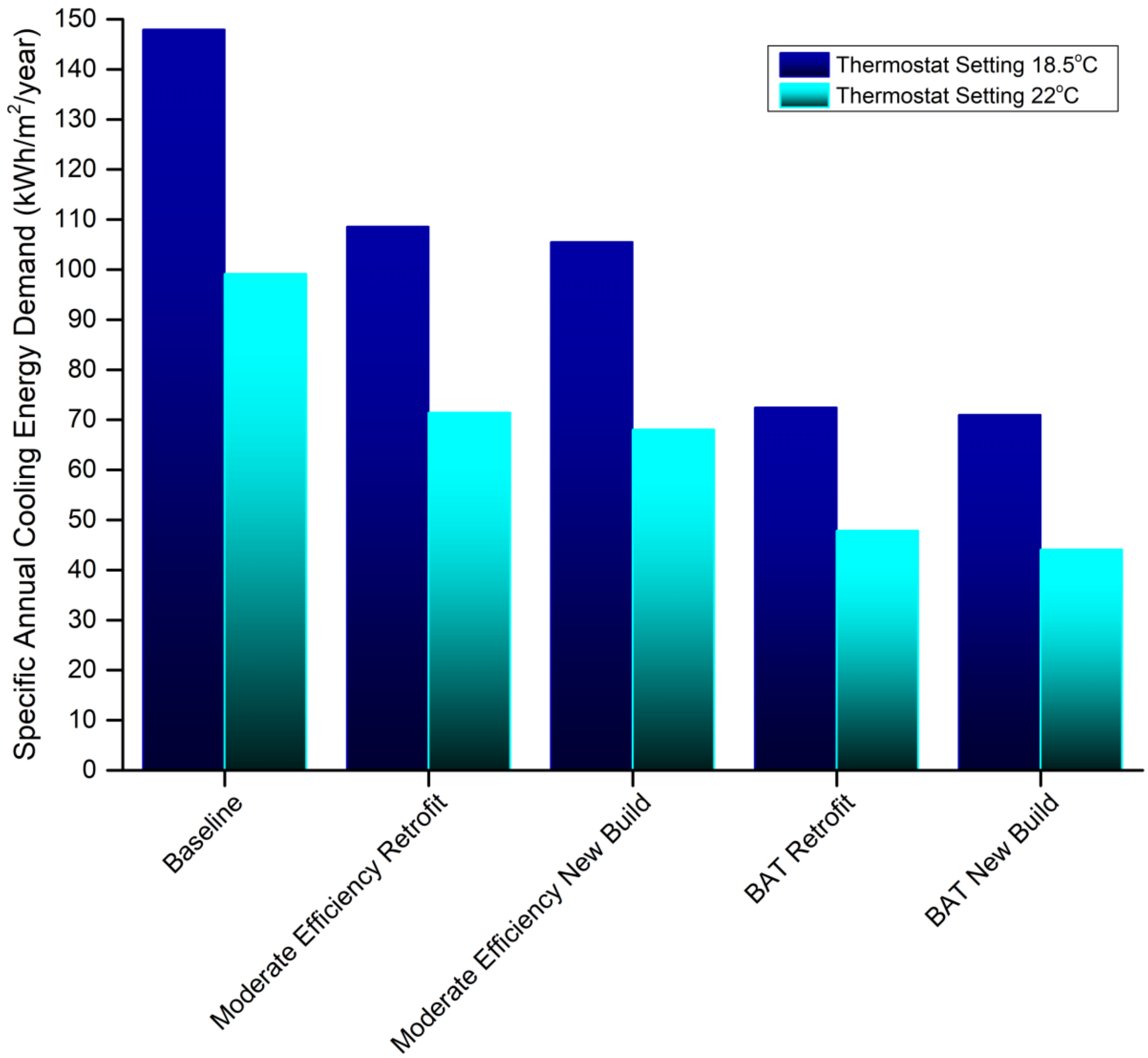

Figure 4.20: Specific annual cooling energy demand as function of building efficiency and thermostat setting.

The options within specific building parameters that define the building's cooling energy efficiency level are based on survey results, literature and expert judgement. The results are therefore subject to and based on the expert assumptions and selections made. The findings in this section are useful to utility services in planning grid capacity and ensuring resource adequacy for characteristic cooling end-use load in clusters of new residential development areas. The results are also useful to residents who want to lower their cooling energy costs, and to real estate developers for construction of energy-efficient buildings. Local authorities that intend to set minimum residential building energy performance standards will find the results in this section particularly useful in policy formulation.

4.2.12 Estimated cooling energy savings for Tema City

The main aim of this section is to reduce the cooling energy intensity of residential buildings in Tema city to a minimum through energy efficiency improvement measures, and evaluate the potential electricity savings that could be realized from a transition to energy-efficient residential cooling between 2020 and 2050. The estimated potential annual energy savings from energy efficiency retrofit of existing base year buildings and construction of new, energy efficient buildings are presented in Figure 4.21 for the three considered scenarios. The BAT scenario has the highest annual retrofit savings, beginning at 40 GWh in 2020 and 24 GWh in 2025 as compared to 10 GWh in 2020 and 8 GWh in 2025 for the MET scenario. Energy savings from retrofit drop for both BAT and MET scenarios in the medium-term to long-term as the numbers of inefficient base year buildings diminish. However, the drop is more drastic in the BAT scenario due to its high conversion rate. By 2050, energy savings from retrofits is 2.2 GWh for the MET scenario while that of the BAT scenario is about 22% less at 1.7 GWh. Energy savings from retrofit under the BAU scenario on the other hand shows a steady rise over the transition period beginning at 0.13 GWh in 2020, to 0.64 GWh in 2025 and 1.62 GWh in 2050 due to gradual improvement in EER of the air conditioner and corresponding reduction in building cooling energy intensity as presented in section 0.

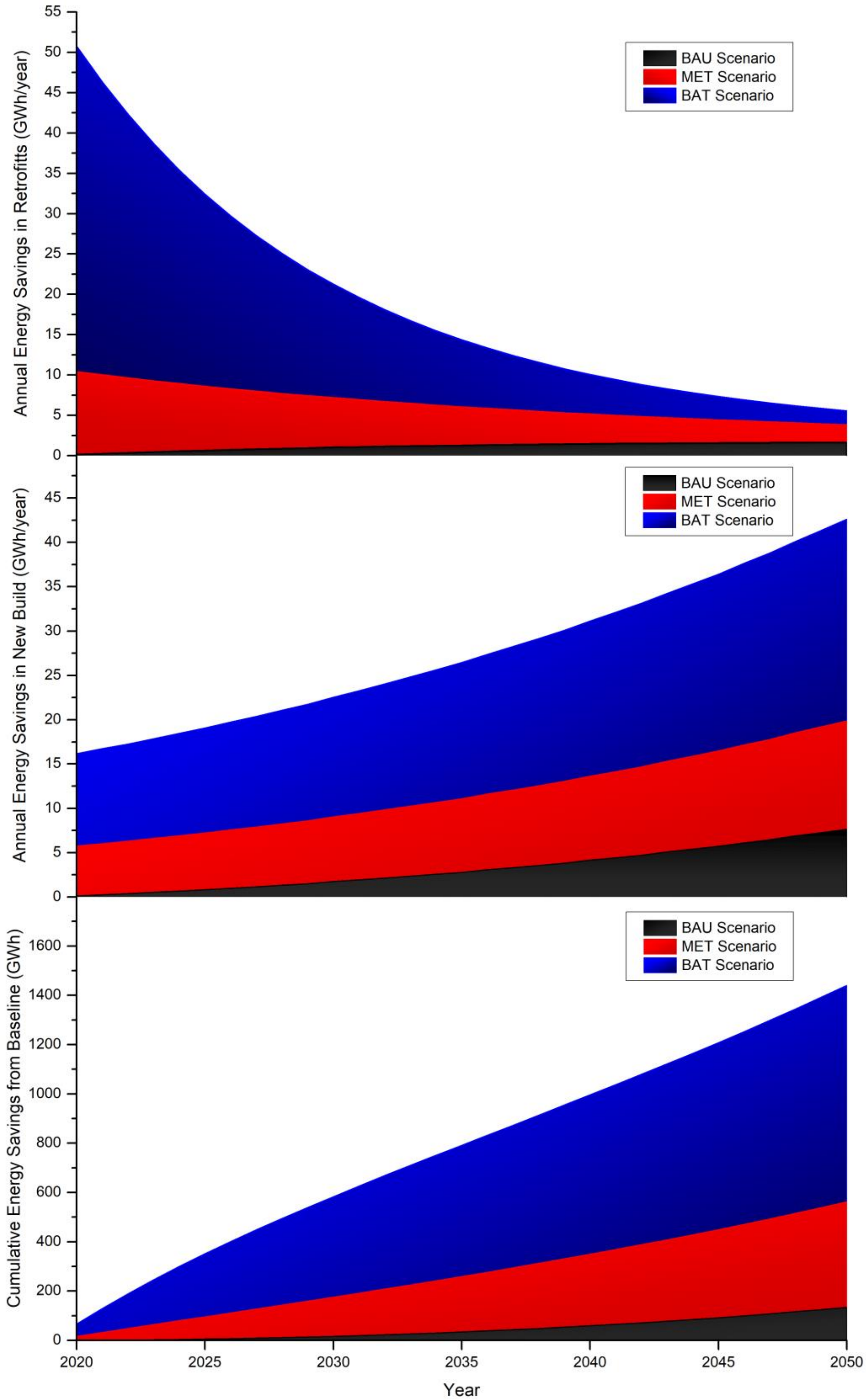

Figure 4.21: Potential energy savings in Tema city for retrofits (annual), new builds (annual) and both (cumulative).

Although the number of projected new buildings added each year is the same for all three scenarios, the annual energy savings of the BAT scenario is significantly higher than the MET and BAU scenarios due to similar variations in their cooling energy intensities. The cumulative annual energy savings from both energy efficient retrofitting and new construction range between 0.25 GWh and 878 GWh. The BAT scenario yields the highest energy savings as expected, beginning at 50 GWh in 2020 and rises a little sharply to 878 GWh in 2050 while the BAU scenario yields the lowest energy savings with 0.25 GWh in 2020 and 134 GWh in 2050. The MET scenario shows expected medium energy savings beginning at 16 GWh in 2020 and rises steadily to 427 GWh in 2050.

The total cumulative energy savings for the transition period of 30 years between 2020 and 2050 is 1.4 TWh, 6.9 TWh and 15.8 TWh respectively for the BAU, MET and BAT scenarios. The energy savings of the MET and BAT scenarios are adjusted by that of the BAU scenario in a further step to yield 5.5 TWh and 14.4 TWh "real-time" future energy savings that would accrue in the 30 year period if investment is made in the MET and BAT scenarios respectively. These savings respectively represent about 40% and over 100% of Ghana's total electricity consumption by all sectors in 2017 (IEA 2017). Using 0.342 CO_2e/kWh as emission factor for future electricity generated with natural gas (US Energy Information Administration 2020), the projected electricity savings translate respectively to 1879 $GgCO_2e$ and 4919 $GgCO_2e$ savings in pollutant emissions that would otherwise contribute to increasing global warming and respiratory diseases.

This study finds that in the absence of building energy performance standards, electricity use for cooling by air conditioning in homes of Tema city, would grow by estimated 215% between 2020 and 2050 even when the historical 0.7% year on year improvement in AC efficiency is applied. Yu et al. (2017) used the Global Change Assessment Model to evaluate growth in the buildings sector and impacts of building energy policies in Gujarat, India, to help the state adopt the Energy Conservation Building Code and expand its building energy efficiency programs. It was found that without energy codes, the energy use by urban residential buildings in Gujarat would grow by 400% between 2010 and 2050, and having energy codes for both commercial and residential buildings could result in 10% savings in electricity use in excess of savings from other energy efficiency programs. Wang et al. (2019) used survey data from 1128 households in Chongqing China, and applied the propensity scores matching method to estimate the effectiveness of two building energy efficiency standards (BEES) levels: the 50%-BEES (low level) and the 65%-BEES (high level). Results show that on average, the high and low level BEES can reduce cooling and heating electricity use intensity in kWh/m^2/yr by 41% and 38% respectively. These results indicate that though there is a performance gap between calculated design savings and actual operational energy savings, with a low of 38% energy use reduction, building energy efficiency standards provide an effective approach to reducing energy consumption and decarbonizing the residential sector.

4.3 Barriers to implementation

The goal of reaching sustainable energy efficiency for residential buildings has been classified as a hierarchical process that begins with retrofitting the building envelope to higher performance standards, followed by improving the energy efficiency of installed equipment with best available technologies and completed with on-site micro-generation of renewable energy with smart grid connections and control (Xing, Hewitt, and Griffiths 2011). In order to implement the pathways identified above for reaching the first two hierarchical levels in Ghana, certain institutional, market and information barriers need to be overcome. Some of these barriers are discussed below.

4.3.1 Lack of building energy standards

Building energy performance certificate (EPC), first emerged in Europe in the early 1990s as an informative tool that allows real estate developers, building owners and occupants to achieve energy-efficient buildings, providing useful recommendations regarding cost-effective measures for improving the building's energy performance (Pérez-Lombard et al. 2009). The promising performance and economic potential of energy efficiency technologies in building energy standards has been acknowledged in residential buildings of the EU (Camarasa et al. 2019), United States (L. Zhang et al. 2018), Australia (S. Berry and Marker 2015), Singapore (Chua and Chou 2010), Egypt and Tunisia (Iwaro and Mwasha 2010), India (S. Yu et al. 2017), Brazil (Triana, Lamberts, and Sassi 2015), and China (X. Wang et al. 2019). A review of research directions regarding building energy performance standards identified four main foci: evaluating the effectiveness of different rating methods; verifying the building energy performance of labelled projects; investigating the practical benefits of energy-efficiency labelling for building owners, real estate actors and governments; comparing domestic labelling schemes with foreign schemes (Y. Yu et al. 2019). Through decades of several studies (Roulet and Anderson 2006; Y. Zhang et al. 2017; K. Janda 2009; K. B. Janda and Busch 1994), the value of building energy performance standards has been explored extensively in developed countries and emerging economies under cold to hot climatic conditions, and the implementation process has been improved significantly to provide valuable learning curves (Y. Yu et al. 2019). In spite of these, Ghana is amongst 25 developing countries that were found to be without any form of building energy standards in 2010. The major impediments to implementing regulations for energy conservation and efficiency in the building sector have been attributed to institutional barriers and market failures rather than technical including lack of owners' awareness of energy conservation benefits, building energy regulations benefits, insufficient awareness and training of property managers, builders and engineers and lack of specialized professionals to ensure compliance (Iwaro and Mwasha 2010). Ghana launched its long awaited building code in November, 2018 to bring an end to the virtual 'free-for-all' in the building and construction sector and set standards to ensure that Ghana's construction environment is safe and meet international standards. It is reported to set out requirements and recommendations for efficiency standards for residential and non-residential buildings that cover planning, management and practices in the construction of buildings (Akplalu and Kyei 2018). Yet, the energy efficiency and sustainability section of the code provides no information on acceptable performance levels or acceptable energy intensity levels for the building envelope or installed equipment. Instead it states that "the Efficiency Standards for Residential and Non-Residential buildings (2008) by the California Energy Commission are relevant" (Tettey et al. 2012). The core technical indicators of which are based on California's climatic conditions and construction materials that are either used differently or not used at all in Ghana. Its adoption in Ghana will therefore create significant gap between potential and actual energy savings from investment in residential building energy efficiency.

4.3.2 Lack of database for residential building characterization and energy use

Determination of consistently accurate residential electricity consumption on a large scale based on individual home by home building simulation is a huge challenge as it involves accurate and reliable input of too many variables into the building energy simulation tool (Hu, Yan, and Qian 2019). Lack of detailed information on the physical and operational characteristics of homes induces consistent under- or overestimates (Glasgo, Khan, and Azevedo 2020). Extensive data gathering and statistical sampling methods could be used to develop tools that can simulate representative homes and address this challenge by generating statistically sound characterization of existing single-family residential building stock as well as baseline models that represent the average home at the district, regional and national levels. This approach could overestimate or underestimate the energy consumption of individual homes but, the batch as a whole would still be representative if the model is validated to the actual energy consumption of the larger population of buildings being modelled as exemplified in the United States' ResStock tool (Wilson et al. 2017). Baseline energy consumption could then be reliably estimated and efficiency savings opportunities quantified as foundation for policy formulation on cost-effective reduction in the energy consumption and environmental impacts of Ghana's residential sector. The method and results presented in this work for the Tema case study, follows this procedure and provides a learning curve for characterizing and simulating the residential building stock to support local energy efficiency policy for other cities in Ghana and the West Africa sub region. Energy Commission Ghana has instituted a National Energy Data Processing and Information Centre (NEDPIC) which aims at becoming a one-stop repository of energy data and information on electricity, renewable energy and energy efficiency, natural gas, and petroleum industries in Ghana. NEDPIC currently exists in name only as there is no information aside its establishing objective (Energy Commission 2020a).

4.3.3 Insufficient awareness and training of building permit issuing officials

Before an estate or a single house can be developed in Ghana, the builder must acquire approval documentation from several governmental agencies such as Lands Commission, District Assembly, Survey Department, Town and Country Planning Department, Environmental Protection Agency, Ghana Fire Service etc. At the Town and Country Planning Department, the architectural and structural design of the building/estate must be reviewed and approved before a building permit is issued (Town and Country Planning Department of Ghana 2020). The bureaucrats involved in these processes do not have the necessary information and training to assess potential building energy performance based on building designs. Although many qualified engineers, technicians and architects lead construction projects in Ghana, Boateng (2019) reports that many of such building professionals lack knowledge and skills in the area of building energy efficiency. In addition, there is no overarching regulatory body, and few legal mandates or enforcement mechanisms for building design and construction practices are currently in place (Oxford Business Group 2020). Numerous stakeholders, including the Association of Building and Civil Engineering Contractors of Ghana, have insisted on the establishment of a dedicated regulatory body or designated national authority for the construction sector to ensure safety and increase professionalism in the industry. It could also serve as an avenue for training and reporting patronage during the awarding of contracts. The Ghana government started exploring the option of establishing a Construction Industry Development Authority in 2014, but had not made significant progress as of October 2019 (Ahadzie 2019; Oxford Business Group 2020). The Ghana Building Code is expected to provide legislation for efficiency standards of residential and non-residential buildings, and covers planning, management and practices in building construction but without the accompanying database and training of specialized compliance enforcers, it is set to be a lonely white elephant.

4.3.4 The landlord-occupant dilemma

Residential buildings in Ghana are usually renovated when external factors such as the weather deteriorate the building's materials to show signs of aging or at the behest of new occupants. Energy efficiency retrofitting is when the building is renovated to primarily improve its energy performance. The landlord/occupant dilemma occurs when a building owner and a tenant/resident have difficulty in agreeing upon a common strategy for energy efficiency improvement of the property. The occupant of the building typically pays for the energy consumption of the property, which is influenced by the condition of the infrastructure and how it is used. Since the benefits of energy renovations go directly to the building's occupant in terms of saved energy costs, the landlord is not motivated to invest in energy efficiency retrofit. The occupant on the other hand is not motivated to invest in retrofitting of unowned property especially for residents with short to medium-term lease agreement (Ástmarsson, Jensenn, and Maslesa 2013). Majority of real estate developers in the Greater Accra Metropolitan Area of Ghana, to which Tema belongs, have fair knowledge on the importance of constructing energy efficient buildings and install energy efficient appliances and lighting when said developers are directly engaged in management of the estate houses. Although majority of homebuyers and renters of estate houses have fair knowledge on the importance of energy efficient buildings, few check for energy efficiency in buildings before they purchase from developers (Boateng 2019). In Tema, the highest proportion of dwelling units are owned by household members at 48.2%, followed by units owned by other private individual at 33.6%, a relative who is not a resident at 8.1% and public or government ownership at 5.2% (Nyarko, 2014). While property owner-residents in Tema could be motivated to invest in energy renovation with direct return on investment in terms of saved energy cost, for over 45% of properties the right balance between the landlord's and the occupant's interest would need to be struck to assure stakeholders' value for money.

4.4 Policy recommendations

4.4.1 Statistical index system for residential cooling energy consumption

Design of district level statistical index for development of technology requirements in residential cooling must capture actual contributors of residential cooling energy consumption as well as their influencing factors. Based on the methodology of this study, Figure 4.22 shows a proposed framework for gathering and collating data pertaining to residential cooling energy consumption at the city, district or municipal level. The framework consists of four kinds of household energy consumption characteristic indices comprising building, household, equipment, and energy supply characteristics. The building characteristics index is further divided into descriptive and energy use characteristics. The descriptive characteristics provide such information as building type, location, orientation, and construction year, number of stories, number and function of rooms as well as their floor areas. The energy use characteristics provide information on the contributors to the cooling energy demand of the building such as: building envelope materials and coverage area, their size and associated U-value, solar heat gains co-efficient, specific heat capacity, density, type of natural or mechanical ventilation and shading, window to wall ratio, as well as lighting density. The household characteristics index provides socio-economic

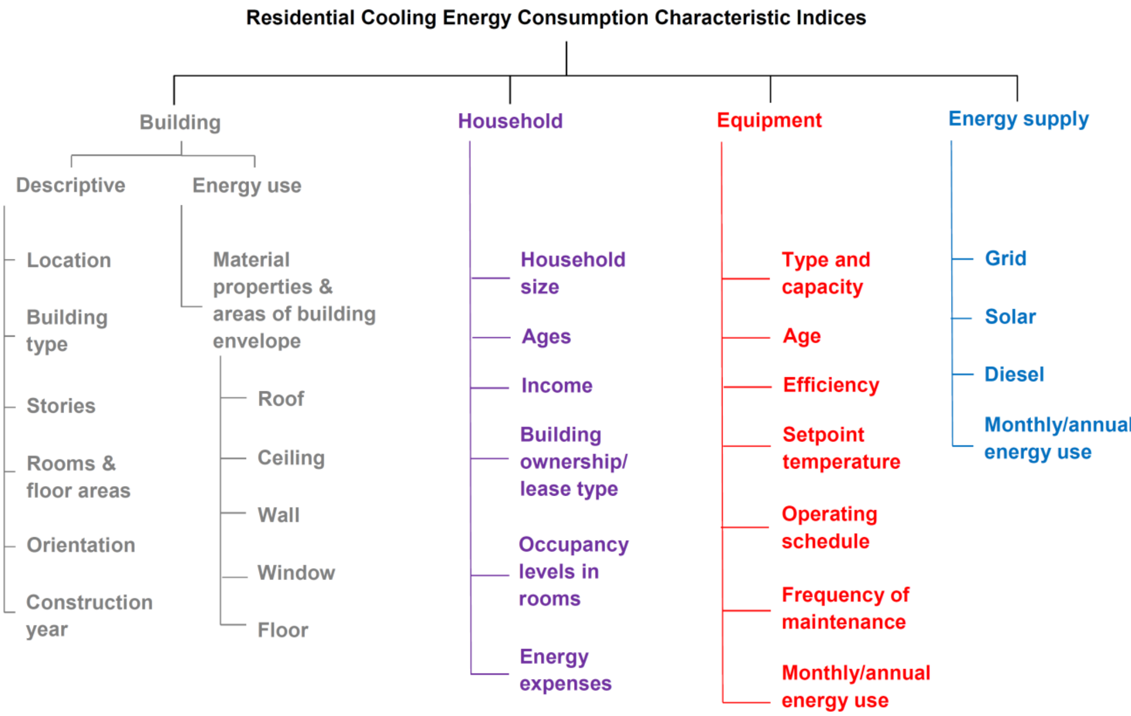

Figure 4.22: Proposed framework for city-level residential cooling energy consumption data collation.

information about the occupants of the home including ownership or type of tenancy, household size, age and occupation of household members, their income and energy expenditure, as well as occupancy levels of bedrooms (i.e. number of persons per sleeping room). The equipment characteristics index provides information about the air conditioning system efficiency, frequency of maintenance, setpoint temperature, and operating schedule for all cooled rooms. It provides information about the monthly/annual electricity consumption of the air conditioner, to give monthly/annual electricity use for space cooling per unit area of cooled rooms. The energy supply characteristics index provides information on the source of energy that runs the air conditioning unit. Since there are no district cooling systems in Ghana, electricity is the energy used by all air conditioning units, and may be generated on-site with a diesel generator, solar panels or supplied by the grid. This index therefore provides information about the amount and source of electricity use for space cooling. For the purposes of estimating the cooling energy intensity of a home, internal heat gains from lighting and other appliances were not considered since appliance ownership varies greatly amongst households. The influencing factors, technology requirement, method and recommendation for standardizing household appliances have been discussed extensively in section 3.1.3.

Implementation of this framework however, will require establishment of dedicated energy efficiency division in the district or municipal assembly to be charged with collecting and processing the data in cooperation with the district offices of the Town and Country Planning Department (Tema Development Cooperation for the case study), Electricity Company of Ghana, Ghana Grid Company, Energy Commission Ghana, Ghana Statistical Service, Building and Road Research Institute, Ghana Standards Boards, Ghana Institution of Engineers, Ghana Institute of Architects, Refrigeration and Air Conditioner Engineers Association of Ghana, National Air-Conditioning and Refrigeration Workshops Owners Association, Ghana Real Estate Developers Association, Ministry of Works and Housing, home owners and other stake holders. The collected data can then be used to develop tools that can simulate representative homes and their associated cooling energy consumption for establishing a building energy performance labelling scheme.

4.4.2 Residential building energy performance labelling

Building energy performance labelling scheme has been established as one of the most effective policies for reducing energy consumption in homes around the world. The Danish energy labelling scheme, which is part of the implementation of European Union's Energy Performance of Buildings Directive (EPBD) for example, requires all buildings to have energy labels that last no longer than 10 years. The purpose of the label is to provide building owners, residents and buyers with clear indication of the condition of the building regarding energy intensity (kWh/m^2/yr), recommended energy efficiency improvement and instructions on where to go for further information (Ástmarsson, Jensenn, and Maslesa

2013). This study finds that there is realistic potential for up to 60% energy savings (i.e. from cooling energy intensity of 147.89 kWh/m^2/yr - 44.06 kWh/m^2/yr) resulting from energy efficiency improvement especially for single family homes in Ghana. It is therefore recommended that Ghana implements a mandatory building energy performance labelling scheme. New builds would then be required to meet given minimum energy performance standards. The legislation should include "push" policy instruments (e.g. regulatory and control instruments) and "pull" mechanisms (e.g. economic or fiscal incentives and support tools for voluntary action) (Camarasa et al. 2019). Similar to the EPBD, the proposed label should provide information about the cooling energy intensity of the building, recommended energy efficiency retrofit and associated savings as well as instructions for acquiring further information. Based on the average lifespan of the components of the building envelope, the maximum repayment term for mortgage loans towards buying or renovating a home in Ghana and the return on investment estimated in this study for cost-effective investment in residential building energy efficiency measures, it is recommended that the label be given a maximum lifespan of 10 years. The energy label is expected to be the foundational market driver for building energy efficiency investment. It is therefore imperative that the content of the label overcomes basic informational barriers and is trustworthy. Directed sources for further information must likewise be reliable and user friendly. For the energy labelling scheme to be effective and achieve its primary objective of reducing residential building electricity consumption, there must be legal and/or economic consequences for non-compliance. Non-labelled houses or properties that do not meet the minimum energy performance requirement could for example, be denied rent increase and/or required to sell below market value.

4.4.3 Responsibility for energy efficiency refurbishment and right to bill savings

Investment in all investigated energy efficiency measures excluding windows for new build, have been demonstrated as cost-effective. Their energy, environmental and financial benefits could be effectively realized by establishing and implementing minimum energy performance standards for residential buildings. This puts the responsibility of investment with the landlord/estate developer who gains return on investment through comparatively higher rent. While building energy standards are in place, energy compliant construction would guarantee high market value of the building with rising energy prices and tightening requirements in building performance regulation (Ástmarsson, Jensenn, and Maslesa 2013).

In the case of energy efficiency retrofit, investment in majority of the measures have been demonstrated as cost-effective with rebate and a little less than half of the measures as cost-effective without rebate. The responsibility of investment however, could lie with either the landlord or the tenant depending on such factors as term of lease agreement and occupancy of the property at the time of implementation. Change and adaptation of existing regulation as well as introduction of few new ones, would need to be implemented simultaneously in an integrated approach to effectively overcome the landlord/tenant dilemma. An overview of recommended new regulation, proposed change and/or adaptation of existing regulation and their expected impact is presented in Table 4.2. This proposal as discussed below is based on the assumption that legislated energy performance standards requiring residential buildings to have an energy label are in effect.

Table 4.2: Suggested policies, adaptation of existing policies and their expected impacts.

Policy	**Adaptation**	**Expected Impact**
Rent Act	The possibility for landlords and property managers to increase rent should be tied to renovations that improve the quality and energy performance of the building.	Homeowners would be incentivized to invest in energy efficiency renovation with clear guidelines for their return on investment.
Energy Label*	Energy label should be required for residential buildings. Noncompliance should be penalised with annual charges for homeowner-residents and strict restrictions on rent increase for private rental accommodation.	The presence of repercussions for noncompliance will motivate a larger share of homeowners to label their properties. Detailed information on the label will increase energy consumption awareness and induce

		conservation.
Green Lease*	Recommended for landlords and tenants in short to medium-term leases. Should be piloted mandatorily with residents of government and/or public estates and houses to gain experience and create demand.	Homeowners would be incentivized to invest in energy efficiency renovation with clear guidelines for their return on investment.
Mandatory Energy Savings*	Oblige energy generation, transmission and distribution companies to achieve a specific amount of energy savings in the residential sector each year.	Power utilities would be incentivised to subsidize non-profit measures. Investment costs would reduce to allow large scale participation by homeowners. Encourage financial institutions to offer low interest loans for energy efficiency renovation.
Tax Incentives*	Offer tax holidays to homeowners whose buildings meet the minimum energy performance standards.	Homeowners would be encouraged to invest in energy retrofits or enter into green leasing with tenants.

**New policy suggestion*

The Rent Act in Ghana permits landlords to charge six months' rent in advance with succeeding rents due every six months for the duration of the lease agreement. However, high rates of urbanization have created a situation where demand for private rental accommodation outstrips supply particularly in metropolitan areas such that, a feature of the Ghana private rental accommodation market is landlords demanding between 12 and 60 months of the rental value of the accommodation in advance before signing a lease agreement (Kufour 2018). This study therefore puts lease agreements between landlords and tenants into three categories based on the lease term. A rental contract that is valid for up to 24 months is classified as a short-term lease while that for above 60 months is classified as a long-term lease. Contracts with validity between 24 and 60 months are classified as medium-term leases. Under current regulation, a landlord can increase the rental rates upon contract renewal if he notifies the tenant three months ahead in writing about the amount of the old rates, the amount of the new rates, and where a part of any premises has been let, the amount of the rates attributable to such part, the amount of the increase in rent and the date from which the new rates take effect (Parliament of the Republic of Ghana 1963). This practice is particularly common for tenants in short-term leases who wish to renew their lease upon expiry. It is recommended that the possibility for landlords and property managers to increase rent be tied to renovations that improve the quality and energy performance of the building such that the amount of the rent increase is dependent on the energy saving potential on the energy label. Landlords would then be incentivized for energy efficiency renovations with clear guidelines for their return on investment.

Residential buildings should be required to have energy labels with repercussions for noncompliance such as annual penalties for homeowner-residents and strict restrictions on rent increase for private rental accommodation. The energy label should be part and parcel of the contractual documents between a tenant and a landlord/property manager for all residential properties on both the formal and the informal housing market. The presence of repercussions for noncompliance will motivate a larger share of homeowners to label their properties, which will improve accuracy of data collation on household energy consumption for clearer overview of the energy consumption characteristics and potential energy savings from the neighborhood, community and city level building stocks. It is expected that detailed information on the label will increase energy consumption awareness and induce conservation. It will also ensure the landlord and tenant have adequate and equal information with regards to the energy performance standard of the building and any associated financial implications.

After introduction of a residential building energy performance standards regime, a landlord and tenant can enter a voluntary "green lease" agreement with the sole purpose of reducing cooling energy and electricity use in compliance with legislations. A green lease typically provides specific information about the type of energy efficiency renovation, requirement for implementation and requirement of use behavior by the tenant who beforehand accepts higher rent for a specific period of time, and is compensated by energy bill savings (Ástmarsson, Jensenn, and Maslesa 2013). The landlord complies with the law and/or is saved from penalties for noncompliance with building energy consumption legislation. Green leases are recommended for landlords and tenants in short to medium-term leases. It is recommended that green leases be piloted mandatorily with residents of government and/or public estates and houses. The experiences gained could be used to create a standardized green lease document that would be made available to the general public together with information on the success story of the piloting thereafter. This is expected to create demand, and significantly lower the transaction costs of acquiring a new green lease.

Provisions of the National Energy Efficiency Action Plan that are currently in force for residential consumers is limited to minimum energy performance standards for household lighting, air conditioners and refrigerators (ECREEE 2015; Agyepong 2019). The utility sector's commitment so far has focused on advocacy for efficient energy use behavior (Electricity Company of Ghana 2020b). While utilities invest in creating consumer awareness for conservative energy use behavior, results in section 6.2.2 show that they would find it cost-effective to invest directly in residential energy efficiency retrofits. It is therefore recommended that legislative instruments be established to oblige the energy generation, transmission and distribution companies to achieve a specific amount of energy savings in the residential sector each year. This mandatory energy saving policy should be designed with restrictions on associated profits to avoid a situation where the consumers end up paying for the investment through electricity price increase. Utilities could meet their residential energy saving targets by directly funding energy efficiency renovation through rebates. The target savings must be achieved as effectively and affordably as possible. Benchmarking would therefore be necessary to monitor and evaluate the performance of the utilities. Savings in cooling energy demand by air conditioners could have the highest benchmarking factor as they yield maximum savings. Homes with the poorest energy performance and hence highest potential energy savings should have a higher benchmarking factor to prevent the utilities from cherry picking low hanging fruits in residential energy efficiency investment.

Financial institutions could offer "soft loans" with low interest rates for residential energy renovation if there is confidence in the information about the potential energy savings from the recommended retrofit on the energy label. When reliability of the energy label is coupled with possible rebate by the utility, a potential investor can prepare a proposal for a project with stable costs and assured return on investment. This is expected to encourage financial institutions, energy efficient air conditioner and building component manufacturers and suppliers, and installation services to actively engage in residential building energy efficiency. An investor, who wants to reduce the energy consumption of a home which in this case could be the homeowner or tenant, could then confidently acquire a low interest loan to finance the energy renovation.

Government could offer tax incentives to landlords whose buildings meet the minimum energy performance standards. Such homeowners could for example be exempted from paying property tax. It is expected that such incentives will urge homeowners to invest in energy retrofits or enter into green leasing with tenants.

Chapter 5

POTENTIAL OF DECENTRALIZED ROOFTOP SOLAR POWER GENERATION FOR SELF-SUPPLY

The IEA forecasts that, under current policies, residential cooling demand will increase from 11 TWh in 2018 to 65 TWh by 2040. Sustainable cooling solutions are necessary to balance electricity demand and supply in line with available power sources (Porcaro 2019). If there is political will for policy makers to prioritize clean energy technologies, solar PV could become the continent's largest electricity source in terms of installed capacity by 2040 (IEA 2019a). Rooftop solar PV systems could technically meet about 30% of cities' electricity demand by 2050 if new urban buildings are designed to cover their own electricity demand (i.e. become so-called prosumers) (IEA 2016). Aside reducing grid dependency, transition to decentralized renewables-based supply on the broader scale has the added advantage of quickly and effectively inducing efficient energy use behavior through awareness creation.

However, the timing of solar power generation usually does not coincide with the need for cooling in homes. Typically, excess PV-generated electricity is exported to the grid or stored with batteries (Porse et al. 2020). Application of the former in Ghana has been impeded by lack of integrated policy planning and infrastructure development failures discussed in section 2.3.2 and the latter by excessive cost of sizeable batteries needed to power air conditioners in the evening. While the non-aligning of solar power generation timing and periods of high electricity demand discourages patronage, it also offers opportunities for innovation in energy use pattern. This study therefore investigates the potential of rooftop-solar generated power to meet evening time cooling demand and daytime baseload of a home by answering the following research questions;

- Can the cooling schedule of a residential air conditioner be shifted without impairing thermal comfort?

- How much of cooling electricity demand can be supplied by rooftop solar PV if demand is shifted to align with solar power generation timing?
- How much peak shaving can be achieved with AC load shifting (pre-cooling)?
- How much of the home's electricity demand can be met by rooftop solar generation with and without AC load shifting (pre-cooling)?

Using the representative home for the Tema case study, these questions are answered for the various household energy demand classes. The methods and analysis to address these questions are described below.

5.1 Data, Assumptions and Methods

5.1.1 Daily load profiles

The homes are grouped by tariff classes (PURC Public Utilities Regulatory Commission 2019). The lifeline tariff homes (LLH) have monthly electricity consumption less or equal to 50 kWh, low tariff homes (LTH) have monthly consumption between 51 and 300 kWh, medium tariff homes (MTH) have monthly consumption between 301 and 600 kWh, and high tariff homes (HTH) have monthly consumption above 301 kWh. Figure 5.1 shows the monitored load profiles for MTH households (for LLH, LTH and HTH see Appendix A.4). As previously established in section 3.2.9.2 the income level of the home largely influences the amount of monthly electricity use. High income homes belong to the high tariff class and vice versa. Pre-cooling is only relevant for households that own air conditioners, so the lower-income LLH and LTH households are not considered. For households in the MTH and HTH categories, in each category the daily load profile measured in the REC survey is averaged over the week and reduced by the part of the load profile that is due to AC. The results are assumed to be the non-seasonal daily baseload profiles for MTH and HTH, and cover all residential appliances except AC.

The standard operating schedule of monitored residential air conditioners involves switching on the appliance when the room is occupied, and switching it off when the room is unoccupied. This study investigates the possibility of using rooftop solar electricity to run residential air conditioners during the day in efforts to "store" cooling energy in the building by pre-cooling the rooms ahead of their occupancy. Using the reference building modeled in DesignBuilder in section 4.1, it is assumed that MTH corresponds to Few Rooms cooled (master bedroom, bedroom and living room) and HTH corresponds to All Rooms cooled (master bedroom, bedroom, living room, study and dining area).

Daily temperature curves and electrical cooling load profiles are simulated in EnergyPlus for two different AC schedules, standard cooling and pre-cooling and for MTH and HTH homes. Temperature setpoint 18.5°C is used for standard cooling, and 18.5°C and 22°C temperature setpoints for pre-cooling. Standard cooling means that the AC operates on the baseline schedule and runs when the rooms are occupied, e.g. the AC in the bedrooms runs from the evening (9 pm) to the morning (7 am). Pre-cooling means that the AC runs during the day only (from 9am to 4pm), when heat gains are highest and at the same time that solar PV generation is available. The daily cooling electricity load profiles are averaged for dry season, rainy season and transition season.

To obtain the household daily load profile with standard cooling for each season, the seasonal daily cooling electricity load curve for standard AC schedule is added to the non-seasonal daily baseload curve. In analogy, the seasonal daily cooling electricity load curve for pre-cooling AC schedule is added to the non-seasonal daily baseload curve to obtain the household daily pre-cooling load profile for each season. This procedure is conducted separately for different households, MTH/Few Rooms cooled and HTH/All Rooms cooled, and at different temperature setpoints.

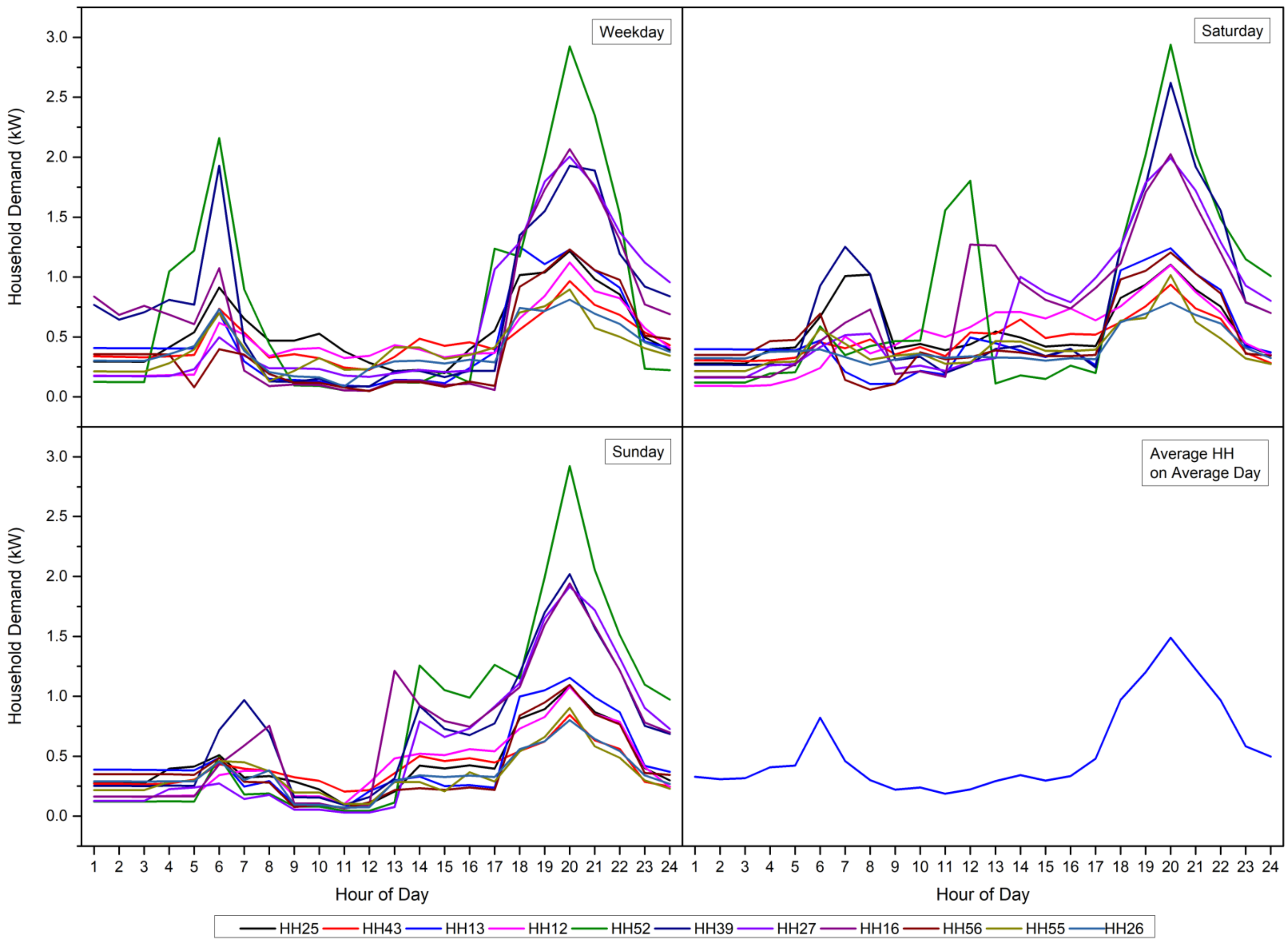

Figure 5.1: Measured hourly load profiles showing variation of electricity consumption in MTH households.

5.1.2 Potential for solar power generation

PVWatts is a web application developed by National Renewable Energy Laboratory for estimating the energy production of a photovoltaic (PV) system using hourly data for one year for two components of solar irradiance (beam and diffuse), as well as ambient dry bulb temperature and wind speed at 10 m above ground level. Technical reference describing the sub-models, documents assumptions and hidden parameters, and explanation of the sequence of calculations that yield the final system performance estimate can be found in

Table 5.1: Input parameters for PVWatts calculation.

Parameter	**Units**	**Value**
Location	-	Tema, Ghana
System sizes	kW (DC)	0.5, 1, 2, 4, 8
Module type	-	Standard Crystalline Silicon
Nominal module efficiency	%	15
Array type	-	Fixed, roof mount
System losses	%	14.08
Tilt angle	Degrees	20
Azimuth angle	Degrees	0, 90, 180, 270
DC/AC ratio	-	1.2
Inverter efficiency	%	96
Roof coverage ratio	-	0.4

(National Renewable Energy Laboratory 2014). The specific input parameters used in this study are as shown in Table 5.1. The PVWatts simulation provided hourly alternating current power output over the year for all investigated system sizes and azimuth angles. The daily AC power outputs were averaged for the dry season, rainy season and transition season.

5.1.3 Seasonal variations

The annual cooling energy demand and annual solar irradiation both show similar variations at different times of the year as shown in Figure 5.2. More solar irradiation means more solar PV power generation but also translates to higher solar heat gain which translates into high cooling electricity demand. Based on these observations, the year was divided into three seasons namely dry, rainy and transition. The dry season spans from January to April while the rainy season spans from June to August. The transition season includes September through December, and May. An average day in terms of cooling demand and solar power generation was calculated for analysis of load profiles in each season.

5.1.1 Prioritization of rooftop orientations for solar power generation

For standard crystalline silicon PV and the given efficiency, the investigated system sizes of 0.5 kW, 1 kW, 2 kW, 4 kW and 8 kW correspond to 3.35 m^2, 6.7 m^2, 13.4 m^2, 26.8 m^2 and 53.6 m^2 coverage areas on the roof of the representative building. Figure 5.2 shows that solar radiation received by the panels varies with season of the year and azimuth angle (orientation). The south roof (180° azimuth) receives the highest solar radiation in the hot and transition months but the lowest in the rainy season. The north roof (0° azimuth) receives the least solar radiation in the hot and transition months but the highest in the rainy season. At 90° and 270° azimuth, the east and west sides receive similar solar radiation through the months except between July and November when west receives slightly higher radiation due to different sun elevation angles in the northern and southern skies. The geometry of solar panels and sloped roofs limit the number of panels that can be mounted

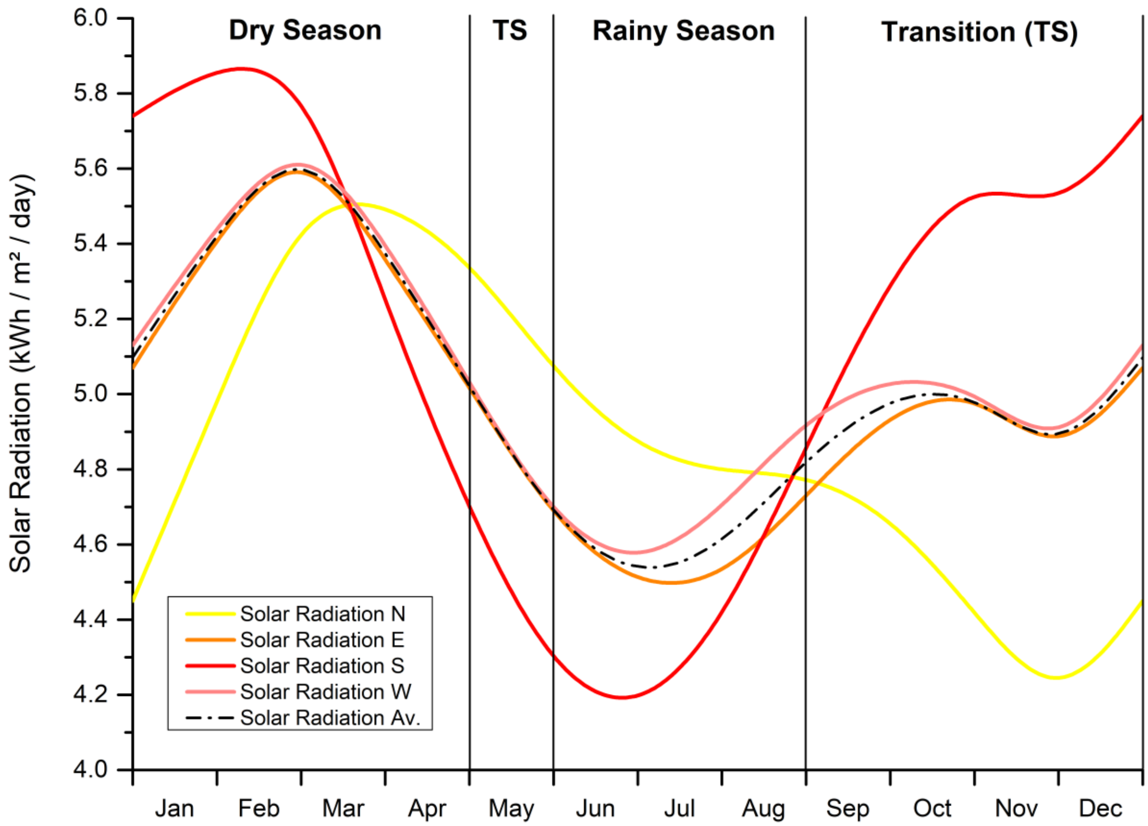

Figure 5.2: Definition of solar seasons for calculation.

on each side of the roof. It is assumed that the roof area is evenly distributed across all four orientations, i.e. distribution of arrays over the roof area is limited to 15 m^2 per side. To optimize electricity gain, priority is given to azimuth angles that receive the highest solar radiation in the hottest periods of the year when cooling is most needed. Therefore arrays of systems whose sizes require up to 15 m^2 roof coverage are mounted on the south side of the roof. Remaining arrays of larger system sizes are then mounted on the west side of the roof until 30 m^2, followed by the east side of the roof until 45 m^2 and lastly by the north side of the roof for the systems whose arrays require up to 60 m^2 of roof area.

5.2 Results

5.2.1 Precooling and thermal comfort

Variation of room air temperature for pre-cooling at setpoint temperatures 18.5°C and 22°C in comparison with uncooled room air temperature is reported in Figure 5.3 for the average day in dry season (the hottest). After the AC is switched off in the late afternoon, the cooled rooms start heating up again to a maximum of ca. 24°C and 25°C at 6pm (sunset) for 18.5°C and 22°C setpoint and maintained through the night. This is higher than the original AC setpoint temperature but remains significantly below the temperature of uncooled rooms. Nonetheless, these temperatures conform to the recommended 25°C thermostat setting for reasonable indoor thermal comfort in Ghana (Electricity Company of Ghana 2020b) and lie within the lower limits of ASHRAE 55-2013 specification of 23-27°C air temperature for indoor thermal comfort during the summer months in the United States (Standard 2013). Thermal comfort can be further improved by using fans in the evening.

It is observed that if the AC setpoint temperature for pre-cooling is increased from 18.5°C to 22°C, the maximum evening and night temperature increases just slightly by approximately +1°C due to the smaller temperature differential to environment and corresponding smaller external heat gains. On the other hand, the required cooling electricity for pre-cooling during the day can be reduced by more than 30% if the higher temperature setpoint is selected. Therefore, it can be concluded that the operating schedule of a residential air conditioner can be effectively shifted to align with solar power generation without impairing the thermal comfort of residents during evening and night occupancy.

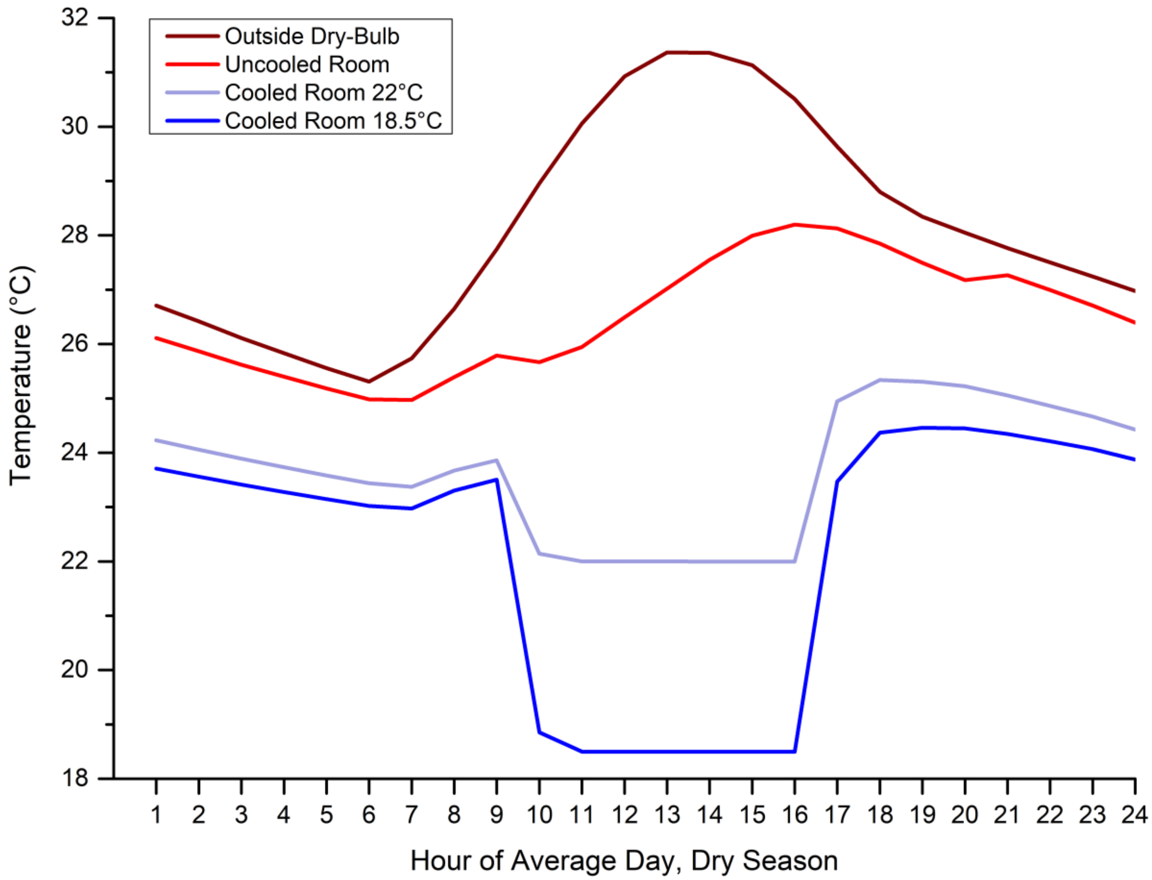

Figure 5.3: Daily variation of room air temperature for AC pre-cooling at 18.5°C and 22°C in dry season.

5.2.2 Potential of rooftop solar PV to meet the energy demand for AC precooling

The average daily electricity demand profiles of the MTH and HTH households are presented for AC operation at standard and pre-cooling schedules in Figure 5.4 and Figure 5.5 together with the power output curve of differently sized solar PV systems for the hot, rainy and transition seasons. As expected, HTH load is higher than MTH load in all cases because more rooms are cooled in the HTH. The load profiles of the standard cooling schedule have flat morning peaks between 6-9 am when solar heat gains start to increase, and high evening peaks around 9 pm when the bedrooms are cooled to the setpoint temperature. It is noteworthy that the evening peak load is highest during transition season, slightly lower during rainy season and lowest during the hot season. The reason is the high air humidity in transition and rainy seasons which requires additional energy for latent cooling by the AC. The load profiles of the pre-cooling schedule have wider peaks that start at 9 am when cooling is activated and solar heat gains increase in line with solar power generation until 4 pm, when cooling is deactivated and solar radiation decreases to less than half of the daily maximum. A 2 kW solar PV system corresponding to 13.4 m^2 of solar array oriented south, generates sufficient power output in all seasons to fully meet the MTH electricity demand for AC precooling and the non-seasonal daily baseload within that period when cooling temperature is set at 22°C. The same holds for a 4 kW solar PV system, corresponding to 26.8 m^2 of solar array with half of the panels oriented south and the other half oriented west. This system can also supply the HTH electricity demand for AC precooling at 22°C setpoint temperature for all seasons. Indeed, when high solar irradiation causes external heat gains and cooling electricity demand to increase in the hot season, the solar PV power output increases also.

It should be noted that adequately sized solar PV generation need not be larger than electricity demand at every point in time as shown in Figure 5.4 and Figure 5.5. When the total solar energy yield is sufficient, the deficit of solar PV output in one hour can in principle be compensated by surplus solar PV output in another since the building acts as cooling energy storage. For example, the solar power generation of a 4 kW system (corresponding to 26.8 m^2 rooftop solar array mounted in south and west orientations) can meet the electricity demand for MTH AC pre-cooling at 18.5°C setpoint temperature and HTH AC pre-cooling at 22°C setpoint temperature. However, as described previously there is only small benefit in evening thermal comfort for pre-cooling at the lower temperature.

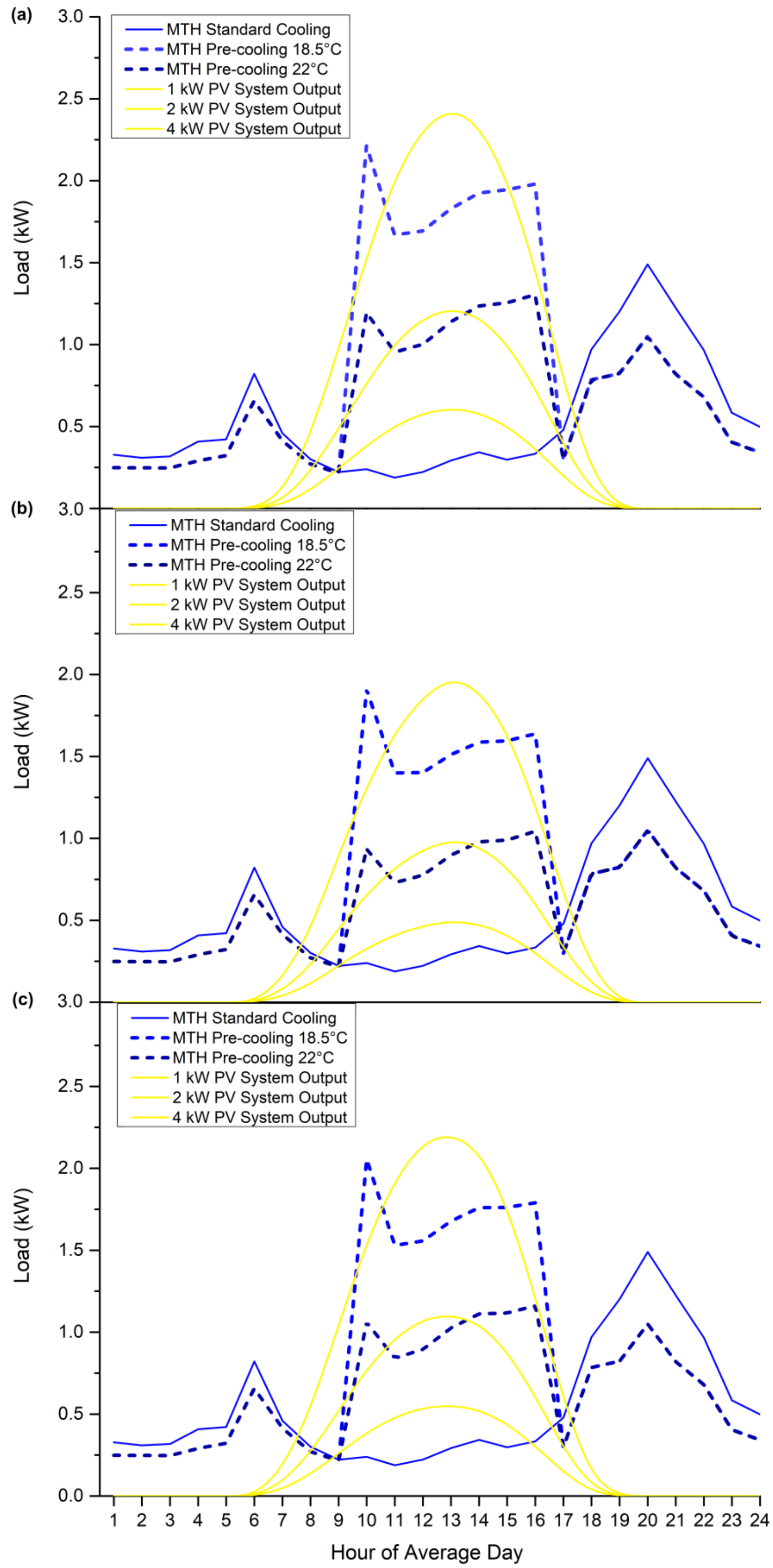

Figure 5.4: Daily profiles of MTH electricity demand for different cooling schedules and solar PV generation for different system sizes in dry (a), rainy (b) and transition season (c).

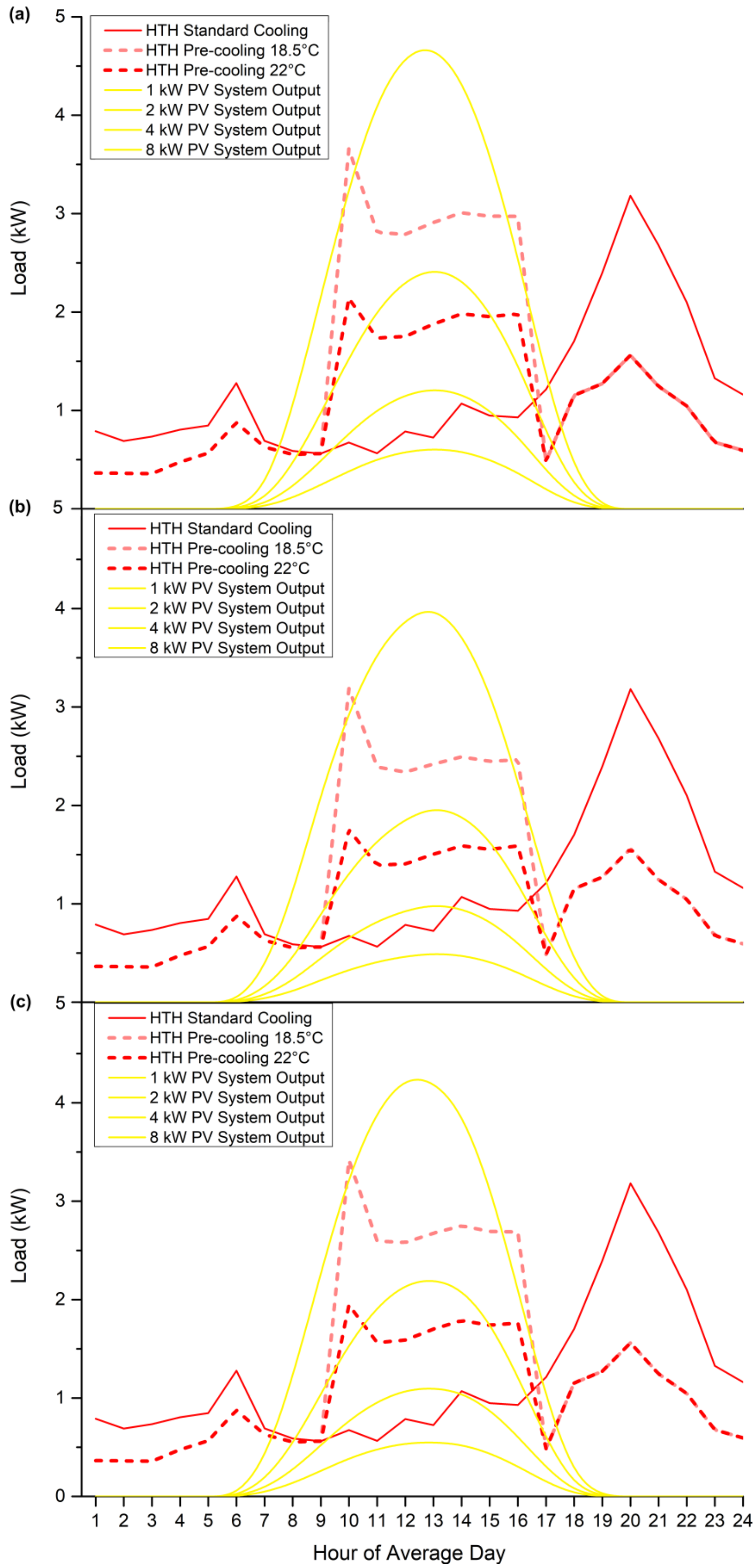

Figure 5.5: Daily profiles of HTH electricity demand for different cooling schedules and solar PV generation for different system sizes in dry (a), rainy (b) and transition season (c).

5.2.3 Potential peak shaving from pre-cooling

Since the AC load can be shifted completely without impairing residents' thermal comfort, and supplied by rooftop solar PV generation, the amount of potential peak shaving with the described cooling schedule corresponds to the AC share of the evening peak load. The AC share of the peak load measured in the residential monitoring study (rainy season) amounts to 30% for the average MTH and 50% for the average HTH. The cooling energy simulation yields between 25% and 31% peak shaving potential depending on the season, with a slight difference between MTH and HTH. This means the HTH sample in the monitoring study uses AC more intensively than the reference HTH modelled in EnergyPlus. Given that residents of Ghana frequently suffer pockets of power supply shortages at peak hours (Diawuo et al. 2019), and expansion of energy supply infrastructure is necessary to accommodate future demand growth (Diawuo et al. 2020), the 30% peak shaving potential is very significant. This potential should encourage utilities to consider financial incentives for consumers to adopt AC pre-cooling particularly if it is combined with rooftop solar PV system to offset the new midday peak.

5.2.4 Solar fraction of household electricity demand

The share of a household's total daily electricity demand that can be met by rooftop solar PV is termed the solar fraction. It is mainly determined by the size of the PV system and the amount of residential load during hours of solar PV generation assuming there is no battery storage system. Table 5.2 shows the seasonal solar fractions for MTH and HTH; standard cooling and pre-cooling schedules; 18.5°C and 22°C AC cooling temperature; and different sizes of solar PV systems. The results were calculated for a baseline efficiency AC with EER 2.8 W/W. If a more efficient AC is installed and all other parameters remain constant, the solar fraction will increase because the total daily electricity demand in the denominator reduces.

The solar fraction is generally higher during hot season and lower for rainy season and transition season, but the seasonal spread is small due to the near-constant annual sun path and solar irradiation affecting both cooling electricity demand and solar PV output. Higher AC cooling temperature decreases the cooling electricity demand and increases solar fraction. The solar fraction increases with the size of the solar PV system as expected, but double system size does not necessarily translate into double solar fraction if part of the PV output curve is in excess of the residential load profile and cannot be used. The shift of AC cooling load allows the homeowner to mitigate this issue and effectively use the PV output of multi-kW solar PV systems, as illustrated by the increase of solar fractions between standard cooling and pre-cooling. If AC pre-cooling at 22°C cooling temperature is adopted, at a PV system size of 4 kW for MTH and 8 kW for HTH, there is sufficient excess solar power generation available for the household to reach grid independency if the excess energy is stored in a battery. This may be a very relevant aspect for affluent homeowners as security of supply is, unlike in Western economies, not a given in Ghana's electricity system. How much of this potential should be realized in practice is typically an economic decision, which is assessed in section 6.3.

Table 5.2: Seasonal solar fractions as function of cooling temperature, cooling schedule, household and size of solar PV system.

Solar Fraction	**18.5°C Cooling Temperature**			**22°C Cooling Temperature**		
Season	Hot	Rainy	Transition	Hot	Rainy	Transition
MTH, Standard Cooling, 500 W PV	9%	7%	7%	-	-	-
MTH, Standard Cooling, 1 kW PV	13%	10%	10%	-	-	-
MTH, Standard Cooling, 2 kW PV	20%	16%	16%	-	-	-
MTH, Standard Cooling, 4 kW PV	28%	23%	23%	-	-	-
MTH, Pre-Cooling, 500 W PV	10%	9%	10%	13%	12%	13%
MTH, Pre-Cooling, 1 kW PV	20%	17%	19%	26%	23%	25%

MTH, Pre-Cooling, 2 kW PV	38%	33%	37%	47%	42%	45%
MTH, Pre-Cooling, 4 kW PV	62%	58%	60%	57%	52%	54%
MTH, Pre-Cooling, 4 kW PV, Battery	78%	73%	76%	103%	96%	100%
HTH, Standard Cooling, 500 W PV	6%	5%	5%	-	-	-
HTH, Standard Cooling, 1 kW PV	12%	9%	10%	-	-	-
HTH, Standard Cooling, 2 kW PV	18%	15%	15%	-	-	-
HTH, Standard Cooling, 4 kW PV	24%	21%	21%	-	-	-
HTH, Standard Cooling, 8 kW PV	31%	28%	26%	-	-	-
HTH, Pre-Cooling, 500 W PV	6%	5%	6%	8%	7%	8%
HTH, Pre-Cooling, 1 kW PV	13%	11%	12%	16%	14%	16%
HTH, Pre-Cooling, 2 kW PV	25%	22%	24%	32%	28%	31%
HTH, Pre-Cooling, 4 kW PV	47%	44%	46%	54%	50%	52%
HTH, Pre-Cooling, 8 kW PV	66%	64%	65%	60%	56%	57%
HTH- Pre-Cooling, 8 kW PV, Battery	96%	94%	93%	124%	122%	120%

5.3 Policy implication

The Government of Ghana implemented the national rooftop solar program in February 2016 as a capital subsidy scheme under which beneficiary homes receive capital subsidies which cover the cost of the solar panel component of the Solar PV system up to a maximum of 500Wp, on condition that the homeowner beforehand purchases and installs the balance of system components such as inverter, batteries, charge controllers, change over switch, wiring, etc. and have only LED lamps in the home (Energy Commission 2016; Appiah 2017). The target of the program is to install 200,000 solar PV systems up to a capacity of 200MW by the end of 2030 on rooftops across the country as part of measures to shave off peak load and reduce dependency on the grid (Appiah 2017).

The national rooftop solar program while commendable has design limitations that inhibit mass patronage and full realization of its intended benefits. The 500Wp cap is disadvantageous to homes with air conditioning and high-end appliances whose owners are most likely to afford the high costs of the balance of system component prerequisite. Such homes would still need to depend on the grid to meet a rather very large fraction of their electricity demand even with battery storage which increases costs exponentially. It can be seen in Appendix A.4 that while the 500Wp is suitable for the daytime energy needs of the financially constrained LLH and LTH homes, it is woefully inadequate for the economically capable HTH homes and some of the MTH homes.

It is recommended that the current capital subsidy scheme shifts focus to low income and low energy intensity homes without air conditioners (LLH and LTH). Policy design for medium and high energy intensity homes with air conditioners (MTH and HTH), should target creating an enabling environment for sustainable cooling by combining room pre-cooling with efficient air conditioners powered with solar PV generation. Similar to the refrigerator rebate program, rebates could be offered on efficient air conditioners to be used in combination with solar PV. It is recommended that such equipment should have minimum EER of 3.8 W/W, and minimum setpoint temperature of 22 ^{o}C. This could enable necessary increase in use of air conditioning in the future without exacerbating current grid supply disruptions.

Chapter 6

ECONOMIC ASSESSMENT OF COOLING DEMAND REDUCTION MEASURES AND SOLAR PV SYSTEMS

The technology options to decrease building cooling energy demand to nearly zero energy standards are readily available and economically viable in many cases (Camarasa et al. 2019). Lessons from the European housing market, where building energy performance regulations and control instruments have been practiced for decades, prove that the potential energy cost savings that are commonly considered as the only financial benefit do not sufficiently motivate building energy efficiency investments (Camarasa et al. 2019). However, such investments yield a wide range of potential positive side effects beyond the direct energy benefits, so-called co-benefits that can be put in four main clusters: economic (e.g. job creation, increase of GDP, energy prices, etc.), social (e.g. energy poverty alleviation, reduction of health expenses, etc.), environmental (e.g. reduction of CO_2, reduction of local air pollution) and energy delivery (e.g. improved utility services and security of supply) (Mzavanadze et al. 2015). The co-benefits of energy efficiency investment can affect stakeholders differently. For example, there are benefits for the homeowner through asset value increase; for the utility service provider by improving security of power supply through resource conservation and mitigating the need for costly capacity expansion of power generation and grid infrastructure; and for society as a whole by decreasing local air pollution, increasing public budget or improving industrial productivity (Camarasa et al. 2019). The following section assesses the cost-effectiveness of investment in residential cooling demand reduction measures in Tema city from three perspectives: 1. the residents who bear the running cost of living in the conditioned space, 2. the utility that generates and/or supplies electrical power to run the AC, and 3. society as a whole which suffers global heating due to associated carbon emissions. All prices were converted to US$ for consistency and ease of comparison.

6.1 Method

The cost-effectiveness of investment is assessed for each measure using the established net present value (NPV) analysis as primary indicator. In addition, static payback time (SPT) and return on investment (ROI) provide useful context and reinforce economic justification for residential building energy efficiency investment from a public policy perspective. The NPV is a sum of all cash flows e.g. costs and savings generated by the investment in the course of the financial analysis period, discounted to their present value. A measure is considered cost effective if the NPV is greater or equal to zero which means the monetary benefits exceed costs, and financially viable if the SPT is less than the financial analysis period or the useful lifetime (whichever is smaller).

6.1.1 Homeowner's perspective

The economic viability of the discussed technology and building measures is assessed from the homeowner's perspective in the following. The cost effectiveness of energy efficiency investment is evaluated for retrofit and new build, where the full investment cost is assumed for retrofit and the efficiency premium compared to baseline solution is adopted for new build. The reason is that retrofit requires full cost of replacement and new build requires incremental cost of the energy efficient technology or material in comparison with the business-as-usual technology or material that would have otherwise been used. A summary of the investment costs for the various energy efficiency measures considered is presented in Figure 6.1. The single measures investigated can be classified as AC efficiency improvement paired with cooling fan and thermostat adjustment (a), new window glazing type (c) for both retrofit and new build, and optimized thermal behaviour of walls for new build only (d). Investment costs associated with walls apply to the entire building whereas the other measures apply to the cooled rooms only.

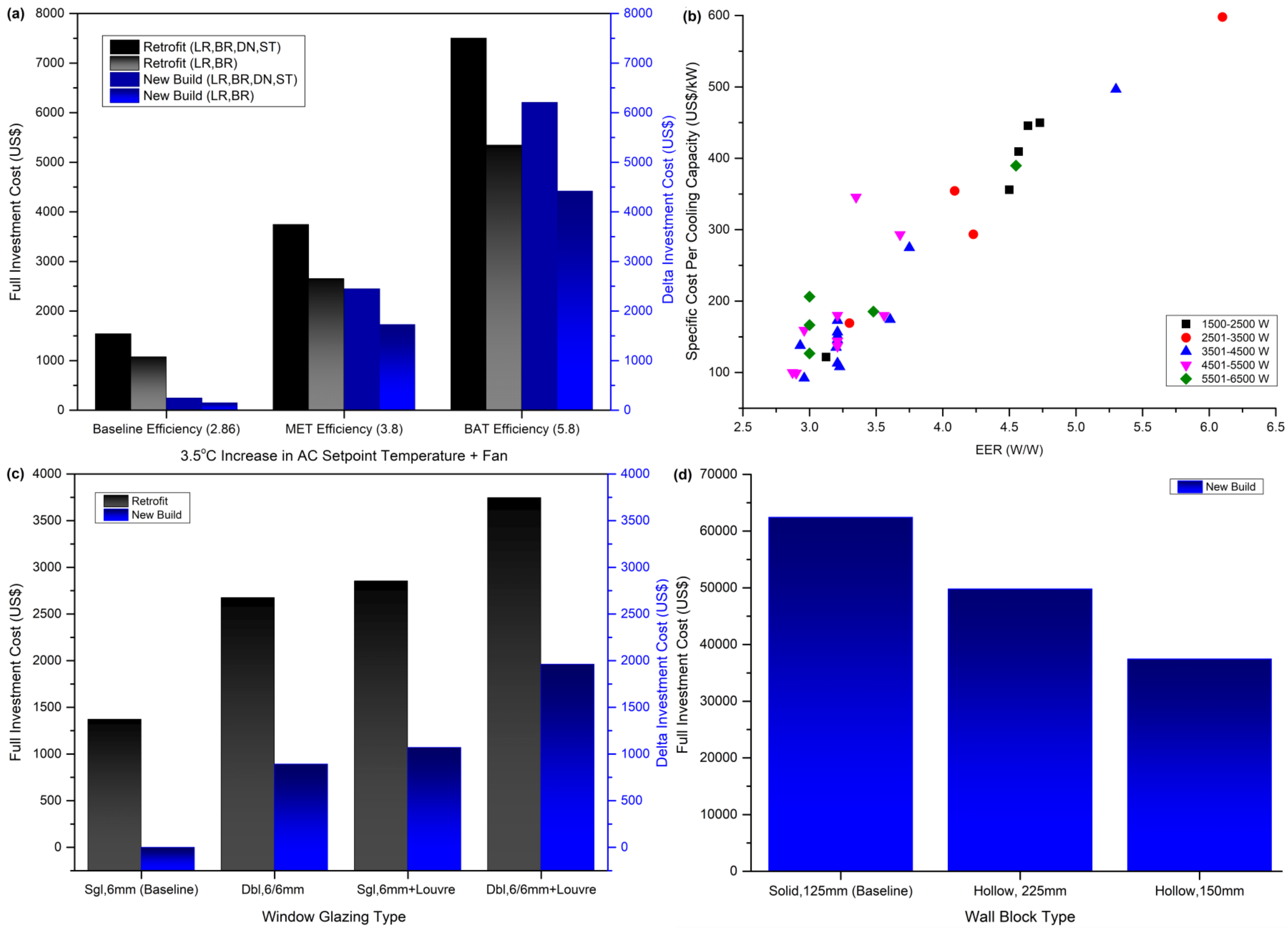

Figure 6.1: AC investment cost, total (a) and specific to unit size (b). Investment blocks for windows (c) and wall blocks (d). Full investment cost is shown to illustrate relative cost savings, but in investment calculation for new build the baseline is set to zero.

Basic input data for evaluating the cost effectiveness of the efficiency measures are given in Table 6.1. Since access to capital is a huge barrier to investment in Ghana (K. A. Agyarko, Opoku, and Buskirk 2020), this study considers implementation of energy efficiency measures as commercial investment, and adopts a ten-year analysis period that matches the maximum time for long-term loan repayment in Ghana (Ecobank Ghana 2020). The useful life of the components of the energy efficiency measures is assumed as 15 years for AC and fan, 30 years for windows and 50 years for walls, all of which continue to provide energy cost savings beyond the analysis period. The selected financial analysis period therefore means that efficiency measures must show a payback time of less than ten years to be considered financially viable. This is stringent in comparison with the US Department of Energy's 30-year analysis period for example (Taylor, Mendon, and Fernandez 2015). It is assumed that the investment is funded upfront with own capital, i.e. there is no additional cost of capital or interest and the discount rate is equal to inflation rate.

Table 6.1: Basic input parameters for financial calculation.

Input parameter	**Unit**	**Value**
Base year	-	2020
Financial analysis period	years	10
Discount rate (WACC)	% p.a.	8
Change of electricity end user tariff	% p.a.	6
AC efficiency decrease, proper maintenance	% p.a.	-1
AC efficiency decrease, unmaintained	% p.a.	-3
Solar PV efficiency decrease	% p.a.	-1
Exchange rate	US$/GHS	0.19
Specific gas fuel cost, West-Africa Pipeline	US$/mscf	9
Change of bulk natural gas tariff	% p.a.	6
Electrical efficiency gas-fired power generation	%	60
Grid efficiency (transmission, distribution)	%	78
Specific investment, combined-cycle single-shaft*	US$/$kW_{el}$	1079
Fixed operating cost, combined-cycle single shaft*	US$/$kW_{el}$ p.a.	14
Variable operating cost, combined-cycle single shaft*	US$/$MWh_{el}$	2.54
Specific CO_2 emissions, combined-cycle single shaft*	Gg/GWh_{el}	0.34

*Source: (US Energy Information Administration 2020)

The price of electricity delivered to residential consumers in Tema city was taken from ECG's electricity tariff reckoner effective October 1st, 2019 (Electricity Company of Ghana 2020a). Unlike some countries where residential electricity tariffs are dependent on time of use, Ghana's residential electricity pricing is based on monthly consumption bands. The monitoring survey found that households with air conditioners had average monthly consumption between 301 kWh and 601+ kWh band ranges, with a majority of about 78% falling in the 301 – 600 kWh band. The sub-tariffs for these bands were thus selected for analysis of delivered electricity prices and cost savings from implementing energy efficiency measures. The unit price of delivered electricity by ECG, which serves the city of Tema, varies significantly between tariff bands and within the same tariff band as shown in Figure *6.2* (a). It can be inferred that in a home with multiple ACs and cooling as the dominant electricity end-use, implementation of energy efficiency measures will likely change the end-user tariff to a lower tariff band. For most simulated scenarios, the reduced cooling electricity use shifted the home's total monthly electricity cost to a lower tariff band in addition to direct cost savings from saved electricity. Ghana's PURC has instituted a lifeline tariff for low income consumers with consumption levels that are lower or equal to 50 kWh/month, at rates below the cost of electricity provision in consonance with the Government of Ghana's Poverty Reduction Strategy though none of the surveyed homes with ACs falls in this tariff category (Kumi 2017). Figure 6.2 (b) shows that electricity tariffs in Ghana are very dynamic, depending on variations in factors such as fuel price (light crude oil, natural gas, diesel fuel oil, etc.), foreign exchange, inflation and the generation mix. The average end-user tariff varied up to 247% between 2006 and 2016. PURC has hence incorporated an Automatic Adjustment Formula (AAF) with the aim of sustaining the real value of electricity provision by adjusting the tariffs in response to variations in the above listed factors. For the ten year analysis period under the homeowner/resident's perspective, projected electricity prices are assumed to conform to the year-on-year average over the last 15 years with average annual growth of 6%.

The costs of wall and window materials for the developed scenarios are taken from DesignBuilder data on construction materials. The investment cost factors of the window glazing types are 130, 195, 208 and 273 US$/m^2 respectively for the single glazing, double glazing, single glazing plus exterior wooden louvre shading and double glazing plus exterior wooden louvre shading. The total area covered by windows and walls are obtained from the model drawing of the representative building. The total mass of material used in constructing the walls is obtained as the product of the total wall area (m^2), thickness of a block unit (m) and density of a block unit (kg/m^3). The total cost of the building wall is then derived as a product of block material cost factor (US$/m^3) and total mass of material used (kg).

The prices of energy performance rated air conditioners of varying cooling capacities were gathered from major retail outlets in Ghana (Electroland Ghana Ltd 2017; Electromart Ghana Inc. 2020; CompuGhana 2020; Daikin 2020; Ultimate Air Ltd 2017), and plotted as specific cost per cooling capacity and energy efficiency ratio (EER) as shown in Figure 6.1 (c). Prices were collated only for new air conditioners. Used or second hand units were not considered because the useful lifetime varies widely. Few data points were available for efficiency higher than 5 W/W. Still, there is clear indication that the cost of an AC unit varies with both capacity and efficiency. This finding contradicts that of Gyamfi et al. (2018) and Agyarko et al. (2020) who found that the price of air conditioners in Ghana do not rise with increase of EER. There are two main reasons for this apparent disparity. Firstly, both studies have a common data source which indicates inclusion of used or second hand air conditioners that typically have lower costs. Therefore at the same rated EER, a used AC would cost much lower than a new unit except that the efficiency of the used unit will deteriorate significantly faster than the new one due to its age. Secondly, the influence of capacity on AC cost was completely ignored by both studies. As this study shows, at the same EER, the price of an AC increases as the capacity of the unit increases.

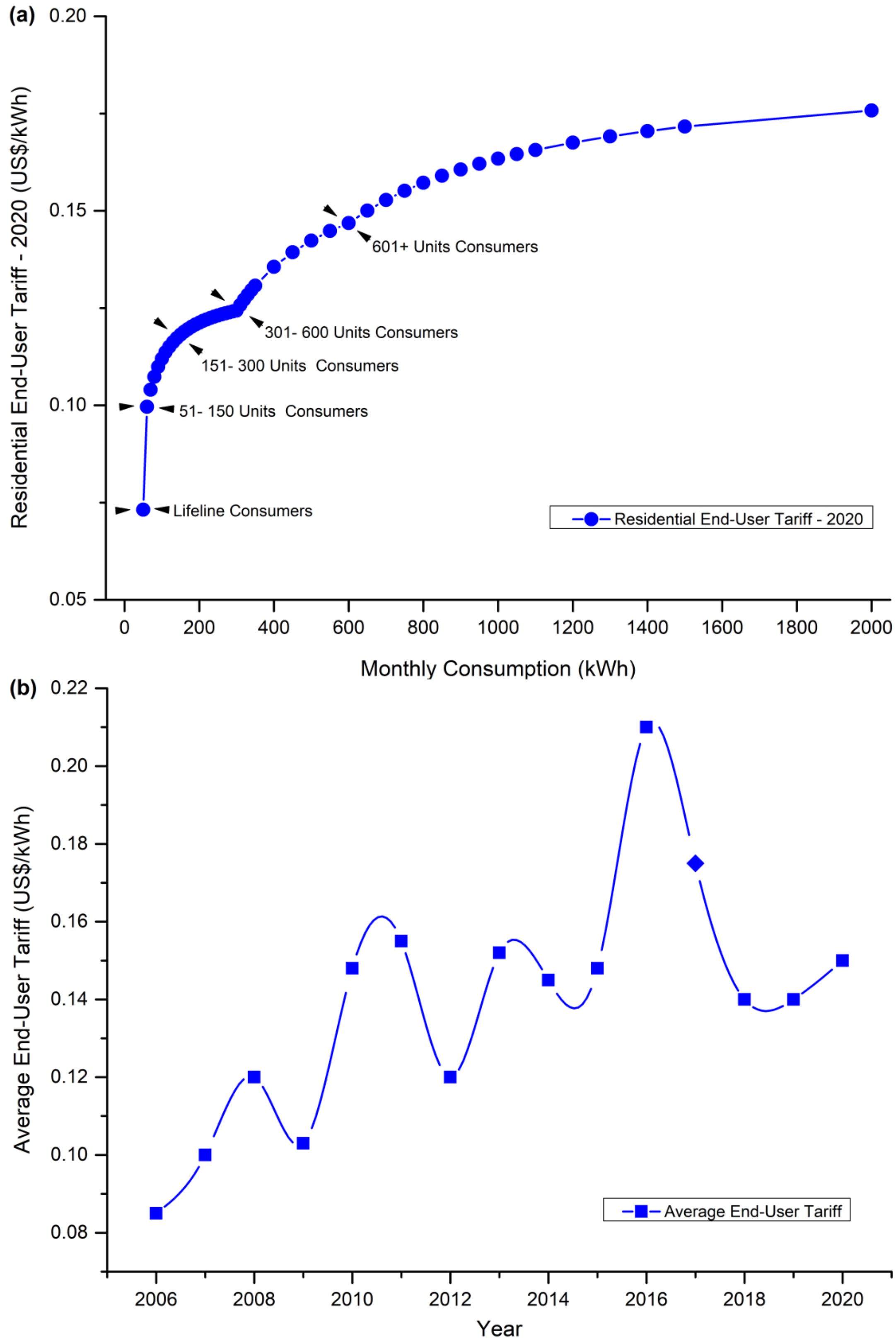

Figure 6.2: Variation of electricity tariff for Tema end users over monthly consumption (a), historical (b).

The simulation assumes uniform efficiency for all ACs in the home. Therefore, the average of all specific costs corresponding to the efficiency level of a defined scenario was adopted as the purchase or investment cost factor of ACs in that scenario. The AC units in the BAU, MET and BAT scenarios resultantly have estimated investment cost factors of 100, 270 and 560 US$/kW cooling capacity respectively. The cooled rooms in the representative home are the living room (LR), two bedrooms (BR), dining (DN), and study (ST) for the high-income household (HTH). Together, the home requires a simulated total cooling capacity of 12.96 kW. The required investment cost is obtained as product of the specific investment cost (US$/kW) and the total cooling capacity (kW). The number of cooled rooms is reduced to living room and two bedrooms for the medium-income household (MTH), with total cooling capacity of 9.28 kW. The energy efficiency of an AC unit is not static, and reduces gradually over its lifespan due to several factors including filter and evaporator coil fouling, improper refrigerant charge and cyclic operations (Fenaughty, Parker, and Solar 2018). An AC performance degradation coefficient, which is a measure of the rate of efficiency loss over the lifetime of the equipment, is introduced to account for this. The annual AC performance degradation coefficient is taken as 1% and 3% respectively for ACs that are maintained per manufacturer's recommendation and ACs without proper maintenance (Matson et al. 2002; Fenaughty, Parker, and Solar 2018).

The thermostat adjustment with complementary cooling fan measure is investigated by increasing the setpoint temperature on the AC from 18.5°C to 22°C, and introducing a fan for optimized circulation of cool air from the AC. Since most indoor units of AC systems from the survey are not centrally located in the rooms they cool, a standing fan is assumed because it offers more flexibility with respect to the position of the AC unit. The Binatone industrial 18 inch stand fan, with 60 Watts power rating and measured average annual electricity use of 100 kWh, was selected to complement ACs in cooled rooms. Its investment cost factor is US$ 50 per fan per room (Melcom Group Ghana 2020a). It should be noted that ceiling fans with similar power rating and annual electricity use are available at lower investment costs (Melcom Group Ghana 2020b).

The cost-effectiveness of using energy efficient walls is considered for new build only. It can be seen that choosing hollow blocks over solid blocks in constructing residential buildings yields significant investment cost savings in addition to potential reduced electricity use for cooling. The 225mm and 150mm hollow blocks respectively provide US$ 12,619 and US$ 24,962 instant investment cost savings for the representative home in comparison with the widely used 125mm solid block. This is because the air gap in the hollow block gives it a lesser density, and requires less mass and/or volume of sand, cement and water to manufacture.

The total investment costs for ACs increase with efficiency. The costs of the BAT AC with EER of 5.8 W/W and the MET AC with EER of 3.8 W/W respectively correspond to 330% and 180% of the BAU AC cost with EER of 2.86 W/W, which conforms to Ghana's minimum energy performance standard for air conditioners. The total investment cost also increases with increasing number of cooled rooms and hence total cooling capacity required in the household. The AC investment cost of the medium-income household is 28 percent lower compared to the high-income household, where dining room and study are cooled also.

The potential impact of a change of cooling habits is investigated via thermostat adjustment with complimentary cooling fan. This measure maintains AC investment cost per EER, with additional US$ 50 investment in one cooling fan per cooled room. Therefore, the added investment cost similarly increases with rising number of cooled rooms. Bill savings gained from reduced electricity use due to increased thermostat setting are expected to offset the small additional expense of fans.

The net present value for investment in an energy efficient retrofit measure is calculated as the present value of all costs and benefits summed over the analysis period:

$$\mathrm{NPV} = -I_0 + S_0 \sum_{t=0}^{n-1} \frac{(1 + e_p + l)^t}{(1 + i)^t}$$

Where I_0 is investment cost of replacement (US$), S_0 is annual electricity bill savings (US$/yr), e_p is annual rate of electricity price increase, l is annual AC efficiency loss (-1% with maintenance and -3% without maintenance), i is annual discount rate, and n is the number of years in the analysis period. The equation is also used for evaluating the NPV of energy efficiency measures in new build, but the total investment cost I_0 is replaced with the efficiency premium on top of baseline cost I_Δ. The incremental cost of investment I_Δ is defined as the difference between total investment cost of the efficiency measure I_0 and the investment cost of the baseline efficiency technology/material I_{base}.

The annual return on investment (ROI) is the NPV divided by investment cost and number of years in the analysis period:

$$\text{ROI} = \frac{\text{NPV}}{n\, I_0}$$

It follows that the investment is positive if ROI ≥ 0. The equation is also used for evaluating the ROI of efficiency investment in new build, but in analogy to NPV the total investment cost I_0 is replaced with the incremental cost of investment compared to baseline I_Δ.

The static payback time (SPT) of an investment is defined as the ratio of the investment cost (I_0 for retrofit, I_Δ for new build) to the net annual electricity bill savings it generates:

$$\text{SPT} = \frac{I_0}{S_0}$$

This metric is useful for simple investment appraisal by homeowners, real estate developers, investors and financial institutions as it represents the number of years required for the energy savings to return the investment cost without discounting over time.

6.1.2 Utility perspective

The height and duration of spikes in electricity demand have significant impact on the cost of generation due to the fact that peak load costs in Ghana include the maintenance of thermal generation, transmission and distribution resources that are rarely used (Electricity Market Oversight Panel Secretariat 2016). These "costs" can be considered potential savings that would occur if peak demand were reduced via residential energy efficiency initiatives. The production cost of gas-fired thermal power generation (Energy Commission 2017), in a combined-cycle gas turbine at 60% heat to power efficiency with transmission and distribution losses at 22.25% (IEA 2017), was determined to assess the economic dimension of residential cooling demand reduction from the utility provider's perspective. As electricity demand grows in the projected homes, reserve plants may become fully operational and/or new generation plants may be required to meet the demand. It is assumed that in all cases the price-setting generation technology in the merit order is gas-fired power generation. The cumulated production cost savings to the utility service provider in terms of avoided import fuel cost are estimated as follows:

$$S_n = \frac{C_0}{\eta_{gen}\eta_{grid}} \sum_{t=0}^{n-1} E_t \ (1+g)^t$$

Where S_n are generation cost savings (US$) cumulated over n years, C_0 is the specific import cost for West-Africa Pipeline gas (US$/GWh$_{th}$), η_{gen} is heat to power efficiency of thermal generation, η_{grid} is efficiency of the transmission and distribution system, E_t are the city-level electricity savings in year t for the given efficiency scenario vs. 2020 baseline efficiency (GWh$_{el}$), and g is the annual price increase for natural gas (%). The latter is set to 6% per year, consistent with the projected price increase in electricity end user tariff.

6.1.3 Society perspective

Residential electricity demand in Ghana is met by generation from a mix of primary energy sources including hydro, natural gas, diesel fuel oil, residual fuel oil, light crude oil and solar PV as discussed in section 2.2.3. Based on current shares in the generation mix, natural gas represents the conservative average in terms of combustion source, emission and generation cost factors. The environmental cost savings to society correspond to avoided carbon emissions G_n due to energy efficiency improvement in homes, and are defined as the product of annual electricity savings E_t (GWh_{el}) cumulated over time and the emissions factor G_E for gas-fired power generation in Ghana ($GgCO_2e/GWh_{el}$):

$$G_n = G_E \sum_{t=0}^{n-1} E_t$$

It should be noted that this simplified calculation underestimates the real emissions because the unknown emissions due to production, processing and transport of natural gas, with a specific greenhouse gas effect about 25 times as strong as CO_2 for a 100-year time frame, are neglected.

6.1.4 Financial assumptions for rooftop solar PV systems

The financial assessment of investing in solar PV is conducted according to the same method described in section 6.1.1 for energy efficiency retrofit from homeowner's perspective (i.e. the full investment cost I_0 is used). Net present value, return on investment and static payback time are the key performance indicators for the assessment. A longer financial analysis period of 20 years is selected, which is considered reasonable as the useful lifetime of properly maintained solar PV is typically 25 years or more. The main difference is the calculation of potential electricity cost savings, assuming that the investment in solar PV is accompanied by a change of cooling schedule from AC standard cooling as a function of room occupancy to AC pre-cooling, in order to coincide with the midday availability of solar PV generation (see sections 5.2.1 and 5.2.2).

The specific investment cost adopted for a solar PV system without battery is 2080 USD/kW in 2020. (Appiah 2016) reported a base cost of 5000 GHC for a 500 kW solar PV system (panels, inverter, charge controller) in Ghana, corresponding to 2600 USD/kW in 2016 using the exchange rate at the time. According to NREL (National Renewable Energy Laboratory 2019), the cost of a solar PV system is expected to decline by 130 USD/kW/year with base year 2017. Assuming this annual cost decline also holds from 2016 to 2017, the resulting cost in 2020 is the stated 2080 USD/kW. It should be noted that NREL's PV base cost of 2770 USD/kW in 2017 is slightly higher than the base cost mentioned above. This is explained with the higher labour costs in the U.S. compared to Ghana, which affect all non-material costs included in the investment cost such as engineering, permitting, roof preparation, installation, inspection and commissioning. The specific cost of a Lithium-Ion battery storage system in 2020 is interpolated from the cost projection in US Department of Energy's Energy Storage Technology and Cost Characterization Report as 439 USD/kWh (National Renewable Energy Laboratory 2019).

The homeowner's annual cost savings generated by the solar PV system are equal to the difference between the baseline electricity bill for standard cooling at 18.5°C and the residual electricity bill, which is reduced by 1. AC load shift to daytime pre-cooling and 2. Use of solar PV output to offset the new load profile (see section 5.2.2). The baseline electricity demand and residual electricity demand are calculated separately based on daily MTH and HTH load profiles and solar PV output curves for hot season, rainy season and transition season. If the hourly solar PV output exceeds the hourly load demand, external grid demand is set to zero (no export to grid). After applying the suitable ECG End User Tariff based on monthly household electricity demand, the annual baseline and residual electricity bill can be determined. The calculated savings are reduced by the operating costs for proper maintenance of the solar PV system, which amount to 20 USD/kW/year (National Renewable Energy Laboratory 2019).

6.2 Results

Results for the cost-effectiveness of measures for reducing household cooling energy demand are presented below for different stakeholders. It is a sensible approach to focus on inefficient electricity end use as a first step before considering solar PV. Results for the cost-effectiveness of homeowner's investment in rooftop solar PV are presented separately in section 6.3.

6.2.1 Homeowner's perspective

The financial implications of investment in each measure are presented separately for new build and retrofit. Generally, the same measure is more attractive financially for new build than for retrofit because the incremental cost I_Δ on top of the baseline solution, such as MEPS compliant AC or single glazing window, is considered rather than the full investment cost. Figure 6.3 shows that the same measure will also yield higher returns for the high-income household (HTH, all rooms cooled) compared to the middle-income household (MTH, fewer rooms cooled) because the baseline electricity consumption is 70% higher, and with it electricity tariff band and potential savings.

Figure 6.4 (a-b) show that the homeowner or real estate developer investing in a new build benefits most from selecting the energy efficient hollow block wall, with NPV of US$ 25,791 and US$ 14,043 respectively for the 150mm and 225mm size and HTH.

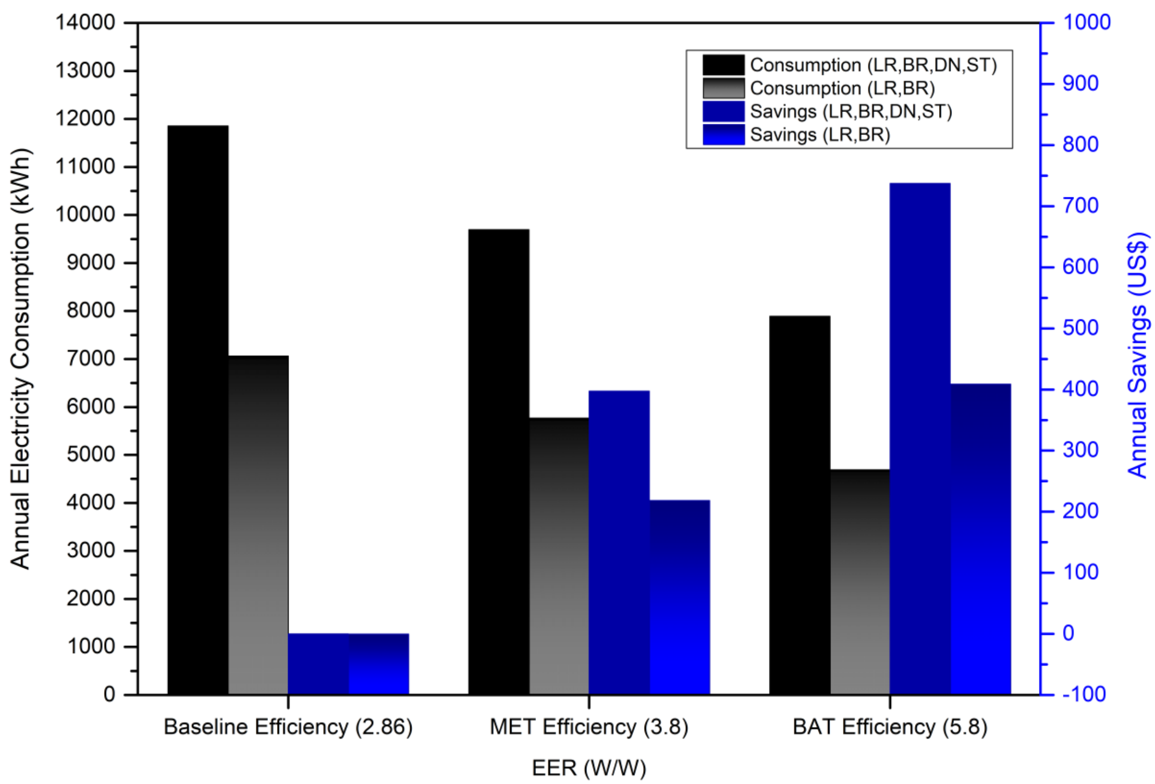

Figure 6.3: Annual electricity consumption and savings for HTH and MTH as function of AC efficiency.

Mathematically, the ROI for hollow block walls is infinite as they require less material than the baseline 125mm solid block, generating instant investment cost savings and extra cooling energy savings over lifetime. This makes the hollow block wall a uniquely low-hanging fruit to be plucked in the form of promulgated requirement in building energy efficiency codes for residential buildings. Another simple efficiency measure that is recommended for inclusion in minimum residential building energy performance standards for new build is orientation. It has been previously shown that aligning the external walls and windows of cooled rooms to the geographic north and south, saves 4% and 2% of the annual electricity use for cooling respectively. This measure can be implemented at the early design stage at no additional cost to the developer. The second attractive investment case is actually more of a behaviour change, namely increasing AC thermostat setting by 3.5°C combined with a cooling fan. The measure is highly cost-efficient in combination with a baseline AC because the added cost is very small compared to savings, with investment and NPV from US$ 148 and US$ 1,822 in MTH to US$ 246 and US$ 3,340 in HTH, and static payback time of less than one year. But this behaviour change is also essential to enhance the investment case for efficient ACs, which is barely viable for 18.5°C setpoint temperature except for MET AC in HTH. If the thermostat setting is increased to 22°C and a fan added, the NPV for MET AC improves from US$ 357 to US$ 1212 in MTH and from US$ 1315 to US$ 3670 in HTH. The NPV for BAT AC improves from US$ -648 to US$ -131 in MTH (still not viable) and from US$ 564 to US$ 1838 in HTH, accordingly. The BAT AC yields the highest energy savings, but suffers from disproportionately high investment costs. The MET AC provides a good trade-off between energy bill savings and investment cost. The better the AC technology, the more important it is to conduct proper maintenance and mitigate efficiency degradation over time. It follows from the NPV assessment that the best choice of AC for new build MTH is the baseline AC with 22°C setpoint temperature and fan (with MET AC also viable), and the MET AC with 22°C setpoint temperature and fan for new build HTH. The MET AC system with EER of 3.8 W/W is therefore recommended as minimum efficiency performance standard for installation in new build residential properties. None of the window configurations are found to be a viable investment, but the NPV for single

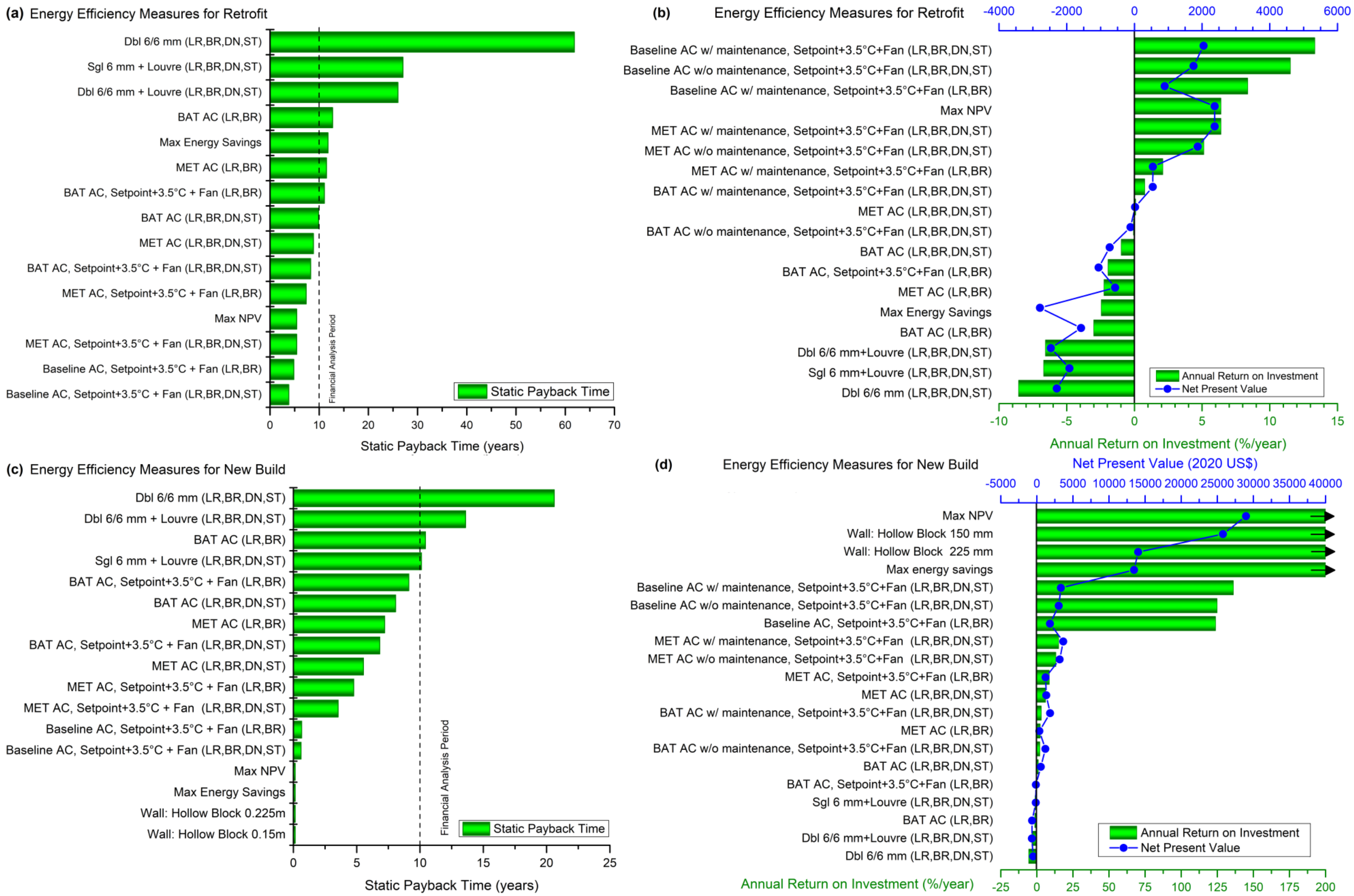

Figure 6.4: Static payback time and Net present value for Retrofit (a-b) and New Build (c-d).

glazing window with louvres is just slightly red and turns positive if a longer financial analysis period is considered.

The cost-effectiveness of the efficiency measures for retrofit differs widely from new build because the full replacement cost is considered although Figure 6.4 (c-d) show that some trends are similar. At 18.5°C thermostat temperature, there is no positive case for investment in efficient AC. If the thermostat temperature is increased to 22°C and a fan added, the NPV for an existing baseline AC is US$ 1,822 in MTH and US$ 3,340 in HTH (like new build); for a newly purchased baseline AC the NPV is US$ 894 in MTH and US$ 2,044 in HTH; the NPV for MET AC improves from US$ -571 to US$ 546 in MTH and from US$ 19 to US$ 2,374 in HTH; the NPV for BAT AC improves from US$ -1,576 to US$ -117 in MTH (still not viable) and from US$ -732 to US$ 542 in HTH. It follows that the best choice of AC for MTH retrofit is the baseline AC with 22°C setpoint temperature and fan (with MET AC also viable), and the MET AC with 22°C setpoint temperature and fan for HTH retrofit.

Section 3.1.3.1 shows the annual income for 82% of Tema households are between US$ 3,600 and US$16,000. Assuming that MTH corresponds to average income and HTH corresponds to the high end of the income range, the purchase of a new MET AC and fans amounts to 27% and 23% of annual household income. Following the success stories of the Efficient Lighting Project 2007 and the Refrigerator Efficiency Rebate Scheme 2012, rebates could be offered on efficient air conditioners in an effort to reduce the economic barrier of upfront cost. The efficiency rebate initiative should be accompanied by mandatory disposal of outdated ACs in case of retrofit, technical requirements to prevent low thermostat settings for the new ACs, and complimentary room fans.

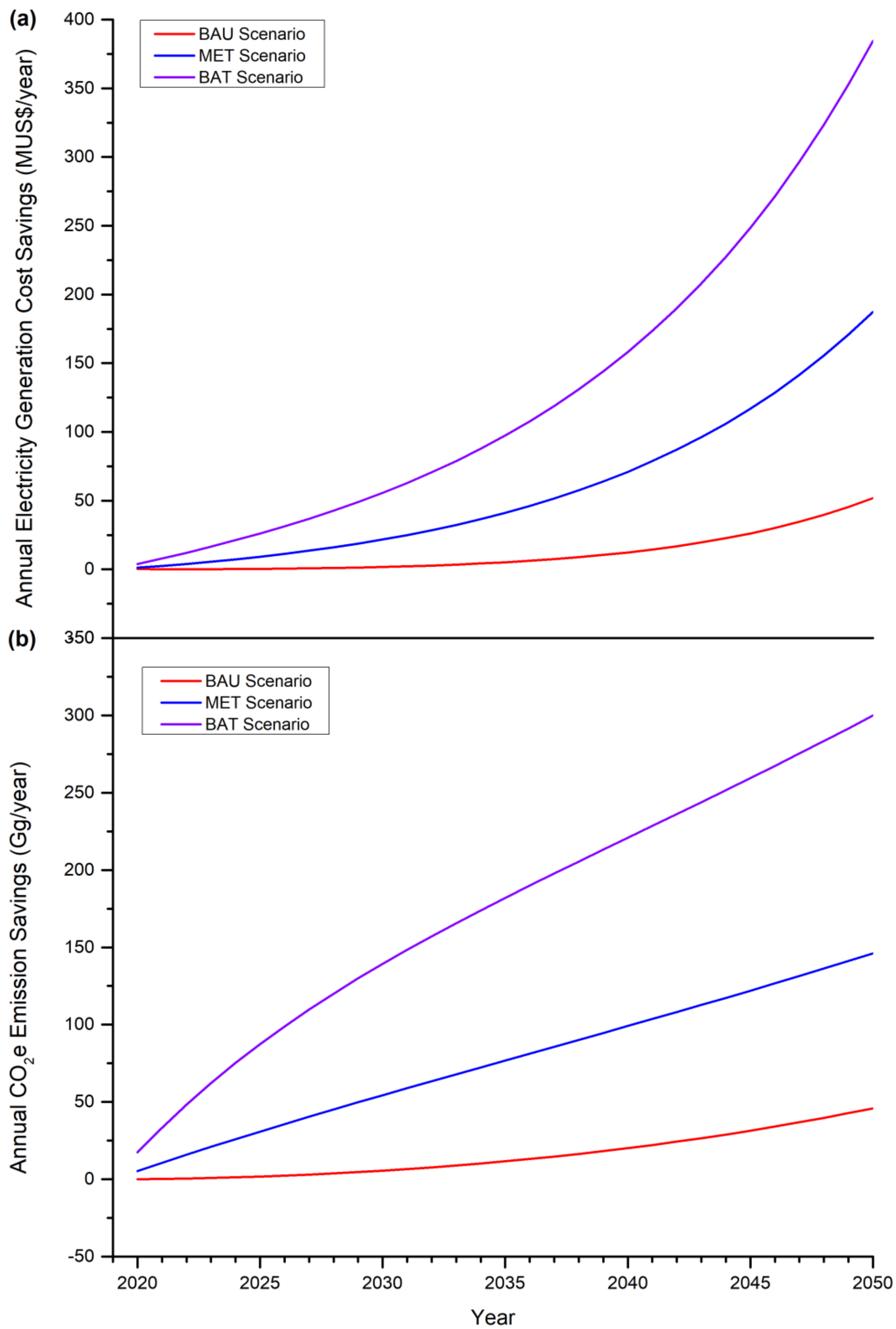

Figure 6.5: Projected utility cost (a) and emission (b) savings for different efficiency scenarios in Tema city.

6.2.2 Utility perspective

The projection of city-scale fuel cost savings for power generation until 2050 is plotted in Figure 6.5. The savings are highest for the BAT scenario at about US$ 384 million, followed by the MET scenario at US$ 187 million and lastly by the BAU scenario at US$ 51 million. These results show that the attractiveness of investment in building energy efficiency from the utility perspective differs from the homeowner/resident's perspective. Efficiency measures with maximum NPV and shortest payback time are most attractive to homeowners/residents while measures with maximum energy savings are most attractive to the utility. Measures that yield the most energy savings, such as BAT AC and 6mm/6mm double glaze window with 500mm external wooden louver shading, have comparatively low NPV and longer payback time especially for retrofits.

Yet, the homeowner/resident's perspective could be influenced with financial incentives from the utility. Since the utility would benefit from mass dissemination of efficient ACs in the form of lower peak generation costs, the utility could transfer some of the prospective savings as incentive to the homeowner/resident and reduce the upfront barrier for efficiency retrofit. While results of this study suggest that subsiding or providing rebates for MET and BAT ACs (i.e. units with EER greater or equal to 3.8 W/W) would benefit the utility, that is currently not happening in Ghana's power sector. The focus has been on advocating conformity to existing AC standards of 2.8 W/W minimum EER, where studies have suggested could save about 950 GWh per year by 2020, freeing up to almost 250 MW (Gyamfi et al. 2018). This study estimates fuel cost for power generation using natural gas as 6.40 US¢/kWh_{el}. The average cost of delivered electricity amongst monitored AC users in the modal tariff band (301 – 600 kWh/month) is 73.34 US¢/kWh. Assuming the difference covers transmission and distribution costs as well as profit margins for the electricity supply value chain to stay operational, the saved fuel cost is assumed to be the maximum rebate that can be feasibly offered by the utility to the homeowner/resident who implements an energy efficiency measure. With this rate of 6.40 US¢/kWh_{el}, the amount offered as rebate would rise appreciably with increasing amount of energy savings to provide very enticing opportunities for residential building energy efficiency investment amongst homeowners/residents and estate managers. It is assumed that the utility or its representative would procure ACs with EER greater or equal to 3.8 W/W with adjusted minimum setpoint temperature of 22°C for targeted distribution. In this scenario, the utility would offer rebates equal to the net present value of prospective generation cost savings generated by the efficient AC, while the homeowner/resident settles the balance. The NPV, ROI and SPT of the considered efficiency retrofit measures were recalculated from the homeowner/resident's perspective with investment costs reduced by utility rebate.

Figure 6.6 shows that investment in all efficiency measures except window glazing and BAT AC at baseline setpoint temperature for fewer rooms cooled become financially viable. At baseline setpoint temperature, the BAT AC for all rooms cooled is most profitable in terms of NPV with US$ 1,514 followed by the MET AC for all rooms cooled at US$ 1,243 and the MET AC for fewer rooms cooled at US$ 162. When the thermostat setting of the ACs is adjusted upwards by 3.5°C with complementary cooling fan, investment in all considered AC efficiency levels becomes cost-effective. The MET AC for all rooms cooled is most profitable in terms of NPV with US$ 4,445 (55% rebate) followed by the BAT AC in all rooms cooled at US$ 3,298 (37% rebate), the baseline AC in all rooms cooled at US$ 3,295 (81% rebate), the MET AC in fewer rooms cooled at US$ 1,785 (47% rebate), the baseline AC in fewer rooms cooled at US$ 1,642 (70% rebate), and lastly the BAT AC in fewer rooms cooled at US$ 590 (31% rebate). Basically, the MET AC still offers the best trade-off between upfront cost and electricity savings but the utility rebate allows for the payback time to be cut in half.

These results confirm that provision of financial incentives would be very instrumental in promoting investment in residential building energy efficiency not just amongst the homeowners/residents or estate managers who can afford it, but also amongst financial institutions which offer soft loans to low and middle income homeowners/residents who cannot afford the high upfront cost. While utilities routinely advocate patronage of the

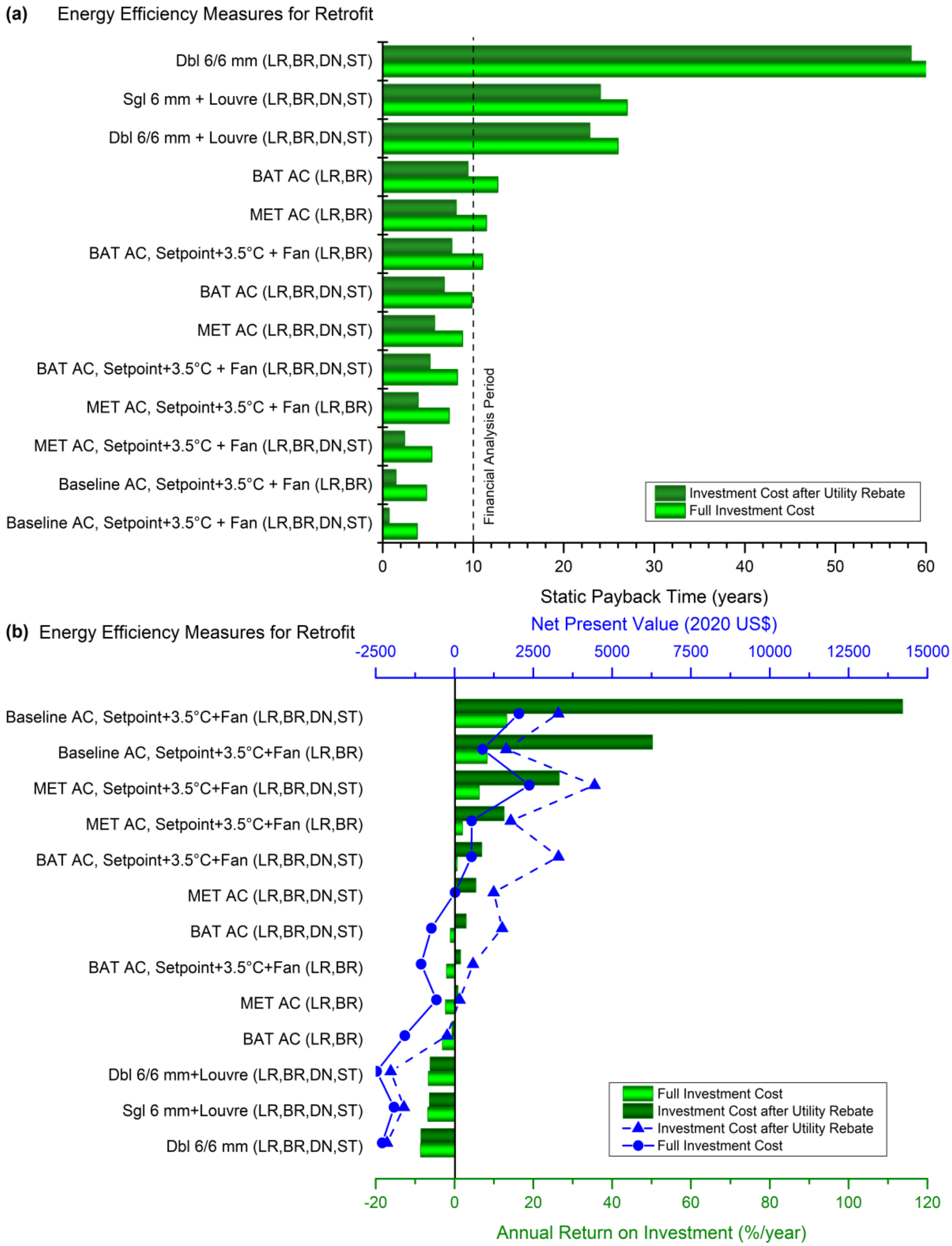

Figure 6.6: Static payback time (a) and Net present value (b) of efficiency retrofits after utility rebate.

standardized AC with EER of 2.8 W/W and conservative energy use behaviour that relies of the goodwill of residents/users, they would find it cost-effective to offer rebates on ACs with EER of 3.8 W/W and higher with adjusted minimum setpoint temperature for more substantial energy savings.

From the utility point of view, incentivizing homeowners to purchase energy efficient appliances is financially attractive to mitigate the growing need for future investment in grid infrastructure and generation capacity. Consider, for example, the annual electricity savings in 2050 for the MET scenario and the BAT scenario, which amount to 427.6 GWh and 878.0 GWh compared to 2020 efficiency levels. Assuming power generation with combined-cycle gas turbines and 6000 equivalent operating hours, these electricity savings translate into generation capacity reduced by 71.2 MW_{el} (MET) and 146.3 MW_{el} (BAT) and investment savings of 76.9 MUS$ and 157.9 MUS$, as well as 1 MUS$/year and 2.1 MUS$/year fixed operating cost (2020 prices).

6.2.3 Society perspective

It can be seen in Figure 6.5 (b) that the society gains maximum avoided annual CO_2e emissions with the BAT scenario, followed by the MET scenario and lastly by the BAU scenario. The avoided emissions reach 300 ktCO_2e, 146 ktCO_2e and 46 ktCO_2e per year by 2050. Aside having measures that yield maximum energy savings, the BAT scenario also has the fastest retrofit rate for existing base year homes, which explains the exponential growth curve for energy savings during the first decade of implementation. The BAU scenario shows a much flatter curve during the same period due to having the lowest retrofit rate and efficiency levels for the considered building energy efficiency measures. The MET scenario represents the middle ground between the BAU and BAT scenarios in terms of retrofit rate and amount of energy savings. Considering the transition period of 30 years, it can be concluded that benefits to the society and the environment grow appreciably each year as more homes undergo energy efficiency retrofitting, and new homes are built to conform to these energy efficiency standards. Figure 6.5 shows that maximum benefit to the society is reached in the long term rather than the short term. This time horizon is in contradiction to the homeowner/resident's perspective. While the homeowner/resident favours efficiency measures that yield maximum bill savings in the shortest timeframe i.e. less or equal to ten years, society and utility benefit most from measures that produce maximum energy savings and hence emission savings over a relatively longer period of time. This study found in section X that only about 17 % of homeowners/residents are influenced by energy efficiency rating in their decision to purchase an appliance and by extension invest in the energy performance of their home. Incentives will therefore be necessary to persuade residents to invest in measures that yield higher energy savings and avoided carbon emissions for the benefit of society and the environment. Given that there is no carbon pricing scheme currently operating in Ghana, it would be difficult to design financial benefits to the homeowners/residents in direct response to avoided carbon emissions. A possible win-win-win scenario for all stakeholders would be for the utility to offer financial incentives or rebate to the homeowner/resident, for implementing the energy efficiency measures identified in this study as cost-effective and financially viable. Homeowners/residents could then choose depending on their financial capabilities whether to implement a single efficiency measure or a combination of measures that yield returns in an acceptable timeframe. The society and environment would benefit from avoided carbon equivalent emissions and their associated health impacts, while the utility benefits from avoided investment in new generation capacity and grid infrastructure.

Ghana's fourth National Greenhouse Gas Inventory shows that in the last decades the energy sector has become a leading national source of carbon emissions, with annual emissions strongly increasing from 3.73 $MtCO_2e$ in 1990 to 15.02 $MtCO_2e$ in 2016. The main reason is that before 1993, power generation was 100% hydroelectric but since then the added power demand was met exclusively by thermal power generation (based on natural gas and fuel oil) since the potential for hydro generation was exploited already. To mitigate this trend and reduce the carbon footprint of future population growth, government and society should make affordable end user efficiency e.g. for residential ACs a priority.

Secondly, the carbon intensity of power generation can be reduced by increasing the efficiency of existing generating units. Project Asona is a good example: the CDM-subsidised conversion of two open-cycle gas turbines in Takoradi to a modern combined-cycle plant, saving 347 ktCO_2e per annum. Thirdly, future growth in power demand should be met by adding significant amounts of solar PV to the Ghanaian generation mix, as solar PV has become cost-competitive or cheaper than thermal power in many locations with sufficiently high solar irradiation. The time difference between the peak in solar PV generation (at noon, when the sun is at its zenith) and the peak in electricity demand (in the evening, when residents return to their homes) can be bridged e.g. by incentivizing end users to switch on their ACs early in the day, when cheap solar power is available, and pre-cool the rooms to arrive at a comfortable temperature for the night.

6.2.4 Sensitivity of results to financial assumptions

Discount rate: In the base case 8% discount rate is assumed as weighted average cost of capital, which corresponds to the Ghanaian level of inflation at the end of 2019. The annual inflation rate in Ghana has changed between 6-20% p.a. since 2010. Higher discount rate due to inflation or the need for upfront loan decreases the financial attractiveness of investing in energy efficiency across the board, see results for 15% p.a. discount rate in Figure 6.7 (a-b). The reason is that the value of future electricity bill savings is discounted more strongly while the investment cost remains the same.

Electricity price: In the base case 6.1% annual electricity price increase is assumed, which is the 15-year average increase of electricity end user tariff. Taking 2006 as base year and assuming future price increase along the price lows or price peaks in Figure 6.2 (b) results in a projected price spread of 5-15% p.a. As expected, higher electricity price increases result in higher value of future electricity bill savings and bolster the investment case for energy efficiency measures, see results for 15% p.a. in Figure 6.7 (c-d).

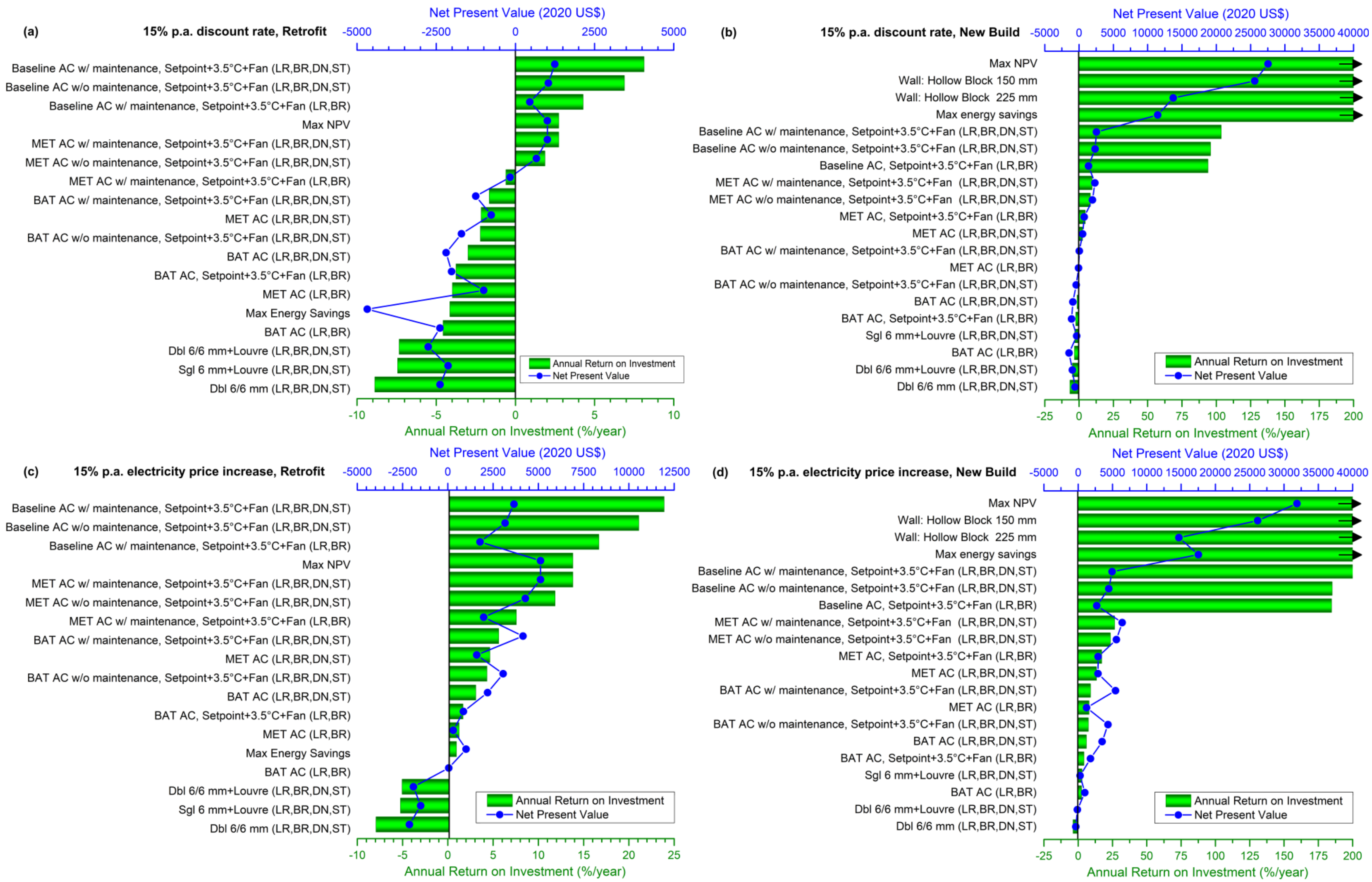

Figure 6.7: Net present value and Return on investment for 15% annual discount rate (a-b) and 15% annual electricity price increase (c-d).

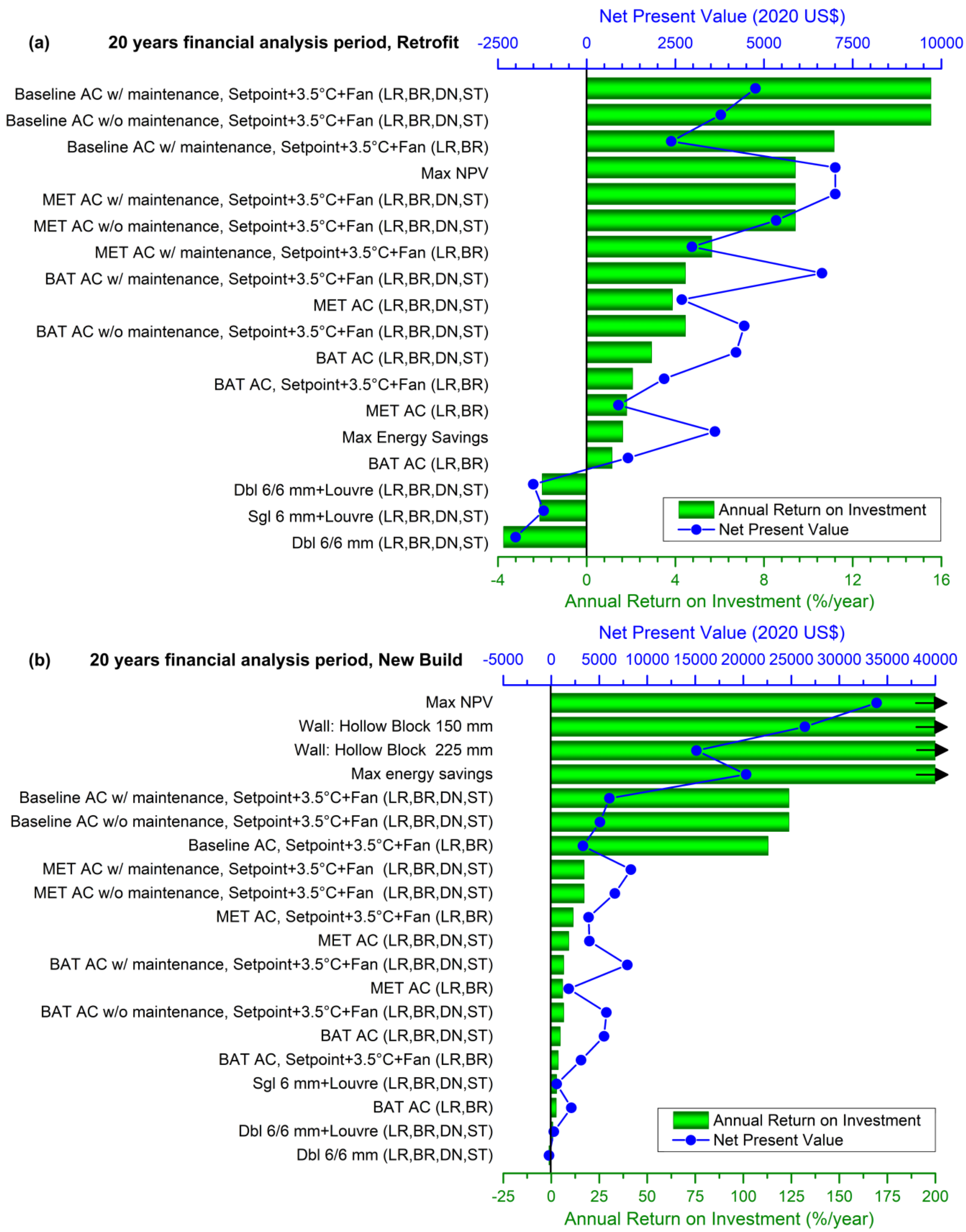

Figure 6.8: Net present value and Return on investment for 20 years financial analysis period (a-b).

Financial analysis period: The ten-year financial analysis period used as base case is smaller than the typical useful lifetime of ACs (15-20 years) and building components (≥ 30 years). Figure 6.8 shows that extending the financial analysis horizon within the useful lifetime of the efficiency measure improves the investment case, since more electricity bill savings will be considered (even if savings in the more distant future are heavily discounted). Note the exception of annual return on investment decreasing slightly for Baseline AC + Fan, because the number of years considered in the denominator increases faster than the discounted electricity bill savings considered in the nominator.

6.3 Investment appraisal of rooftop solar PV systems for residential cooling

In this section, the economic attractiveness of investing in rooftop solar PV retrofit to power residential AC pre-cooling and reduce household dependence on external grid supply is assessed. The calculation of annual cost savings generated by the solar PV system and the estimation of capital expenditure for solar PV systems and battery storage is described in section 6.1.4. Standard cooling by room occupancy at 18.5°C is set to calculate the baseline utility bill. Solar PV systems (mono-crystalline silicon) from 500W to 4kW size without battery storage and 4kW size with battery storage are considered for medium-income household (MTH, fewer rooms cooled) using AC pre-cooling at 18.5°C or 22°C. Solar PV systems (mono-crystalline silicon) from 500W to 8kW size without battery storage and 8kW size with battery storage are considered for high-income household (HTH, all rooms cooled) using AC pre-cooling at 18.5°C or 22°C.

Figure 6.9 shows the financial assessment results for the different investment cases. It is noteworthy that the static payback for all cases is less than half of the 25-year useful lifetime of a solar PV system due to the AC load shift and the constantly high level of solar irradiation in Ghana with relatively small seasonal variation. All investment cases are therefore deemed positive, although some are more profitable than others. The cases with pre-cooling at 22°C are significantly more attractive than the cases with pre-cooling at

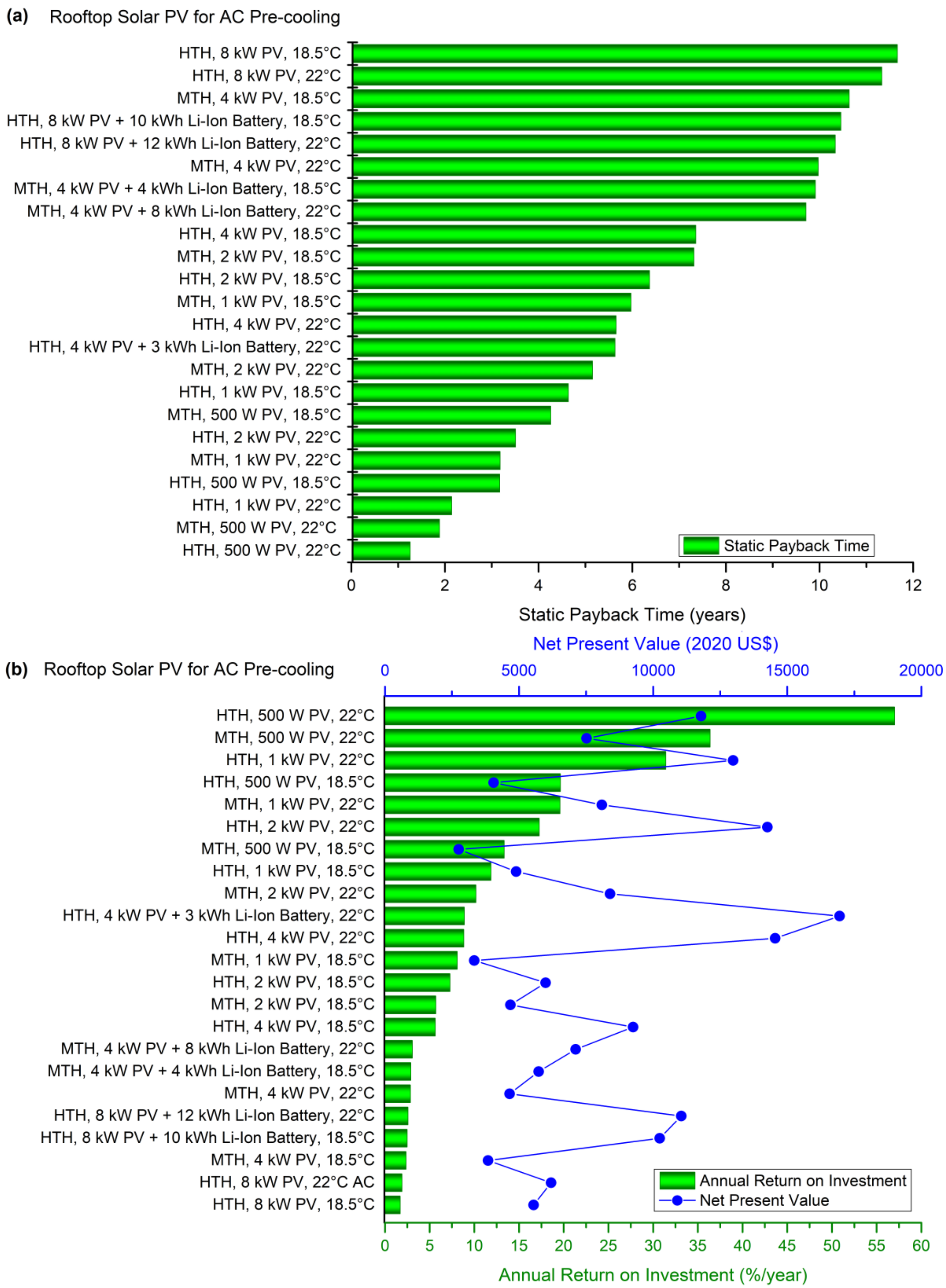

Figure 6.9: Static payback time (a) and Net present value (b) of differently sized solar PV systems for AC pre-cooling.

18.5°C because the solar fraction is higher for the same size of PV system. The same holds if a more efficient AC is installed. The return on investment is highest for the small 500W PV system since the incremental electricity savings decrease with system size, with high returns of 13%-36% per year for MTH and 20%-57% per year for HTH. Investment returns are higher for HTH compared to MTH because of the more energy-intensive lifestyle translating into higher potential savings. The NPV increases with system size up until a maximum at 2 kW PV system size for MTH and until 4 kW system size for HTH. Further than these sizes, NPV reduces because the higher output of larger sized PV systems cannot be used effectively without battery storage. If battery storage is added, 4 kW PV system size for MTH and 8 kW PV system size for HTH become feasible if the homeowner is willing to pay a premium for grid independence (compare Table 5.2).

The investment decision should be based on a suitable trade-off between net present value and return on investment. On balance, the most attractive options purely from an investor's point of view are the 500 W PV system for MTH with 18.5°C pre-cooling, 1kW PV system for MTH with 22°C pre-cooling, 1kW PV system for HTH with 18.5°C pre-cooling and 2kW PV system for HTH with 22°C pre-cooling. The economic and environmental calculus for solar PV becomes even better when considering that many Ghanaians use inefficient, costly diesel generators to power residential AC due to the frequent disruptions of electricity grid supply. Decentralized, adequately sized solar PV proves a good investment for the household to reduce electricity demand, generate electricity bill savings and decrease grid dependency.

Chapter 7

SUMMARY

In this work, a pathway to sustainable residential cooling for West African cities was developed. As meaningful data were basically non-existent, an electricity end use monitoring and survey of 60 households in Tema city was conducted, the first of such study in Ghana. A detailed building energy model, representative in terms of archetype and cooling demand, was created based on and calibrated with the collected data. The validated model was used for dynamic energy simulation to study the impact of key determinants including AC efficiency, setpoint temperature and operating schedule, building orientation and design of envelope, and identify specific measures to reduce the cooling energy demand. Dynamic energy simulation of the cooling schedule was used to demonstrate that there is ample potential for rooftop solar PV to meet this energy demand if residential cooling load is shifted to coincide with solar power generation. The work was complemented by policy recommendations to incentivize renewable energy deployment and investment appraisal of the various demand reduction measures and solar PV systems.

The existing power generation landscape in Ghana is dominated by fossil fuels, which are sensitive to volatile market price and supply disruption, and hydro power, which is low cost but subject to seasonal water constraints. Solar PV accounts for only 0.24 percent despite the massive potential, specifically annual radiation yields that are 27-45% higher compared to the best locations in Germany. Feed-in-tariff and net metering scheme exist to support decentralized renewable energy deployment, but the absence of adequate infrastructure and funding severely undermine the effectiveness of these policies.

The residential electricity end use monitoring study found that lighting, air conditioning, refrigeration, television and fan collectively contribute 85% of residential peak load. The survey results suggests that space cooling appliances such as air conditioner and fan are the most significant contributors to peak load that households are willing to shift. Income, household size, floor area and ownership of cooling appliances are found as key socio-economic determinants of household electricity consumption.

Results of the cooling energy demand simulations show that between 25% and 50% of electricity savings are feasible via use of medium-efficiency AC and high-efficiency BAT AC. In terms of building envelope, replacing standard blocks with hollow blocks translates into smaller thermal storage capacity of the walls and up to 11% cooling energy savings. Furthermore, the addition of local shading louvres to existing single-glazed windows is more effective than the much promoted replacement with double-glazed windows. A crucial finding of the simulation campaign is that AC cooling operation can be shifted to the daytime when solar power is available, without unduly impairing the thermal comfort of residents during night occupancy (the room temperature rebounds to 23-25°C at 6pm and a simple fan can be added). Increasing the AC pre-cooling temperature from 18.5°C to 22°C offers electricity savings of 35%, with small impact on 6pm room temperature. Rooftop solar PV has sufficient generation potential to self-supply the full household electricity demand for AC pre-cooling. Solar fractions of more than 60% are feasible depending on PV system size, and even higher solar fractions can be realized with battery storage.

In practice, the choice in favor or against such measures is typically the result of economic consideration. Potential electricity savings of the given measures are weighed against the upfront investment costs. From a homeowner's perspective, the simple behavior change of setting a 3.5°C higher AC temperature (optionally combined with a fan) pays off almost instantly. Investment in medium-efficiency AC is also economically viable, if it can be financed. New build homes should use hollow blocks rather than solid blocks to save material cost in the present and utility costs in the future. If AC pre-cooling during daytime is adopted, there is a strong investment case for small-to-medium sized solar PV systems with payback time of 5 years or less. The value is even more apparent when considering that many homes in Ghana use inefficient diesel generators to power their AC during grid supply outages. From a utility point of view, the energy savings of Tema households projected in 2050 for a medium-efficiency scenario and a BAT scenario vs. baseline amount to 430 GWh/year and

880 GWh/year respectively, roughly equivalent to the output of 70 MW_{el} and 150 MW_{el} gas-fired combined-cycle power generation with 80 MUS$ and 160 MUS$ capital expenditure.

The pathway to sustainable cooling in West African cities starts with embracing the urgent need for action as a society in light of the profound social and economic implications of cooling access, rapid expansion of inefficient air conditioners with an electrical system already disrupted by frequent supply constraints and massive solar PV generation potential that so far is all but untapped. It is recommended that the Ghana government establish legislation to bind utilities, TSOs and DSOs to mandatory annual electricity savings targets in the residential sector, and put in adequate resources to enforce the legislation and benchmark savings performance. The power companies can meet these targets effectively by granting rebates for households to purchase efficient ACs, replace old inefficient ACs and install small-scale rooftop solar PV for AC pre-cooling during daytime. In return, both the companies' current supply constraints and future need for costly investment in power generation and grid capacity are mitigated. With the upfront cost barrier to efficient ACs removed, households should also adopt efficient cooling habits, in particular higher AC setpoint temperature combined with a fan, and use daytime AC pre-cooling if solar PV output is available. Stringent minimum energy performance standards and labelling for air conditioners, which makes electricity bill savings transparent, are required to put efficiency front and center in the choice of an AC. Similarly, policymakers should mandate residential building energy performance labelling to encourage energy retrofitting and implement energy standards for building fabric in new residential construction. Building designers and architects in Ghana should consider the cooling system as an integral part of the building from an early design stage. Among the most effective measures identified to reduce cooling energy demand are considering sun path and placement of cooled rooms, using local shading to reduce heat gain through windows and using local sandcrete hollow blocks instead of solid blocks to reduce heat storage in the building wall structure. Crucially, in addition to demonstrating that this proposed pathway to sustainable cooling is both technically feasible and environmentally sound, the results also offer attractive investment opportunities for households, power producers and utilities with massive benefits for Ghana's economic development and its society as a whole.

Chapter 8

OUTLOOK

In the last two decades since many countries announced long-term commitments to reduce their building sectors' contribution to climate change, high energy performance and zero-to-very low energy consumption enabled by on-site renewable energy sources have become pillars of sustainable urban development, and one of the most active areas of research. This study has identified the key determinants of electricity consumption in Ghana's residential buildings, with promising results revealing a pathway to sustainable cooling that is transferable to the entire West Africa sub-region.

However, further research work is required to address the limitations of the present study. Plausibility of the city's baseline cooling energy use was checked with measured aggregate AC electricity consumption. Full validation requires macroscopic, city-level building energy end-use data that is currently not available. High costs of end-use monitoring limited data coverage to 60 households over a 24-hour period on a weekday as well as Saturday and Sunday. The weekday measurements were assumed to be representative of all other weekdays during the year, as were the Saturdays and Sundays. Further research with a larger sample size and year-long end-use monitoring, is recommended to accurately capture seasonal variations and ensure better level of representation with regards to the wider population of West African households.

The 2050 projections assumed that ACs installed between 2020 and 2050 would function until 2050 with annually deteriorating efficiency. A detailed stock turnover model that additionally captures retrofits due to retired/aged ACs would make the projections more realistic. The representative/baseline building that was used in the precooling analysis is a single story semi-detached house with 125mm solid sandcrete block walls. Further research that investigates optimization of building envelope design and materials would be useful in assessing the potential of precooling for other building types.

Appendix

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A.2 CHARACTERISTICS OF APPLIANCE OWNERSHIP

Factors	Lighting		Air Conditioner	
	Number of households owning 1 or more & percentage	Average number of appliances per household	Number of households owning 1 or more & percentage	Average number of appliances per household
Income grade				
A	13 (10%)	22	4 (33%)	1.50
B	25 (20%)	25	4 (33%)	1.50
C	36 (29%)	14	2 (17%)	1.50
D	47 (37%)	8	2 (17%)	1.00
E	5 (4%)	2	0	
Employment status				
Self employed	18 (14%)	4	0	
Full-time paid work	83 (66%)	16	11 (92%)	1.36
Retired	15 (12%)	10	1 (8%)	1.00
Unemployed	5 (4%)	9	0	
Full-time higher education	5 (4%)	6	0	
Household size				
1	5 (4%)	12	0	
2	18 (14%)	33	2 (17%)	1.00
3	25 (20%)	10	1 (8%)	1.00
4	37 (29%)	11	2 (17%)	1.50
5	20 (16%)	8	2 (17%)	1.50
6+	21 (17%)	25	5 (41%)	1.40
Household composition				
Single person	5 (4%)	12	0	
Couple only	5 (4%)	36	2 (17%)	1.00
Couple with dependent children	52 (41%)	17	6 (50%)	1.33
Couple with non-dependent children	15 (12%)	13	1 (8%)	2.00
Family with dependent children	34 (27%)	9	3 (25%)	1.33
Family with non-dependent children	15 (12%)	15	0	
Age of household head				
19-34	21 (17%)	7	2 (17%)	1.50
35-44	20 (16%)	18	3 (25%)	1.67
45-54	35 (28%)	14	5 (41%)	1.20
55-64	35 (28%)	12	0	

65-74	11 (9%)	16	2 (17%)	1.00
75+	4 (3%)	17	0	
Building type				
SFD	64 (51%)	22	10 (84%)	1.40
SFSD	18 (14%)	8	1 (8%)	1.00
AB	34 (27%)	7	1 (8%)	1.00
MFH	5 (4%)	3	0	
IM	5 (4%)	3	0	
Energy efficiency awareness and practice				
High	39 (31%)	16	7 (58%)	1.29
Fair	9 (7%)	18	1 (8%)	2.00
Low	45 (36%)	14	3 (25%)	1.33
Lack	30 (24%)	11	1 (8%)	1.00
Did not answer	3 (2%)	12	0	
Factors	**Refrigeration**		**Television**	
Income grade				
A	5 (10%)	2.20	5 (10%)	2.40
B	10 (20%)	1.50	10 (20%)	1.70
C	15 (29%)	1.45	15 (29%)	1.40
D	19 (37%)	1.27	19 (37%)	1.17
E	2 (4%)	1.00	2 (4%)	1.00
Employment status				
Self employed	7 (14%)	1.14	9 (16%)	1.11
Full-time paid work	34 (66%)	1.39	42 (72%)	1.50
Retired	6 (12%)	1.17	6 (10%)	1.50
Unemployed	2 (4%)	1.00	1 (2%)	1.00
Full-time higher education	2 (4%)	1.00	0	
Household size				
1	2 (4%)	1.00	2 (3%)	1.00
2	7 (14%)	1.43	6 (10%)	1.33
3	10 (20%)	1.20	12 (21%)	1.25
4	15 (29%)	1.47	17 (29%)	1.35
5	8 (16%)	1.5	12 (21%)	1.17
6+	9 (17%)	1.89	9 (16%)	2.33
Household composition				
Single person	2 (4%)	1	2 (3%)	1.00
Couple only	2 (4%)	2.5	2 (3%)	2.00
Couple with dependent children	21 (41%)	1.43	21 (36%)	1.57
Couple with non-dependent children	6 (12%)	1.83	7 (12%)	1.71
Family with dependent children	14 (27%)	1.36	18 (31%)	1.22
Family with non-dependent children	6 (12%)	1.33	8 (14%)	1.25
Age of household head				
19-34	11 (22%)	1.27	10 (17%)	1.30

35-44	7 (14%)	1.57	9 (16%)	1.56
45-54	13 (25%)	1.69	16 (28%)	1.50
55-64	13 (25%)	1.23	16 (28%)	1.06
65-74	5 (10%)	1.6	5 (9%)	2.00
75+	2 (4%)	2.00	2 (3%)	2.50
Building type				
SFD	26 (51%)	1.65	27 (47%)	1.74
SFSD	7 (14%)	1.43	7 (12%)	1.43
AB	14 (27%)	1.07	16 (28%)	1.13
MFH	2 (4%)	1.00	2 (3%)	1.00
IM	2 (4%)	1.00	6 (10%)	1.00
Energy efficiency awareness and practice				
High	16 (31%)	1.47	18 (31%)	1.61
Fair	3 (6%)	1.00	4 (7%)	1.50
Low	18 (35%)	1.00	21 (36%)	1.29
Lack	13 (26%)	1.15	14 (24%)	1.36
Did not answer	1 (2%)	2.00	1 (2%)	2.00
Factors	**Fan**		**Computer**	
Income grade				
A	5 (10%)	4.40	5 (19%)	2.33
B	10 (20%)	3.30	9 (33%)	1.67
C	15 (29%)	3.15	8 (30%)	1.33
D	19 (37%)	2.67	7 (26%)	1.00
E	2 (4%)	2.00	0	
Employment status				
Self employed	6 (11%)	2.33	0	
Full-time paid work	39 (74%)	3.13	22 (81%)	1.36
Retired	6 (11%)	3.33	3 (11%)	1.67
Unemployed	1 (2%)	1.00	0	
Full-time higher education	1 (2%)	2.00	2 (7%)	1.00
Household size				
1	2 (4%)	2.00	1 (4%)	1.00
2	7 (13%)	3.29	5 (19%)	1.00
3	10 (19%)	3.40	3 (11%)	1.00
4	16 (30%)	2.56	7 (26%)	1.14
5	10 (19%)	2.90	5 (19%)	1.20
6+	9 (17%)	3.11	6 (22%)	2.33
Household composition				
Single person	2 (4%)	2.00	1 (4%)	1.00
Couple only	2 (4%)	4.00	1 (4%)	1.00
Couple with dependent children	16 (30%)	3.40	8 (30%)	1.88
Couple with non-dependent children	17 (32%)	4.14	5 (19%)	1.67
Family with dependent children	14 (26%)	3.14	9 (33%)	1.00

Family with non-dependent children	7 (13%)	3.29	3 (11%)	1.33
Age of household head				
19-34	10 (19%)	2.20	3 (11%)	1.33
35-44	8 (15%)	3.50	7 (26%)	1.60
45-54	14 (26%)	3.07	9 (33%)	1.33
55-64	13 (25%)	3.31	6 (22%)	1.00
65-74	5 (9%)	2.80	2 (7%)	3.00
75+	3 (6%)	4.50	0	
Building type				
SFD	24 (45%)	3.42	18 (67%)	1.50
SFSD	6 (11%)	2.50	2 (7%)	1.00
AB	17 (32%)	3.12	7 (26%)	1.14
MFH	2 (4%)	1.50	0	
IM	4 (8%)	2.00	0	
Energy efficiency awareness and practice				
High	18 (34%)	2.72	9 (33%)	1.44
Fair	4 (8%)	4.50	5 (19%)	1.67
Low	18 (34%)	2.83	11 (41%)	1.36
Lack	13 (25%)	3.69	2 (7%)	1.00
Did not answer	1 (2%)	2.00	0	

Factors	**Satellite receiver**		**Iron**	
Income grade				
A	4 (15%)	2.00	5 (10%)	1.00
B	9 (35%)	1.33	10 (20%)	1.00
C	9 (35%)	1.11	15 (29%)	1.00
D	4 (15%)	1.00	19 (37%)	1.00
E	0		2 (4%)	1.00
Employment status				
Self employed	1 (4%)	1.00	6 (12%)	1.00
Full-time paid work	24 (92%)	1.21	39 (76%)	1.00
Retired	0		4 (8%)	1.00
Unemployed	1 (4%)	1.00	1 (2%)	1.00
Full-time higher education	0		1 (2%)	1.00
Household size				
1	0		2 (4%)	1.00
2	5 (19%)	1.40	7 (14%)	1.00
3	7 (27%)	1.00	10 (20%)	1.00
4	6 (23%)	1.17	16 (31%)	1.00
5	3 (12%)	1.00	8 (16%)	1.00
6+	5 (19%)	1.40	8 (16%)	1.00
Household composition				
Single person	0		2 (4%)	1.00
Couple only	2 (8%)	2.00	2 (4%)	1.00

Couple with dependent children	13 (50%)	1.08	20 (39%)	1.00
Couple with non-dependent children	1 (4%)	2.00	5 (10%)	1.00
Family with dependent children	6 (23%)	1.00	16 (31%)	1.00
Family with non-dependent children	4 (15%)	1.00	6 (12%)	1.00
Age of household head				
19-34	5 (19%)	1.20	10 (20%)	1.00
35-44	5 (19%)	1.00	8 (16%)	1.00
45-54	10 (38%)	1.30	15 (29%)	1.00
55-64	4 (15%)	1.00	12 (24%)	1.00
65-74	2 (8%)	2.00	4 (8%)	1.00
75+	0		2 (4%)	1.00
Building type				
SFD	14 (54%)	1.36	26 (51%)	1.00
SFSD	3 (12%)	1.00	6 (12%)	1.00
AB	8 (31%)	1.00	14 (27%)	1.00
MFH	1 (4%)	1.00	2 (4%)	1.00
IM	0		3 (6%)	1.00
Energy efficiency awareness and practice				
High	8 (31%)	1.13	18 (35%)	1.00
Fair	2 (8%)	1.50	4 (8%)	1.00
Low	10 (38%)	1.10	16 (31%)	1.00
Lack	4 (15%)	1.25	12 (24%)	1.00
Did not answer	2 (8%)	1.00	1 (2%)	1.00
Factors	**Washing machine**		**Kettle**	
Income grade				
A	4 (21%)	1.00	4 (18%)	1.00
B	5 (37%)	1.00	7 (32%)	1.00
C	6 (32%)	1.00	6 (27%)	1.00
D	2 (11%)	1.00	5 (23%)	1.00
E	0		0	
Employment status				
Self employed	0		0	
Full-time paid work	16 (84%)	1.00	18 (82%)	1.00
Retired	3 (16%)	1.00	3 (14%)	1.00
Unemployed	0		1 (5%)	1.00
Full-time higher education	0		0	
Household size				
1	0		1 (5%)	1.00
2	4 (21%)	1.00	3 (14%)	1.00
3	4 (21%)	1.00	6 (27%)	1.00
4	3 (16%)	1.00	3 (14%)	1.00
5	1 (5%)	1.00	2 (9%)	1.00
6+	7 (37%)	1.00	7 (32%)	1.00

Household composition				
Single person	0		1 (5%)	1.00
Couple only	2 (11%)	1.00	2 (9%)	1.00
Couple with dependent children	10 (53%)	1.00	8 (36%)	1.00
Couple with non-dependent children	3 (16%)	1.00	4 (18%)	1.00
Family with dependent children	3 (16%)	1.00	5 (23%)	1.00
Family with non-dependent children	1 (5%)	1.00	2 (9%)	1.00
Age of household head				
19-34	0		4 (18%)	1.00
35-44	2 (11%)	1.00	3 (14%)	1.00
45-54	8 (42%)	1.00	7 (32%)	1.00
55-64	5 (26%)	1.00	4 (18%)	1.00
65-74	3 (16%)	1.00	3 (14%)	1.00
75+	1 (5%)	1.00	1 (5%)	1.00
Building type				
SFD	12 (63%)	1.00	15 (68%)	1.00
SFSD	3 (16%)	1.00	2 (9%)	1.00
AB	4 (21%)	1.00	3 (14%)	1.00
MFH	0		2 (9%)	1.00
IM	0		0	
Energy efficiency awareness and practice				
High	7 (37%)	1.00	7 (32%)	1.00
Fair	2 (11%)	1.00	5 (23%)	1.00
Low	4 (21%)	1.00	6 (27%)	1.00
Lack	5 (26%)	1.00	6 (27%)	1.00
Did not answer	0		0	

Factors	Microwave oven		Rice cooker	
Income grade				
A	3 (13%)	1.00	4 (21%)	1.00
B	9 (38%)	1.00	5 (37%)	1.00
C	7 (29%)	1.00	6 (32%)	1.00
D	5 (21%)	1.00	2 (11%)	1.00
E	0		0	
Employment status				
Self employed	1 (4%)	1.00	0	
Full-time paid work	21 (88%)	1.00	16 (84%)	1.00
Retired	2 (8%)	1.00	3 (16%)	1.00
Unemployed	0		0	
Full-time higher education	0		0	
Household size				
1	1 (4%)	1.00	0	
2	6 (25%)	1.00	4 (21%)	1.00
3	3 (13%)	1.00	4 (21%)	1.00

4	2 (8%)	1.00	3 (16%)	1.00
5	5 (21%)	1.00	1 (5%)	1.00
6+	7 (29%)	1.00	7 (37%)	1.00
Household composition				
Single person	1 (4%)	1.00	0	
Couple only	2 (8%)	1.00	2 (11%)	1.00
Couple with dependent children	10 (42%)	1.00	10 (53%)	1.00
Couple with non-dependent children	2 (8%)	1.00	3 (16%)	1.00
Family with dependent children	6 (25%)	1.00	3 (16%)	1.00
Family with non-dependent children	3 (13%)	1.00	1 (5%)	1.00
Age of household head				
19-34	3 (13%)	1.00	0	
35-44	5 (21%)	1.00	2 (11%)	1.00
45-54	8 (33%)	1.00	8 (42%)	1.00
55-64	4 (17%9	1.00	5 (26%)	1.00
65-74	2 (8%)	1.00	3 (16%)	1.00
75+	2 (8%)	1.00	1 (5%)	1.00
Building type				
SFD	17 (71%)	1.00	12 (63%)	1.00
SFSD	3 (13%)	1.00	3 (16%)	1.00
AB	4 (17%)	1.00	4 (21%)	1.00
MFH	0		0	
IM	0		0	
Energy efficiency awareness and practice				
High	8 (33%)	1.00	7 (37%)	1.00
Fair	2 (8%)	1.00	2 (11%)	1.00
Low	9 (38%)	1.00	4 (21%)	1.00
Lack	4 (17%)	1.00	5 (26%)	1.00
Did not answer	1 (4%)	1.00	0	

A.3 SUMMARY OF INPUT THERMAL PROPERTIES FOR BUILDING MATERIALS IN DESIGNBUILDER

Input parameter			
Wall types	*Heat capacity*	*U-Value*	*Specific cost*
Brick (burned), 100 mm	1260 KJ/m^3-K	8.50 W/m^2K	-
Solid block, 125 mm	1473 KJ/m^3-K	5.28 W/m^2K	650 $US\$/m^3$
Solid block, 150 mm	1478 KJ/m^3-K	4.40 W/m^2K	650 $US\$/m^3$
Solid block, 175 mm	1484 KJ/m^3-K	3.77 W/m^2K	650 $US\$/m^3$
Solid block, 200 mm	1489 KJ/m^3-K	3.30 W/m^2K	650 $US\$/m^3$
Solid block, 225 mm	1495 KJ/m^3-K	2.93 W/m^2K	650 $US\$/m^3$
Hollow block, 125 mm	753 KJ/m^3-K	3.84 W/m^2K	650 $US\$/m^3$
Hollow block, 150 mm	739 KJ/m^3-K	3.20 W/m^2K	650 $US\$/m^3$
Hollow block, 175 mm	725 KJ/m^3-K	2.74 W/m^2K	650 $US\$/m^3$
Hollow block, 200 mm	711 KJ/m^3-K	2.40 W/m^2K	650 $US\$/m^3$
Hollow block, 225 mm	697 KJ/m^3-K	2.13 W/m^2K	650 $US\$/m^3$
Window types (Solar Heat Gain Co-efficient)	*Unit*	*Value*	*Specific cost*
Single clear 6mm glazing	SHGC	0.810	130 $US\$/m^2$
Double clear 6mm/6mm with air gap glazing	SHGC	0.693	195 $US\$/m^2$
Single clear 6mm glazing with 500mm louvre shading	SHGC	0.656	208 $US\$/m^2$
Double clear 6mm/6mm air gap with 500mm louvre shading	SHGC	0.539	273 $US\$/m^2$
Roofing material (Solar absorptance)	-	-	-
Roof tile	-	0.7	-
Concrete roof slab	-	0.6	-
Asbestos cement sheet	-	0.7	-

Aluzinc sheet	-	0.6	-
Aluminum sheet	-	0.3	-
Ceiling material (Conductivity)	*Unit*	*Value*	-
Wood panels	W/m-K	0.10	-
PVC ceiling tiles	W/m-K	0.19	-
Gypsum plastering	W/m-K	0.40	-
Heavyweight plywood	W/m-K	0.15	-
Lightweight plywood	W/m-K	0.15	-
Floor material (Conductivity)	*Unit*	*Value*	-
Smooth cement finish	W/m-K	0.72	-
Terrazzo finish	W/m-K	2.00	-
Carpet or textile flooring	W/m-K	0.06	-
Wood flooring	W/m-K	0.14	-
Porcelain tiles	W/m-K	1.30	-
Others	*Unit*	*Value*	-
Location	º	N5.6 , W-0.17	-
Occupancy (living room)	People	4	-
Occupancy (bedroom)	People	2	-
Natural ventilation rate (fresh air)	l/s-person	10	-
Lighting density (100 lux)	W/m^2	5	-
Infiltration	ac/h	0.7	-

A.4 MEASURED RESIDENTIAL LOAD PROFILES

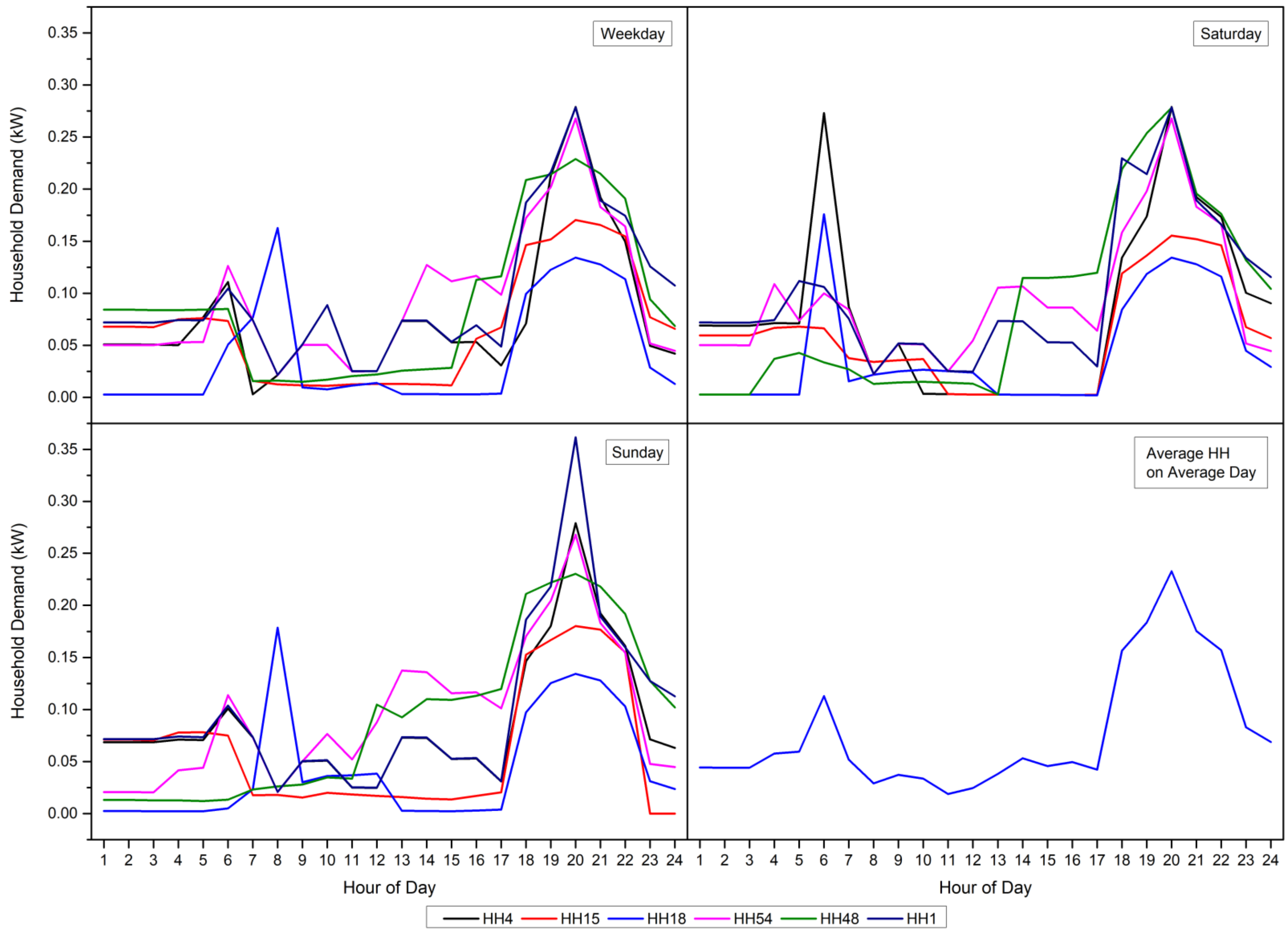

Figure 9.1: Measured hourly load profiles showing variation of electricity consumption in LLH households.

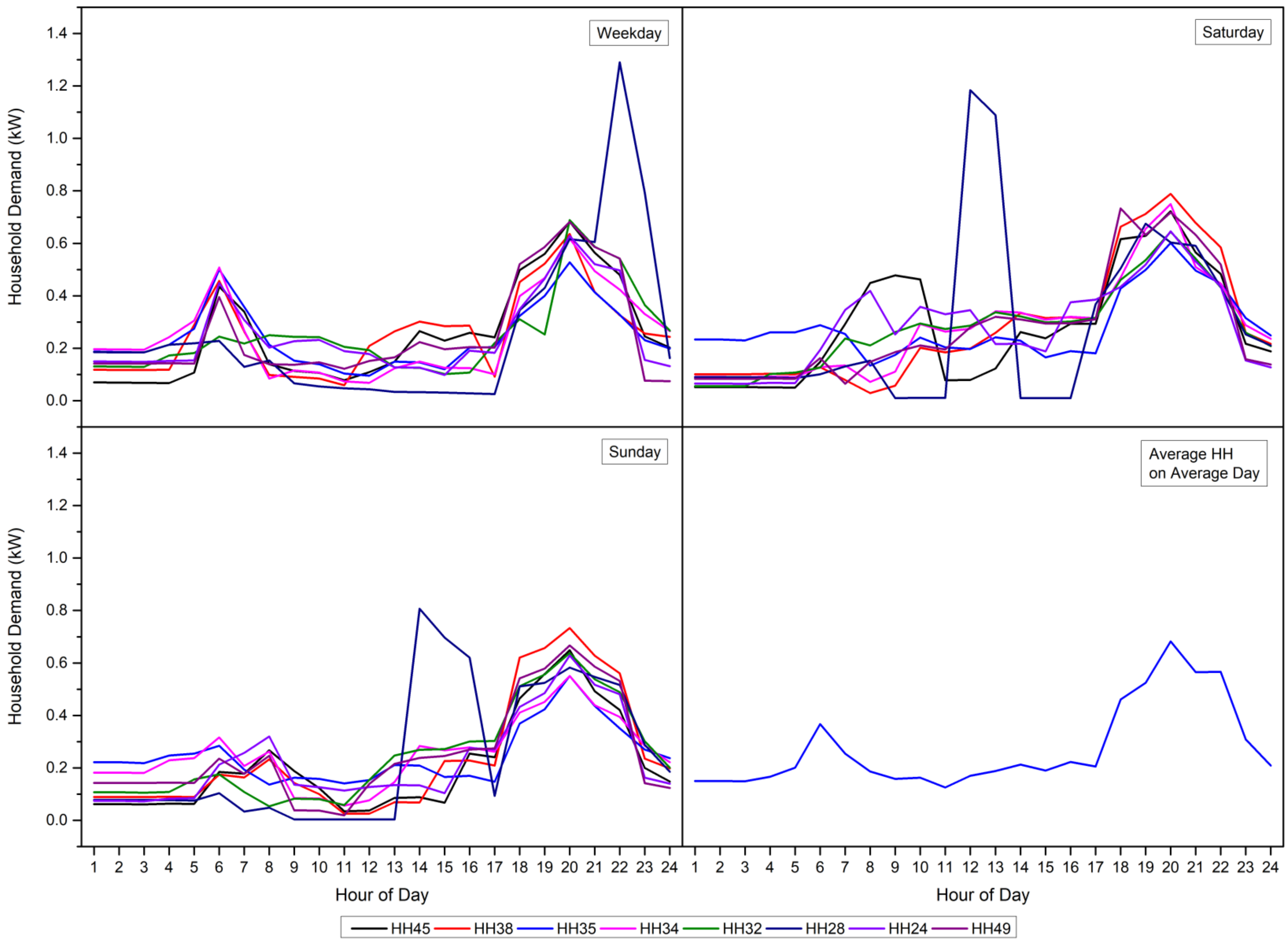

Figure 9.2: Measured hourly load profiles showing variation of electricity consumption in LTH households.

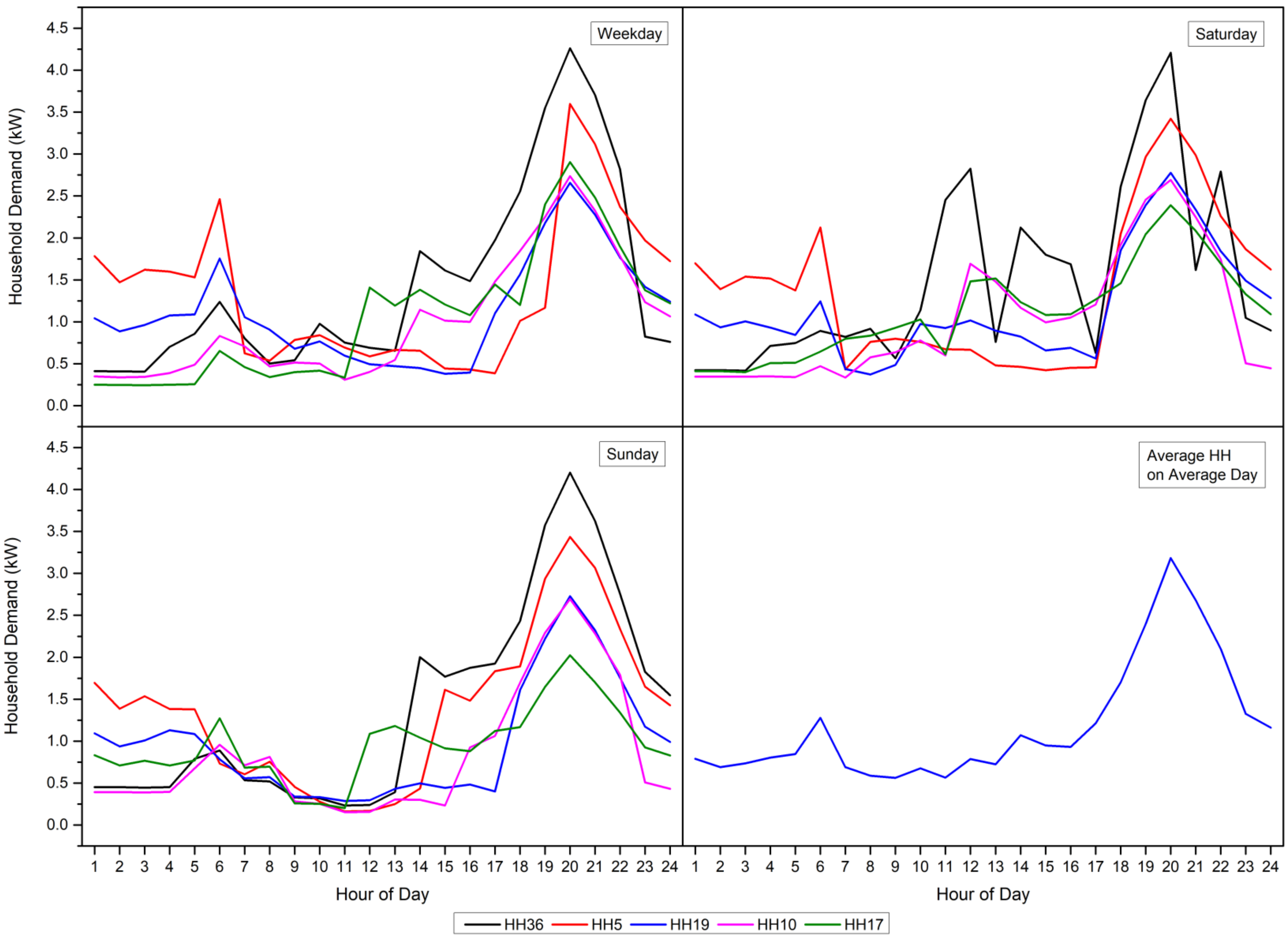

Figure 9.3: Measured hourly load profiles showing variation of electricity consumption in HTH households.

A.5 LIST OF PUBLICATIONS

- **Sakah, Marriette**, Felix Amankwah Diawuo, Rolf Katzenbach, and Samuel Gyamfi. "Towards a sustainable electrification in Ghana: A review of renewable energy deployment policies." *Renewable and Sustainable Energy Reviews 79 (2017): 544-557.* www.sciencedirect.com/science/article/pii/S1364032117307177

- **Sakah, Marriette,** Stephane de la Rue du Can, Felix Amankwah Diawuo, Morkporkpor Delight Sedzro, and Christoph Kuhn. "A study of appliance ownership and electricity consumption determinants in urban Ghanaian households." *Sustainable Cities and Society 44 (2019): 559-581.* www.sciencedirect.com/science/article/pii/S2210670718315695

- Diawuo, Felix Amankwah, **Marriette Sakah,** Stephane de la Rue du Can, Patricia C. Baptista, and Carlos A. Silva. "Assessment of multiple-based demand response actions for peak residential electricity reduction in Ghana." *Sustainable Cities and Society (2020): 102235.* www.sciencedirect.com/science/article/abs/pii/S2210670720302225

- Diawuo, Felix Amankwah, **Marriette Sakah**, André Pina, Patricia C. Baptista, and Carlos A. Silva. "Disaggregation and characterization of residential electricity use: Analysis for Ghana." *Sustainable Cities and Society 48 (2019): 101586.* www.sciencedirect.com/science/article/pii/S2210670718318766