



Environmental Carbon Footprints

Industrial Case Studies

Edited by
Subramanian Senthilkannan Muthu



ENVIRONMENTAL CARBON FOOTPRINTS

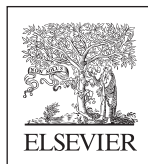
This page intentionally left blank

ENVIRONMENTAL CARBON FOOTPRINTS

Industrial Case Studies

Edited by

SUBRAMANIAN SENTHILKANNAN MUTHU



Butterworth-Heinemann
An imprint of Elsevier

Butterworth-Heinemann is an imprint of Elsevier
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, United Kingdom
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States

Copyright © 2018 Elsevier Inc. All rights reserved.

No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. Details on how to seek permission, further information about the Publisher's permissions policies and our arrangements with organizations such as the Copyright Clearance Center and the Copyright Licensing Agency, can be found at our website: www.elsevier.com/permissions.

This book and the individual contributions contained in it are protected under copyright by the Publisher (other than as may be noted herein).

Notices

Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

Library of Congress Cataloging-in-Publication Data

A catalog record for this book is available from the Library of Congress

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library

ISBN: 978-0-12-812849-7

For information on all Butterworth-Heinemann publications visit our website at <https://www.elsevier.com/books-and-journals>



Working together
to grow libraries in
developing countries

www.elsevier.com • www.bookaid.org

Publisher: Matthew Deans

Acquisition Editor: Ken McCombs

Editorial Project Manager: Ashlie M. Jackman

Production Project Manager: Mohanapriyan Rajendran

Designer: Victoria Pearson Esser

Typeset by TNQ Books and Journals

CONTENTS

<i>Contributors</i>	<i>xi</i>
<i>Biography</i>	<i>xv</i>
1. The Need for Greenhouse Gas Analyses in Industrial Sectors	1
Oludolapo Akanni Olanrewaju, Charles Mbohwa	
1.1. Introduction	1
1.2. Decomposition Method	5
1.3. Applications of Logarithmic Mean Divisia Index	7
1.4. Conclusion	15
References	16
2. Booming and Stagnation of Spanish Construction Sector Through the Extended Carbon Footprint Concept	19
Jorge E. Zafrilla, Luis A. López	
2.1. Introduction	19
2.2. Methodology and Database	21
2.3. Main Results	28
2.4. Conclusions	39
Acknowledgment	41
References	41
3. The Environmental Impact of Magnetic Nanoparticles Under the Perspective of Carbon Footprint	45
Sara Feijoo, Sara González-García, Yolanda Moldes-Diz, Carlos Vázquez-Vázquez, Gumersindo Feijoo, María T. Moreira	
3.1. Introduction	45
3.2. Materials and Methods	48
3.3. Environmental Results	56
3.4. Conclusions	74
Acknowledgments	74
References	75

4. Carbon Footprint of Municipal Solid Waste Considering Selective Collection of Recyclable Waste	79
Luíza S. Franca, Marina S.R. Rocha, Glaydston M. Ribeiro	
4.1. Introduction	79
4.2. Logistic Chain of Recyclable Waste	82
4.3. Brazilian Waste Management Outlook	84
4.4. Case Study	90
4.5. Applied Carbon Footprint Methodology	95
4.6. Results and Discussion	98
4.7. Conclusions	102
Annex I	103
Annex II	104
References	110
 5. Carbon Footprint Analysis of Personal Electronic Product—Induction Cooker	 113
Winco K.C. Yung, Subramanian Senthilkannan Muthu, Karpagam Subramanian	
5.1. Introduction	113
5.2. Methodology	114
5.3. Carbon Footprint Analysis	119
5.4. Life Cycle Inventory for Product Carbon Footprint	121
5.5. Life Cycle Impact Assessment of Product Carbon Footprint Analysis	122
5.6. Life Cycle Interpretation	128
5.7. Conclusion	135
Appendix	136
Acknowledgments	139
References	139
Further Reading	140
 6. Carbon Footprint Analysis of a Selected Indian Power Plant	 141
Debrupa Chakraborty	
6.1. Introduction	141
6.2. Review of Literature	143
6.3. Goals and Objectives	144
6.4. Research Methodology and Data Sources	145
6.5. Results and Analysis	149
6.6. Conclusions	157
Acknowledgments	157
References	158
Further Reading	160

7. Carbon Footprint in the Wine Industry	161
Flavio Scrucca, Emanuele Bonamente, Sara Rinaldi	
7.1. Introduction	161
7.2. The Wine Sector Worldwide	162
7.3. Available Literature and Existing Experiences Regarding Carbon Footprint Calculation	163
7.4. Carbon Footprint Methodology in the Wine Industry	169
7.5. Case Studies and Results	175
7.6. Conclusions	191
References	192
8. Carbon Footprint of Aluminum Production: Emissions and Mitigation	197
Meenu Gautam, Bhanu Pandey, Madhoolika Agrawal	
8.1. Introduction	197
8.2. Aluminum Production	200
8.3. Carbon Footprints	206
8.4. Socioeconomic and Ecological Threats	213
8.5. Mitigation Strategies in Carbon Emissions Reduction	215
8.6. Conclusions	223
Acknowledgments	223
References	223
9. Carbon Footprint of Utility Consumption and Cleaning Tasks in Buildings	229
Alejandro Martínez-Rocamora, Jaime Solís-Guzmán, Madelyn Marrero	
9.1. Introduction	229
9.2. System Boundaries	231
9.3. Methodology	233
9.4. Case Study	248
9.5. Results	250
9.6. Conclusions	254
References	256
10. Greenhouse Gas Emissions From Coal Mining Activities and Their Possible Mitigation Strategies	259
Bhanu Pandey, Meenu Gautam, Madhoolika Agrawal	
10.1. Introduction	259
10.2. Types of Air Pollutants Due to Coal Mining	267

10.3. Coal Mining Contribution to Global Warming	270
10.4. Carbon Footprint for Coal Mining	271
10.5. Important Greenhouse Gas Inventory Calculations for Coal Mining	280
10.6. Case Studies	283
10.7. Strategies in Mitigating Carbon Emissions Reduction From Coal Mining	284
10.8. Conclusion	288
Acknowledgments	289
References	289
11. Life Cycle Assessment of an Academic Building: A Case Study	295
Himanshu Nautiyal, Venu Shree, Paramvir Singh, Sourabh Khurana, Varun Goel	
11.1. Introduction	295
11.2. Life Cycle Analysis	298
11.3. Methodology	300
11.4. Case Study	304
11.5. Discussions	309
11.6. Conclusions	312
Acknowledgments	313
References	313
Further Reading	315
12. The Role of Demand-Side Management in Carbon Footprint Reduction in Modern Energy Services for Rural Health Clinics	317
Olubayo M. Babatunde, Peter O. Oluseyi, Tolulope O. Akinbulire, Henry I. Denwigwe, Tolulope J. Akin-Adeniyi	
12.1. Demand-Side Management	317
Appendices	361
References	361
13. Carbon Footprint Analysis of Printed Circuit Board	365
Winco K.C. Yung, Subramanian Senthilkannan Muthu, Karpagam Subramanian	
13.1. Introduction	365
13.2. Methodology	366
13.3. Carbon Footprint Analysis	372

13.4. Life Cycle Inventory for Product Carbon Footprint	374
13.5. Product Carbon Footprint Analysis	411
13.6. Life Cycle Interpretation	411
Appendix 1	427
Appendix 2	428
Appendix 3	428
Acknowledgments	430
References	430
Further Reading	431
<i>Index</i>	433

This page intentionally left blank

CONTRIBUTORS

Madhoolika Agrawal

Department of Botany, Institute of Science, Banaras Hindu University, Varanasi, India

Tolulope J. Akin-Adeniyi

Department of Electrical Electronic Engineering, University of Lagos, Akoka, Nigeria

Tolulope O. Akinbulire

Department of Electrical Electronic Engineering, University of Lagos, Akoka, Nigeria

Olubayo M. Babatunde

Department of Electrical Electronic Engineering, University of Lagos, Akoka, Nigeria

Emanuele Bonamente

University of Perugia, Perugia, Italy

Debrupa Chakraborty

Netaji Nagar College, Kolkata, India

Henry I. Denwigwe

Department of Electrical Electronic Engineering, University of Lagos, Akoka, Nigeria

Sara Feijoo

University of Santiago de Compostela, Santiago de Compostela, Spain

Gumersindo Feijoo

University of Santiago de Compostela, Santiago de Compostela, Spain

Luíza S. Franca

Federal University of Rio de Janeiro, Rio de Janeiro, Brazil

Meenu Gautam

Department of Botany, Institute of Science, Banaras Hindu University, Varanasi, India

Varun Goel

NIT Hamirpur, Hamirpur, India

Sara González-García

University of Santiago de Compostela, Santiago de Compostela, Spain

Sourabh Khurana

OM Institute of Technology and Management, Hisar, India

Luis A. López

University of Castilla-La Mancha, Albacete, Spain

Madelyn Marrero

University of Seville, Seville, Spain

Alejandro Martínez-Rocamora

University of Bío-Bío, Concepción, Chile

Charles Mbohwa

University of Johannesburg, Johannesburg, South Africa

Yolanda Moldes-Diz

University of Santiago de Compostela, Santiago de Compostela, Spain

María T. Moreira

University of Santiago de Compostela, Santiago de Compostela, Spain

Himanshu Nautiyal

THDC Institute of Hydropower Engineering and Technology, Tehri, India

Oludolapo Akanni Olanrewaju

University of Johannesburg, Johannesburg, South Africa

Peter O. Oluseyi

Department of Electrical Electronic Engineering, University of Lagos, Akoka, Nigeria

Bhanu Pandey

Department of Botany, Institute of Science, Banaras Hindu University, Varanasi, India

Glaydston M. Ribeiro

Federal University of Rio de Janeiro, Rio de Janeiro, Brazil

Sara Rinaldi

University of Perugia, Perugia, Italy

Marina S.R. Rocha

Federal University of Rio de Janeiro, Rio de Janeiro, Brazil

Flavio Scrucca

University of Perugia, Perugia, Italy

Subramanian Senthilkannan Muthu

Bestseller, Kowloon, Hong Kong SAR

Venu Shree

NIT Hamirpur, Hamirpur, India

Paramvir Singh

NIT Hamirpur, Hamirpur, India

Jaime Solís-Guzmán

University of Seville, Seville, Spain

Karpagam Subramanian

The Hong Kong Polytechnic University, Kowloon, Hong Kong SAR

Carlos Vázquez-Vázquez

University of Santiago de Compostela, Santiago de Compostela, Spain

Winco K.C. Yung

The Hong Kong Polytechnic University, Kowloon, Hong Kong SAR

Jorge E. Zafrilla

University of Castilla-La Mancha, Albacete, Spain

This page intentionally left blank

BIOGRAPHY

Dr. Subramanian Senthilkannan Muthu

is currently working for Lidl Hong Kong as a Sustainability Manager, based out of Hong Kong. He has gained his PhD from The Hong Kong Polytechnic University. He was an outstanding student throughout his studies and bagged numerous awards and medals including many gold medals in his study period. He is a renowned expert in the areas of Environmental Sustainability in Textiles and Clothing Supply Chain, Product Life-Cycle Assessment (LCA), and Product Carbon Footprint Assessment (PCF) in various industrial sectors. He has 5 years of industrial experience in textile manufacturing, research and development, and textile testing and around 7 years of experience in LCA, carbon, and ecological footprints assessment of various consumer products. He has completed many LCA, carbon footprint, and environmental assessment projects in Asia and Europe from both cradle-to-gate and cradle-to-grave stages of many products including apparels, plastics, chemicals, and packaging. He has a wide experience in environmental assessment of textiles and clothing supply chain, and he has worked on recycling of plastics and textiles, green claims, and validation of different consumer products. He has delivered extensive trainings on PCF and LCA to many external clients in India, Colombo, Bangladesh, China, and Hong Kong, apart from the delivery of many invited talks. He has delivered many invited key note speeches in various international conferences across the globe.



He has published more than 75 research publications, written numerous book chapters, and authored/edited multiple books in the areas of carbon footprint, recycling, environmental assessment, environmental sustainability, etc. (over 40 books to his credit). Famous titles of his books list include Assessment of Environmental Impacts of Textiles and Clothing Supply Chain, Assessment of Carbon Footprint in Different Industrial Sectors (two volumes), Roadmap to Sustainable Textiles and Clothing (three volumes),

Handbook of Carbon Footprint, Handbook of Life Cycle Assessment (LCA) in Textiles and Clothing, Handbook of Sustainable Apparel Production, and Textiles and Clothing Sustainability (six volumes).

He is acting as an editor, editorial board member, and reviewer for many international peer-reviewed journals of textiles and environmental science disciplines. He is also the series editor of two books series of Springer namely Textile Science and Clothing Technology and Environmental Footprints and Eco-design. He is one of the directors of Textile and Bioengineering Informatics Society, which is a charitable organization created to foster, develop, and promote all aspects of science and technology in bioengineering of materials, fibers, and textiles.

CHAPTER 12

The Role of Demand-Side Management in Carbon Footprint Reduction in Modern Energy Services for Rural Health Clinics

**Olubayo M. Babatunde, Peter O. Oluseyi, Tolulope O. Akinbulire,
Henry I. Denwigwe, Tolulope J. Akin-Adeniyi**

Department of Electrical Electronic Engineering, University of Lagos, Akoka, Nigeria

12.1 DEMAND-SIDE MANAGEMENT

12.1.1 Introduction

Because of globalization, industrialization, and development due to technology, the demand for electrical energy is on the increase. There is therefore a need for efficient energy measures to ensure conservation, thereby saving costs. Demand-side management (DSM) deals with conversion of energy demand of consumers into activities/programs/tactics (e.g., financial incentives and public awareness/education), which brings about less use of energy by the consumers.

Gellings and Parmenter gave a history of DSM in the United States and its influence on energy resources. They also explained the role of DSM in integrated resource planning, the main elements of DSM programs and summarized the key best practices for program design and delivery.

Palensky and Dietrich (2011) described DSM as using measures such as sophisticated real-time control of distributed energy resources, better materials, smart energy tariffs with incentives for certain consumption patterns to improve energy efficiency. Various types of DSM were analyzed, and an overview of modern DSM projects was given.

Haney et al. (2010) highlighted how integrated government DSM policies, targeting residential demand for electricity and heat are more likely

to be successful than single policies. DSM was also used to show how large untapped potentials could be uncovered through barriers to energy demand reduction.

A study on sustainable energy regulation and policymaking for Africa ([Demand-side management sustainable energy regulation and policymaking for africa](#)) examined some of the challenges facing the implementation of DSM programs and also gave a detailed review of DSM measures (this includes review of housekeeping and preventive maintenance, which are the simplest and most effective ways of reducing demand, and marketing of DSM programs) managing and controlling loads from the utility side, converting unsustainable energy practices into more efficient and sustainable energy use, thereby reducing energy demand for the end user. Worldwide, the consumption of energy is massively on the rise, and as a result, the carbon footprint is also increasing in an exponential manner. The rise in energy consumption and carbon footprint are the significant components responsible for “Global Warming.” Currently, climate change a consequence of global warming is a global challenge with severe penalties for our socioeconomic infrastructure as well as the natural environment, and future generation. Long-terms planning will be required to slow down the grave effect of climate change. One of the ways of reducing the energy consumption is the adoption of sustainable DSM programs. Sustainability is also imperative in DSM programs. Sustainability means “meeting the needs of the present without compromising the ability of future generations to meet their own needs.”

The rest of this chapter gives an in-depth background into the importance of DSM, DSM program types, and the various benefits of its adoption. It further presents the opportunities of adopting DSM in rural healthcare centres (RHC). Finally, a case study validating the effect of adopting DSM in sizing of hybrid renewable energy systems for RHC is analyzed.

12.1.2 Importance of Demand-Side Management

The importance of DSM can be summarized into the following ([Demand-side management sustainable energy regulation and policymaking for Africa](#)):

- Reduction in cost of producing energy by generating companies and purchasing energy by consumers.
- Provision for modern technologies and innovation, which create job and bring about economic development.
- Air pollution is reduced, therefore having a positive impact on the environment and social life.

12.1.3 Motivation Behind Demand-Side Management

According to [S. Saini](#), the major motives behind DSM are the need for cost to be reduced and continued sustenance of the environment, also the need for reliability in energy efficiency through the network infrastructure is a motive that encourages DSM.

As a result of the rising costs of power generations and environmental hazard potentials available in power-generating stations because of generation of electricity, DSM therefore not only provides integrated resource planning for reducing costs of generation but also meeting the demands for generation ([Course Module](#)). This can be achieved by setting up energy commissions or agencies, which set targets and goals toward energy conservation, load management, and environmental protection. These agencies are to work with public energy utility companies that oversee generation, distribution, and transmission of electricity to ensure the success of these programs. It is very important that, good policies are put in place to sustain DSM programs. Some of these policies include a standard program for cost-benefit analysis of DSM activities, a predetermined target for energy savings, which is generally accepted, a system of funding, which promotes the competitive nature of energy companies practicing DSM, and finally regulation of prices of energy sold by the energy companies to customers who are noneligible for DSM financial incentives to increase sales, save incentives for eligible customers and therefore save energy ([Course Module](#)). The implementation of DSM programs can be incurred in cost, either by the government through taxes or by the electricity companies through higher tariffs whose burden on the consumers can be eased by the government through subsidies and loans. The energy commissions and agencies are to also ensure that, no planning of theirs affects environmental and infrastructural development, even as they ensure that the natural environment is not polluted, and it is therefore sustained.

Because of increasing demand for electricity and inadequate infrastructure for transmission and distribution networks in developing and developed countries, the need for DSM program is therefore of priority. Planning through DSM can reduce the need and possibly eliminate the cost of constructing transmission and distribution network infrastructure expansion ([Course Module](#)).

12.1.4 Types of Demand-Side Management Measures

DSM measures are classified into three ([Demand-side management sustainable energy regulation and policymaking for Africa](#)), namely: energy

reduction programs, load management programs, and load growth and conservation programs.

12.1.4.1 Energy Reduction Programs

This is also referred to as “energy-saving tips”. Some of the programs require capital, whereas others are capital free.

Energy-saving tips for steaming and heating systems include the following:

1. It should be ensured that there are adequate control for adjusting the quantity of combustion air.
2. It should be ensured that, insulation and refractory pipes are in good condition, their thicknesses should also be appropriate for good modern practice.
3. Combustion conditions should be routinely monitored, and the efficiency should always be kept as high as possible.
4. It should be ensured that, the water treatment system is always in good working order, and there should be constant and regular monitoring of the boiler feed water quality.
5. It should always be ensured that, there are no areas for steam and water leaks in the equipment.
6. Vessels, return lines, and fittings should always be condensed, and any steam present should be insulated
7. Steam leaks and steam traps should always be maintained and repaired when faulty.
8. Flash steam in the plant should always be considered during use.
9. Automatic temperature controls should be placed correctly in equipment wherever waste of steam that can overheat equipment or processes is minimized.

Energy-saving tips for lighting include the following:

1. Efficient energy fluorescent tubes, CFLs, and other low-energy light sources should be used.
2. Luminaries should be cleaned regularly.
3. Appropriate lighting levels at different periods and different zones should be used.
4. Natural light should always be encouraged in areas where possible, e.g., roof panels and skylights, etc.
5. Walls and ceilings should be painted with white or bright colors to improve reflection of light.

Energy-saving tips for motors include the following:

1. Use of highly efficient motors should be encouraged.
2. Improved bearings should be installed, and there should be regular and constant lubrication.
3. Motors should be properly sized and should be used only when needed.
4. All equipment should be maintained regularly.
5. Controls having electronic variable speed where motor loads vary in normal operation should be used.
6. Power factor should be checked regularly and should also be improved using capacitor banks, preferably closely installed to the running equipment.

Energy-saving tips for compressed air systems include the following:

1. Wrong use of compressed air should be discouraged and eliminated.
2. Leaks should be checked out when workshops are typically quiet and are not supposed to be using air.
3. Important parts of the system should be checked regularly to prevent the effect of early damage.
4. Overall system efficiency should be ensured by checking compressor running times to improve the system.
5. System pressure should always be optimized.
6. Heat recovery systems should be installed.

In households, some energy-saving tips include the following:

1. Air infiltration or hot air escapes, and inadequate or failed insulation should be eliminated in fans and vents, heating, cooling and ventilating ducts, and fireplaces, electric outlets, plumbing penetrations through walls, floors, walls, ceilings, doors, and windows.
2. Insulating blankets, insulating pipes, and thermostat set to 50°C should be encouraged for use in hot water cylinders.
3. Incandescent lightings should be replaced with CFLs and LEDs of appropriate and equivalent illumination.
4. Curtains should be used as insulators at night and as a blind against the sun to cool when hot; the curtain should also be open for sun to enter to heat when cold.
5. Dryers, dishwashers, and washing machine should only run with full load.

Some energy-saving measures that require investments include the following:

1. Replacing appliances that are old and worn-out.
2. Making use of a solar water heater.
3. Making use of double-glazing windows.

The measures discussed above are not generally applicable. Some of the generally applicable measures include the following:

1. *Efficient Lighting*: Efficient lighting measures which require investments, are not so large, and the investments are eased through paybacks and subsidies. Changing light bulbs, fittings, switches, and increased use of natural light are some of the tips involved in efficient lighting. Incandescent bulbs lose energy to heat and are therefore inefficient, compact fluorescent lamps with electronic ballasts are more efficient than incandescent bulbs with conventional ballasts, although they are more expensive, they last longer and consume less energy than the required energy for transmitting the light energy output. Some of the most common opportunities involved in efficient lighting include
 - a. Long-term benefits by replacing existing lamps with more efficient light sources. This is known as light retrofitting.
 - b. Safety in lighting by removing selected lamps, which do not support safety of the lighting zones from existing light fixtures in a uniform pattern throughout specific zones.
 - c. Switching off selected areas of lighting with absence of people, whereas adjacent areas remain switched on to save energy, which can be wasted because of little or nonusage.
2. *Energy-efficient Motors*: Energy-efficient motors are needed to sustain manufacturing and mining industries and the natural environment. Many opportunities exist through energy-efficient motors. Air-conditioning for air circulation and compressor motors is a major source of power usage in industries to remove heat, dust, and gases, which can cause loss in energy. High efficiency motors can reduce electrical loads, thereby saving energy and ensuring the ventilation of mines ([Pitis \(Femco\) and Livingstone \(Anglo Gold Mining Motors\), 2004](#)). Per feasibility studies carried out in 1999 for establishment of motor repair and sales centers in Ghana based on sustainable energy regulation and policymaking training manual ([Demand-side management sustainable energy regulation and policymaking for africa](#)). It was concluded that, repeated motor rewinding and refurbishment lead to significant efficiency in losses. The study also made a recommendation on developing and implementing procedures on motor testing, labels, and standards for minimum efficiency and also setting up a facility in Ghana for the manufacture of small electric fan and pump motors ([Ahenkorah](#)).

12.1.4.1.1 Energy Management Practices in Organizations

Energy management practices through DSM are very important in industries/organizations for cost reduction of energy. Energy

management in organizations depends on organizational budget, skills of staff available, and the nature of the organization. Energy management programs include: capital investment management (including equipment procurement), energy purchasing, performance measurement, energy policy development, metering and billing, energy surveying and auditing, awareness-raising, and training and education. An energy manager in any organization is usually tasked with the following responsibilities:

- Development and evaluation of projects to save energy.
- Proper and regular identification of energy-saving opportunities.
- Regular collection and analysis of energy-related data.
- Constant supervision of energy purchases and equipment procurement.
- Project implementation and future monitoring of implementation performance.
- Effective communication and public relation skills.

Cost-management activities that aid DSM programs include (Martel, 2000) the following:

- Accounting of energy and base-lining analysis.
- Billing of tenants for multiple occupancy buildings.
- Verification of utility bills and tracking of budget.
- Production of load profiles of individual and multiple facilities to ease energy decisions.
- Reporting of management of facility to the senior managers.
- Benchmarking of internal and external energy performance.

12.1.4.1.2 Energy Management in Households

Some good housekeeping tips for energy savings in households include:

- Switching off loads that are not in use: e.g., lightings, computers, monitors, sockets, etc.
- Removing lighting fixtures and pipings that are redundant and contribute to unnecessary heat losses.
- Faulty electricity lines should be replaced to prevent losses and distribution systems should be improved regularly for efficient output.
- Steam leaks and faulty equipment should be replaced or prevented to prevent losses.

12.1.4.1.3 Precautions to Prevent Energy Losses in Building

Some preventive measures for ensuring that energy losses do not occur in industries include the following:

- Filter cleaning on air compressors, pumps, upstream of steam traps in ventilation ducts, and others should be undertaken regularly.

- Hot spots on boilers and furnaces should be monitored regularly and checked for refractory failure.
- Transformer temperatures should be monitored regularly to prevent abnormalities.
- Noise and vibration of bearings should be monitored regularly to prevent failure of bearings.
- Having a routine schedule for lubrication of parts and equipment.
- Regular replacement of worn-out equipment.

Building regulations and standards are also important practices of DSM. Building regulations has an impact on energy efficiency of buildings. Some of these regulations include the following:

- Passive lighting should be encouraged.
- Use of quality building construction materials to reduce heat losses.
- Roof spaces should be insulated.

It is also important as part of customer awareness that, equipment and buildings indicate their expected energy consumption. Customer education and labeling of appliance help customers make good judgment when buying appliances and equipment, thereby reducing energy consumption.

12.1.4.1.4 Energy Auditing

Energy auditing deals with analyzing and surveying the flow of energy to conserve energy in a building/plant. This can be done by using energy record keeping and measuring equipment like energy meters. Energy auditing is an essential component of energy management program, whereby a complete review of energy consumption activities, such as energy consumed in manufacturing and energy consumed in heating or cooling. Energy audits then collate all relevant data to carry out a detailed analysis of the performance of the building or system and to identify deficiencies and make recommendations for improvement.

Kumar et al. ([Sameeullah et al., 2014](#)) identified energy-saving methods experienced during an energy audit of a building in India and also gave a detailed explanation on how these methods could be implemented. This was done with the aim of showing the importance of energy audit in energy conservation.

[Lamba and Sanghi \(2015\)](#) gave a complete emphasis and explanation as to how energy audit is a continuous process toward achieving energy efficiency. They gave a detailed analysis on how to conserve and efficiently utilize scarce resources and how to identify and implement energy saving

potentials through energy auditing. Opportunities using renewable energy technologies were also discussed.

The following steps explain how energy audit can be carried out in a building:

- Information on the processes employed, machinery characteristics, plant equipment and physical facilities, design data, and production capacities are obtained and collated.
- Historical records, the emissions, energy consumptions, and production levels for machines and energy consuming equipment (over a period of say 2–3 years) are determined.
- The actual operating parameters and performance of equipment and processes should be determined.
- The data obtained and the observations made should be properly established in efficiency of energy utilization by key equipment.
- Constraints to improving performance, including organizational, technical, and financial constraints should be identified and characterized.
- Potential measures for improvement should be identified and financial evaluation, where investment is needed should be carried out.
- A comprehensive action plan, which is very logical to address the constraints, should be developed, including specific recommendations and priorities for the different measures.

Audits can be divided into preliminary audit and detailed audit, which are both discussed, respectively.

1. Preliminary audit: This is an exercise in form of a fieldwork to gather initial data at the primary stages of the auditing program. It is also known as walk-through or short audit. In this type of survey, there is no need for the use of equipment because data from the building are sufficient. Data is collected via a “walk-through” of the building during which the general condition of equipment, the standard of maintenance, the level of operations control exercised by management, and the reporting procedures in effect are observed.

Dongellini et al. (2014) gave a good explanation on how “walk-through” audit is important in reducing energy consumptions for sustainable and energy-efficient manufacturing, continuous energy audit, and process tracking of industrial machines. This was carried out on eight large industrial buildings of a famous car manufacturing holding in Italy. Preliminary audit is very easy and less stressful as few measurement and easy calculations are used. It is therefore quick and can be completed within a

short period. The information obtained from a preliminary audit is used for a thorough analysis of the energy performance of a building/plant.

2. Detailed Audit: This is a more comprehensive form of energy auditing. It deals with a survey on home energy by obtaining more detailed information on the home's energy usage, as well as a more proper financial analysis of its energy costs. Portable instruments are commonly used for accessing parameters on equipment and processes, the auditors must be well experienced with a good sense of judgment when collecting and interpreting data. Half of the effort put into a detailed audit should be spent on collecting data on-site, whereas the other half on proper analysis of the data and preparing the report. Detailed energy audit takes a longer time to complete, and it is used for a longer-term performance monitoring.

Singh et al. (2012) defined detailed audit as one, which provides a dynamic model of energy use characteristics of both existing facilities and all energy conservation measures identified, and therefore calibrates the building model against actual utility data to provide a realistic baseline and to compute operating savings for the proposed measures. They also presented a detailed energy audit, for design and implementation of a physically based model for industrial load management, thereby improving the plant efficiency and reducing the energy wastages.

Srinath and Uday Kumar (2014) explained detailed audit in the industrial sector as one requiring a comprehensive recording and analysis of energy consumption data, which is split into various sectors (steam/hot water production, compressed air, electricity, and heating, ventilation, and air conditioning). This is done to present and analyze different parameters that determine each type of energy use (e.g., production capacity, climate conditions, raw materials, and others). A list of potential energy-saving measures, which requires investment capital are presented together with a cost-benefit analysis for each proposed measure.

12.1.4.2 Load Management Program

Load management programs include: load leveling, load control, tariff incentives, and penalties.

12.1.4.2.1 Load Leveling

Load leveling optimizes the generating base load, operating at the present time without the need for reserve capacity to meet the periods of high

demand. It therefore reduces fluctuations in customer demand. Classic forms of load leveling include the following:

- **Peak clipping:** Here the peaks of demand are clipped to reduce the load at peak times and intervals. The diagram of peak clipping is represented in the first diagram of Fig. 12.1.
- **Valley filling:** Here the low-demand periods are “filled” by building up off-peak capacities achieved by using thermal energy storage to displace fossil fuel loads. The diagram of valley filling is represented in the second diagram of Fig. 12.1.

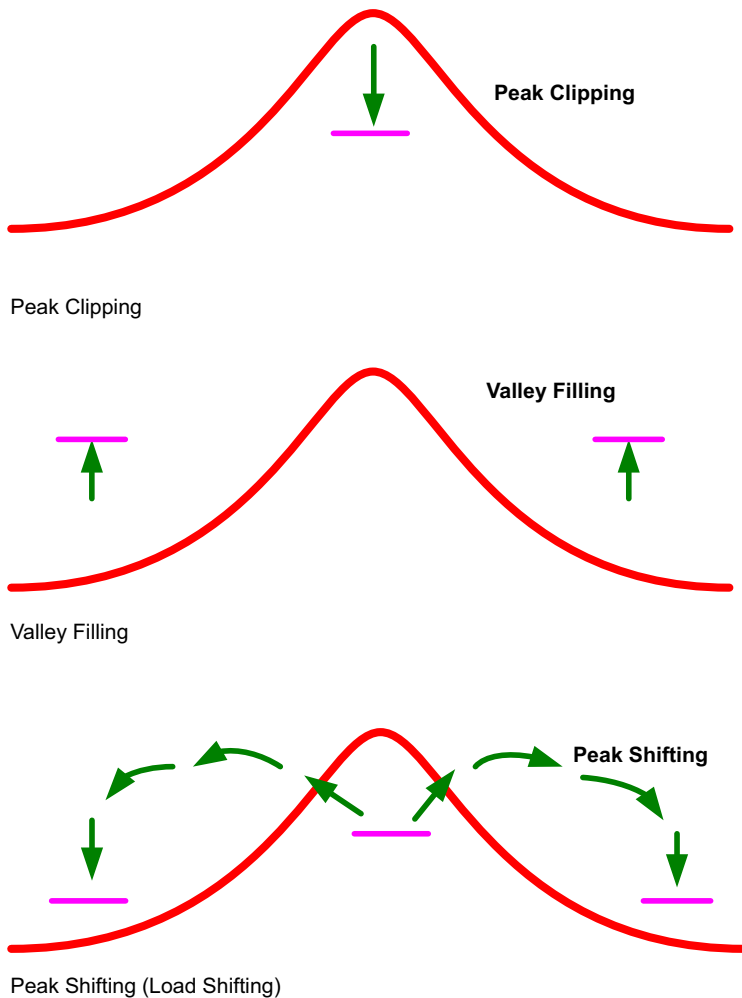


Figure 12.1 Classic forms of load leveling. (From <https://image.slidesharecdn.com/presentazionecordoba-160319093812/95/residential-demand-response-operation-in-a-microgrid-8-638.jpg?cb=1458380410>.)

- **Load shifting:** Here loads are “shifted” from high demand to low demand to achieve clipping and filling. Some applications of load shifting include: storage space heating, storage water heating, customer load shifting, and coolness storage. The diagram of load shifting is represented in the third diagram of [Fig. 12.1](#).

12.1.4.2.2 Load Control

This is the automatic regulation of load because of heating, cooling, ventilation, and lighting by the utility or electricity company. Here, agreements are made between the customers and utility company to meet peak demand on the grid. This is done by customers using energy storage equipment and generators for backup. Electricity companies can organize a publicized schedule for a systematic switching off supply to different areas within a particular region at different intervals, whereby different areas take turns in losing supply. This is done to enable businesses and homes to plan their use of energy for that period.

12.1.4.2.3 Tariff Incentives and Penalties

Whenever customers use energy at some certain periods of time to ensure a better-priced rate for their energy use, the electricity companies encourages tariff incentives as a reward for these customers. These include the following:

- Providing different charges for power use at different periods, whereby high peak time charges encourage users to carry out their activities requiring high load in an off-peak period when the rates are lower. This is known as time-of-use rates.
- Penalizing users for going below a fixed power factor threshold, usually between 0.90 and 0.95. This is also known as power factor charges.
- Ensuring that, energy rates vary based on the energy provided by the electricity company. This is known as real-time pricing.

12.1.4.3 Load Growth and Conservation Programs

These programs are carried out with the aim of ensuring productivity and environmental compliance on the part of customers while making sure that, electricity companies increase their sale of energy. These programs can eliminate energy practices, which are unsustainable and bringing about more efficient practices such as: reducing the use of fossil fuels and also raw materials. Some of these programs include the following:

- *Strategic load growth:* This is the change of shape in load supplied to the customers by the electricity company which means that, there is a general increase in sales of electricity. This is represented in [Fig. 12.2](#).

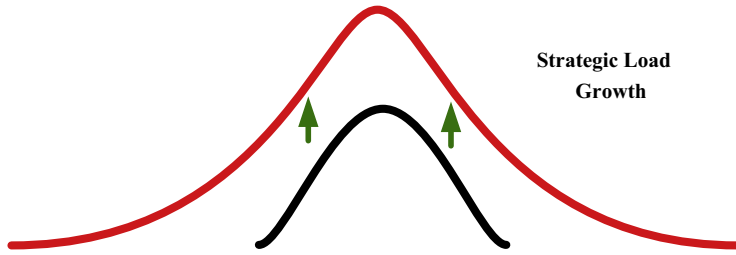


Figure 12.2 Diagram representing strategic load growth. (From <https://image.slidesharecdn.com/presentazionecordoba-160319093812/95/residential-demand-response-operation-in-a-microgrid-8-638.jpg?cb=1458380410>.)

Increase in market share of loads that are or can be served by competing fuels, as well as new areas development encourages load growth. Electrification involving electric technologies, industrial process, heating, and automation are modern day techniques for encouraging load growth.

- *Strategic load conservation:* These are programs targeted at the end use customers, whereby reducing sales as well as a change in the pattern of use is highly encouraged. Some of these programs include: insulation, sealing, and double-glazed windows (also known as weatherization). This is done for improvement in efficiency, in homes, and appliance. Strategic conservation is the change of shape in load supplied to the customers by the electricity company, which is directed at the end use consumption. This is represented in Fig. 12.3.

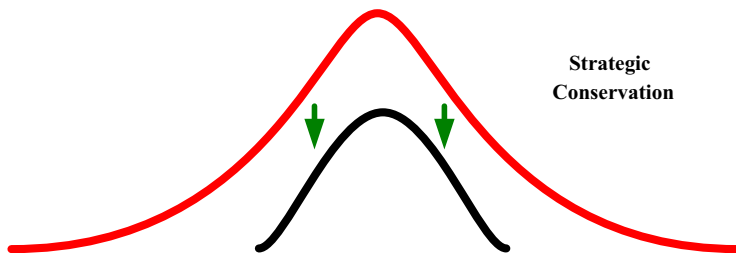


Figure 12.3 Diagram representing strategic load conservation. (From <https://image.slidesharecdn.com/presentazionecordoba-160319093812/95/residential-demand-response-operation-in-a-microgrid-8-638.jpg?cb=1458380410>.)

12.1.5 Information Dissemination on Demand-Side Management

This involves a collective effort from different stakeholders in developing, and implementing energy efficiency policies that are necessary for uninterrupted energy efficiency improvement. Information can be disseminated by awareness through campaigns promoting energy efficiency options and specific DSM techniques. This can be done through visual media (e.g., leaflets, brochures, fliers, posters, and video clips). Advertising and conducting energy audits are modern day forms of information dissemination.

12.1.6 Challenges of Implementing Demand-Side Management Programs

Challenges, ranging from insufficient provision, low awareness of energy, and efficiency/DSM programs to inability of industrial and commercial companies to carry out energy audits to obtain important information on their current operations are current trends affecting developing nations today. This can be as a result of failure by the company's management to explore the potential benefits of energy efficiency and also lack of skilled personnel for performing audits. Some measures that organizations can use in overcoming these challenges include the following:

- Ensuring that, competence and comprehensiveness of the assessment of DSM programs and audits are accomplished.
- Ensuring that, DSM systems and opportunities are well known and understood.
- Ensuring that, accuracy of assumptions is always considered.
- Ensuring that, there is proper awareness on production and safety constraints of involved plants/companies.

Factors that load management programs need to consider increasing energy efficiency include the following:

- Varying prices of electricity and other fuels.
- Cost burden on the customer.
- The value of losses prevented by ensuring an improved and reliable electricity system.
- Losses that can occur in production when implementing DSM programs.

Thorough financial analysis of the benefits of energy efficiency improvement needs to be undertaken when planning to set up DSM activities. Every DSM investments need to be properly accounted for to

ensure easy assessment of funds for DSM projects because, if a project is not properly evaluated, approval of funds would be difficult, and this is the most vital challenge of implementing DSM projects.

12.1.7 Case Study—Energy Efficiency Opportunities for Rural Health-Care Facilities

Energy efficiency and conservation are a well-established practice in developed country hospitals and few developing countries. Energy efficiency measures have the tendency to reduce energy consumption as well as health facility's energy bill (Oluseyi et al., 2016). Apart from these, it can reduce emissions from conventional captive diesel/gasoline generators used in powering the facility and also allow backup systems to work more effectively during power outages or failure. Energy-efficient equipment is important for any facility, which is intended to operate off grid or on intermittent power sources or which must rely on battery storage.

Like in other power-consuming sectors, energy efficiency measures should be an essential factor in all existing and new health-care facilities in developing countries. Hence, the use of energy-efficient modern and functional medical equipment should be encouraged. This at times is usually a complex issue as agreement needs to be reached between medical personnel, design engineers, and other stakeholders. For example, in most developing countries with hot climate, there is usually the need for air-conditioning, which usually consumes significant amount of energy. Also, air-conditioning units are particularly sensitive to power fluctuations and, as such, are difficult to keep operational in developing countries. On the other hand, air-conditioned rooms are essential for sensitive laboratory equipment as well as sanitary purposes. In addition to sizing and designing, the operation of the health clinic can also affect its energy efficiency and power demand. The type of equipment purchased is important in reducing power consumption at health facilities. Energy star-rated equipment perform better in energy consumption when compared with conventional and obsolete equipment. All equipment and lighting connected to the storage device (backup) should be energy star-rated. If air-conditioning must be used, units with a high ratio of British thermal unit to watts should be procured. Training of both medical and maintenance staff on the importance of utilizing and ensuring efficient, low-energy operation of a health facility should also be ensured.

Typically, energy-efficient equipment and appliances are more expensive than standard-efficiency models. Conversely, this high cost may be

Table 12.1 Energy efficiency opportunities in health-care centers

Appliance	Energy efficiency/conservation measures
Lights	Lighting retrofits with energy-efficient light bulbs such as CFL or LED lamps. Switch off redundant lamps.
Vaccine refrigerator and ice pack freezer	Energy-efficient refrigerators should be encouraged because these refrigerators use 20% less energy.
Centrifuge	Turn off redundant centrifuge. Select centrifuge models that have relatively low rotor friction, which generates less heat, specifying smaller energy.
Autoclave	The equipment is fitted with a timer to cycle off when not in use. This will save maintenance by replacing the element as well as save energy.
Air-conditioner	Air-conditioner energy efficiency is measured by the energy-efficient ratio (EER) of the equipment. When buying new systems, buy the model with the highest EER rating. For operation, ensure coils are kept clean and that the thermostat is set at a comfortable, but not overly cool, temperature.
Computer	Energy star computers with flat screens and enabled with power management software can consume 40% less electricity than the conventional counterparts.
Printer	60% energy can be saved if printers that enable power management and duplexing features are used.

From <http://www.poweringhealth.org/index.php/topics/technology/energyefficiency>.

recovered through reduced operational costs of a smaller electricity generation system. [Table 12.1](#) shows energy efficiency opportunities for some appliances/devices used in health clinics.

12.1.7.1 Need for Reliable Electricity in Rural Healthcare Centres

The need for a constant and efficient electrical power supply in our rural and local health-care centers all over the world is now a major concern. This is because of the adverse effect; the lack of a reliable electrical power system exposes the operators of these rural health-care systems and their patients, thereby posing a risk when saving human lives ([Jimenez and Olson, 1999](#)). Today, the distribution of vaccines and other temperature sensitive drugs and substances such as: antiretroviral drugs in our health-care

centers globally. This has placed its own demand for electricity in health centers where there are limited or even no access to reliable power supply (Olatomiwa et al., 2016). The emergence of highly communicable diseases in modern time such as: the HIV/AIDS and Ebola virus, which were predominant in western Africa, and the Zika virus, which was and is still intense in South American countries, has necessitated the need for an efficient and reliable electricity power supply to fight these diseases to a standstill. For instance, unreliable power supply can hinder the treatment process of these diseases, if there are no refrigerators to store most of the vaccines, which are temperature sensitive, needed to fight these diseases. Also, a health personnel, attending to a patient or trying to take samples for medical tests in an enclosure or room without proper illumination stands the risk of being infected with these diseases easily as a result of poor illumination to comply with the laid down ethics and procedures for fighting the disease. The chances of carrying out the required medical tests could be impeded even during the day because electricity is required to power most medical equipment required to carry out these tests. Furthermore, a patient that arrives a health center that lacks electric power at night for medical attention will have to wait till the next day before proper examination can be carried out, which could be fatal.

Nigeria as a country has persistently been facing the challenge of lack of access to constant modern energy services over the years with the high dependence of its citizens on petroleum fuel for its individual electricity production. This challenge has its tremendous effect in other facets of the economy. In a country where about 40% of its citizens have access to electricity and 80% of this percentage lives in the urban areas (Nwulu and Agboola, 2011), this means that, most rural areas in Nigeria are not connected to national grid and therefore do not have access to electricity. These rural areas depend mostly on their traditionally domestic sources of energy for their livelihood. In a country with an electricity installed capacity of ~6538.3 MW, not more than 4500 MW is ever produced (Nwulu and Agboola, 2011), and with the ever growing demand for electricity all over the country in both urban cities and rural areas, especially in sectors that need critical attention such as: the health sector, there is the need to provide electricity that is reliable, efficient, and constant. As at present, Nigeria has not utilized or tapped fully the renewable energy technology to solve its electricity problems even though it is highly endowed with renewable energy. This form of energy will provide an affordable, reliable, efficient as well as constant source of electrical power, especially to critical sectors of the

economy such as: health and in the rural areas that face utmost lack of these basic social amenities for the provision of good, reliable, and stable health-care system.

Only a few know that, Nigeria is endowed with abundant renewable energy resources such as: solar energy, hydroelectric power resources, wind, biomass with potentials for hydrogen utilization and development of geothermal, and ocean energy (Ohumakin, 2010). As a result of the different resources of renewable energy, various approaches have been applied to determine and meet the optimal size of the system and components (Zhou et al., 2010; Bajpai and Dash, 2012). Renewable energy have been proved to provide quality and reliable electricity for different applications in rural areas (Dihrab and Sopian, 2010; Hiendro et al., 2013).

12.1.8 Methodology

12.1.8.1 Sizing Hybrid Renewable Energy Systems

12.1.8.1.1 Hybrid Optimization Model for Electric Renewables

A typical hybrid system will comprise a photovoltaic (PV) array, wind turbines, possibly a diesel generator, inverters, and battery bank with associated control devices (Lal and Raturi, 2012). Software tools such as Hybrid Optimization Model for Electric Renewables (HOMER) can be used to carry out simulation and optimization of hybrid systems. There are three main tasks that can be carried out by HOMER, which are simulation, optimization, and sensitivity analysis (HOMER Energy LLC: Hybrid optimization model for electric renewable, 2009). The HOMER is designed to perform simulation on long-term operation of a combination of micropower system configurations, with the inclusion of components like PV, wind, small hydro, diesel generators, and storage devices that can be battery banks. The HOMER can also be used for the modeling of grid-connected systems. After the simulation of quite a number of combinations, HOMER will make suggestions based on the net present cost (NPC) optimal configuration of the system. The sensitivity analysis can be performed using the sensitivity variables, i.e., wind, speed, and diesel price, which will enable the designer to determine the best combination of system components under different conditions.

12.1.8.1.2 Researches for Renewable Energy Access for Rural Healthcare Centres

Several researches have been carried out to study the hybrid systems in many locations around the world (Bekele and Palm, 2010; Akinbulire et al., 2014;

Hassan et al., 2011; Nandi and Ghosh, 2010; Rahman and Al-Hadhrami, 2010), Bekele and Palm researched on the feasibility study for a stand-alone solar wind based on hybrid energy system for application in Ethiopia and determined the optimal system for supplying electricity to a neighborhood of 200 families in Ethiopia and discovered that the price for diesel in 2009 was the most cost effective for the diesel generator/battery/converter set up (Bekele and Palm, 2010). The study of the optimization and life cycle cost of a hybrid system for a rural area health clinic in southern Iraq using HOMER software was carried out by Al-Karaghoul and Kazmerski. It was discovered that, the system when consisting the PV/battery inverter, was the most economic system (Al-Karaghoul and Kazmerski, 2010). The study of the technoeconomic evaluation of PV/diesel/battery systems for rural electrification in Saudi Arabia was carried out by Akinbulire et al. (2014). They researched on the effect of the increase in PV/battery on the cost of energy, operational hours of diesel generators, and the reduction in greenhouse gas (GHG) emissions. The study of the renewable energy technologies in the Maldives was performed by Van Alphen et al. (2007), and it was discovered that, 10% of the total electricity needed by Maldives can be supplied using renewable energy resources. Benghamem performed a study of the optimization of tilt angle for solar panel to increase the energy production, using Madinah, Saudi Arabia as case study (Benghamem, 2011) and revealed a gain of 8% at a tilt of solar collector in a particular angle on monthly basis when compared with tilting it annually. Besarati et al. (2013) studied the potential of harnessing solar radiation in different parts of Iran was analyzed and the results revealed that, there is greater potential for renewable energy application in the central and southern part of Iran.

12.1.8.2 Site Description

The sites used for the research were six towns selected across the six geopolitical zone/regions of Nigeria. The towns were selected across the six geopolitical zones to enable the study covers all the characteristics of the weather and climatic conditions of all the zones in Nigeria. Also, the towns selected are not the popular urban cities well known in Nigeria but are towns that are rural in nature and close to rural areas. The towns include: Okrika (south south zone), Ihiala (south east zone), Igbeti (south west zone), Kabo (north east zone), Abadan (North West zone), and Gboko (north central zone). Analysis was performed on these selected sites on the prospects of PV to power RHC.

12.1.8.3 Solar Resource

The NASA website provided the metrological data used in the analysis of this research work. The agency provided the average solar radiation for a stipulated range of time used for the analysis for the sake of the study.

12.1.8.4 Proposed Hybrid System

Based on the amount of solar resources present at these selected sites, the proposed hybrid system will be a combination of PV modules, diesel generators, power converters, and storage batteries. HOMER is the software to be used for this study. It is a general purpose system design tool for electric power systems. The software has several inputs, as well as component's technical and economic details (Olatomiwa et al., 2016). To arrive at an optimal value for system components, HOMER accepts more than one value to be entered to a tune of multiple values. Reliability and efficiency can be strengthened when the right merging of different sources of energy is done. The energy storage requirements are also reduced when compared with systems that have only one renewable energy source (Zhou et al., 2010; Olatomiwa et al., 2014). When solar energy resources and diesel generators are combined, a hybrid solar/diesel generator configuration is formed with an energy storage system to make the system a more reliable source of electrical power. The diesel generator in the hybrid system acts as a backup energy source, when there is redundancy or insufficient renewable energy resources.

The hybrid system design is better because there is more than one source of energy for alternation, and compliments the efforts of one another to achieve a reliable and efficient system in producing the much-needed electrical power for rural health centers, unlike the one source of renewable system that does not have these benefits. Also, in the hybrid system, different components need to be sized so as to achieve the required load demand, while in a single source of renewable system, the system to accommodate the load demand, the becomes oversized.

12.1.8.5 Data Requirements

To achieve the aim of this study, the data required for this analysis are categorized into three, namely: (1) metrological (solar irradiance), (2) estimated load, and (3) the component data. These are discussed in the next section.

12.1.8.6 Metrological Data

For the purpose of this study, a town each falling within a geopolitical zone in Nigeria is picked as a pilot study for the entire geopolitical zone.

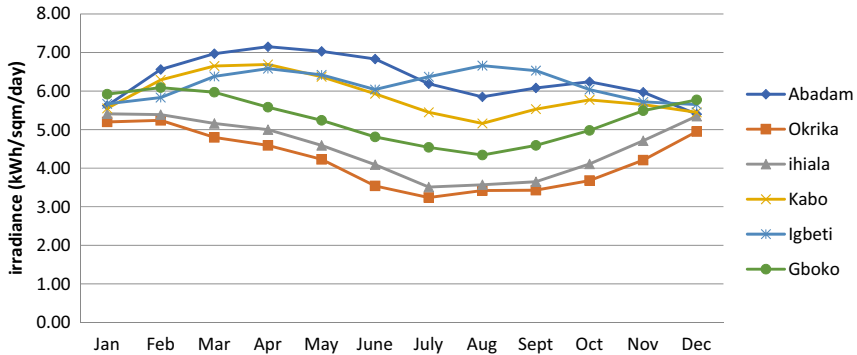


Figure 12.4 The solar irradiance for the chosen cities.

Fig. 12.4 shows the solar irradiance for the chosen cities as obtained from NASA's global satellite database. This serves as input into HOMER to ascertain if the load demand of the clinic can be met.

12.1.8.6.1 Load Data

12.1.8.6.1.1 Categorization of Health Clinics To adequately capture the energy demand of a health facility, it is essential to categorize health facilities based on size and energy consumption. This section describes classes of health facilities and their corresponding energy demand. The energy demands of a health facility will be a critical component in the selection of the most appropriate electrification technology. The descriptions provided are according to United States Agency for International Development documents available in open literature (<http://www.poweringhealth.org/index.php/topics/technology/energyefficiency>).

12.1.8.6.1.2 Health Post Health post is the smallest, most basic health facility in terms of size and services provided. These facilities usually do not have a permanent doctor or nurse. Most times, the health post may have a full- or part-time primary health-care provider and trained health officers. Services provided by health post facilities include: the treatment of minor illnesses, the nursing of minor injuries and, and the provision of basic immunization services. Because of the limited medical services provided, the medical equipments are few, and as a consequence, the overall energy consumption is moderately low. The energy demands of a health post will be satisfied through category of health clinic electrification options, while taking into account the reduced daily demand for energy.

12.1.8.6.1.3 Health Clinics Health clinics are generally larger than health posts and engage one or more full-time nurses. Clinics may also employ part-time medical doctors, depending on the services provided, size and location. Health clinics offer comprehensive category of services when compared with health post. Therefore, it is expected that it acquires more medical equipment so as to enable more sophisticated and advanced diagnoses. They can be subdivided into the three categories (Categories I, II, and III). Rural health clinics generally fall into one of the three categories, based on the type and number of medical devices used in the facility and the frequency with which they are used on a daily basis (<http://www.poweringhealth.org/index.php/topics/technology/energyefficiency>).

Category I Health Clinic (low-energy requirements, 5–10 kWh/day)

1. Typically located in a remote setting with limited services and a small staff.
2. Approximately 0–60 beds.
3. Electric power is required for:
 - lighting the facility during evening hours and to support limited surgical procedures (e.g., suturing)
 - maintaining the cold chain for vaccines, blood, and other medical supplies—one or two refrigerators may be used
 - utilizing basic lab equipment—a centrifuge, hematology mixer, microscope, incubator, and hand-powered aspirator.

Category II Health Clinic (moderate energy requirements, 10–20 kWh/day)

1. Approximately 60–120 beds.
2. Medical equipment similar to Category I Health Clinic; frequency of use and number of devices are key factors of differentiation between Category I and II health clinics.
3. Separate refrigerators may be used for food storage and cold chain.
4. Communication device, such as a radio, may be utilized.
5. May accommodate more sophisticated diagnostic medical equipment and perform more complex surgical procedures.

Category III Health Clinic (high energy requirements, 20–30 kWh/day)

1. Approximately 120 beds or more.
2. May serve as a regional referral center and coordinate communication between several smaller facilities and hospitals in large cities.
3. May need to communicate with remote health centers and hospitals by way of telephone, fax, computer, and Internet.

4. May contain sophisticated diagnostic devices (X-ray machine, CD4 counters, blood typing equipment, others) requiring additional power.

12.1.8.6.1.4 Energy Assessment of a Rural Health Center Because health-care facilities offer a comprehensive variety of health services, it is essential to specify energy needs based on equipment required for such services. In literature and practice, this has enjoyed limited attention (http://www.who.int/hia/green_economy/modern-energy-services/en/). Therefore, this area needs more attention by health and energy professional at the international, regional and national level, and grassroots. Nevertheless, infrastructural studies such as Service Availability and Readiness Assessment (SARA) itemized a detailed list of medical equipment accessible in health facilities, and the outcome of these reviews can be adopted as a basis for evaluating prevailing energy needs. In the survey, SARA classified health services, essential electric equipment and its indicative power requirements as: (1) infrastructure (lighting, communication, water supply, and waste management); (2) medical devices; and (3) support appliances for specific health services, which include vaccination, infectious and non-communicable disease treatment, emergency care such as blood transfusions and surgical services. An extract of this is presented in [Table 12.2](#).

12.1.8.6.1.5 Criteria for Selection of the Appropriate Energy System for the Load For the selection of appropriate hybrid power system for health-care facilities, a list of factors needs to be considered. These include the following:

- *Peak power capacity*: This is defined as the maximum capacity the system can supply.

Different appliances consume different amount of electricity, which ranges from a few watts to several kilowatts. Similarly, the various power-generating systems generate different quantities of electricity. The generated electricity should adequately meet the expected electrical load demand. Hence, the use of energy-efficient equipment is of great emphasis, so as to reduce the available peak power needs of the health-care facilities.

- *Daily energy capacity*: Generally, energy use by various appliances in health-care facility could be classified as continuous (e.g., refrigerators and space heating) and intermittent such as in laboratory equipment. The intermittent loads are load that are operated periodically, either in the evening or early morning (radio, laptop, and others) or some

Table 12.2 Health equipment by power load level

Health services	Electrical devices	Indicative power rating (W)	AC power supply	DC power supply
<i>Infrastructure</i>				
Basic amenities	Lightings:			
	Incandescent bulb	10.8 W/m ²	110/220 V	—
	Halogen bulb	1.8 W/m ²	110/220 V	12 V
	CFL bulb	2.16 W/m ²	110/220 V	—
	LED bulb	1.8–2.14 W/m ²	110/220 V	10–30 V
	Security lighting/outdoors	40–160 W	110/220 V	10–30 V
	CFL/LED			
	Laptop desktop incandescent	200–600 W	110/220 V	10–30 V
		20–60 W	110/220 V	12–20 V
	Mobile phone battery (charging)	5–20 W	110/220 V	5–16.5 V
	Desktop computer	15–200 W	110/220 V	8–20 V
	Printer (ink jet)	65–100 W	110/220 V	12–20 V
	VHF radio receiver: standby	2 W	110/220 V	12 V
	transmitting	30 W	110/220 V	12 V
	Ceiling fan	50–100 W	110/220 V	—
	Refrigerator (for food and water)	150–200 W	110/220 V	—
	Portable air-conditioner (AC)	1000–1500 W	110/220 V	48 V

Specific services

General outpatient services	Nebulizer	80–90 W	110/220 V	—
	Oxygen concentrator	270–310 W	110/220 V	—
	Pulse oximeter	50 W	110/220 V	—
Antenatal child and adolescent health	Vaccine refrigerator	60–115 W	110/220 V	N/A
Obstetric and new born	LED lighting (phototherapy)	440 W	110/220 V	—
	Suction apparatus	90–200 W	110/220 V	—
	Vacuum aspirator	36–96 W	110/220 V	3–6 V
	Neonatal incubator	800–1035 W	110/220 V	—
	Ultrasound	800–1000 W	110/220 V	—
	Laboratory refrigerator	60–160 W	110/220 V	—
General diagnostics, blood analysis, and laboratory equipment	Centrifuge	250–400 W	110/220 V	—
	Hematology analyzer	230–400 W	110/220 V	—
	Blood chemistry analyzer	45–88 W	110/220 V	—
	CD4 counter	200 W	110/220 V	12 V
	Microscope (with LED light)	20–30 W	110/220 V	3–6 V
	X-ray machine (portable)	3–4 kW	110/220 V	—
Basic surgical services	Laboratory incubator	200 W	110/220 V	12 V
	Suction apparatus	90–200 W	110/220 V	—
	Anesthesia machine	1440 W	110/220 V	—

From http://www.who.int/hia/green_economy/modern-energy-services/en/.

medical equipment operated once or twice a day (e.g., autoclaves for instrument sterilization). The breakdown for expected daily energy capacity needed for the health-care facilities considered for this chapter is presented in [Table 12.3](#). This is an extract from the SARA requirement ([Table 12.2](#)). The proposed energy system must be capable of supplying the daily energy requirements of a typical rural health clinic.

- *Evening peak hours' supply:* In a typical RHC, some patients, including pregnant women may show up for treatment in the evening time. To avoid or minimize wasting time during their daytime jobs. In case of first aid emergencies, the availability of power supply in health-care facility in the evening and during the night hours is considered imperative for quality health-care delivery, especially when there are no referral clinics nearby. In RHC that have enough personnel to do night duties, electric power supply in the evening is vital to enable them feel secured and improve their productivity during night shifts. Therefore, the power supply is designed to suit the expected nighttime load demand.
- *Duration of supply:* The duration of power supply to health-care facility is dependent on size as well as types of health-care services rendered. It is expected that, electricity supply be available to power all equipment required to enhance quality medical services delivery at all times RHCs, with maternal health care and childbirth services or other emergency services are expected to have power supply for basic applications. Some equipment, such as laboratory equipment, for testing of samples collected during the day and analyzed in a batch is used intermittently. However, other appliances such as of refrigerators are run as base load and may require continuous electricity supply.
- *Reliability:* Reliability in this context deals with the probability of power failure because of unmet load. Unmet load is electrical load that the power system is unable to serve. It occurs when the electrical demand exceeds the supply. Because of the sensitive nature of services rendered by RHCs during power disruptions, health facility is expected to be provided with backup power generators. This will improve the reliability of the system and as such, reduce the loss of load. Backup generators may not provide sufficient electricity for all the equipment; nevertheless, it should serve as support to priority applications such as: lighting, refrigerators, and other critical equipments. Consequently, reliability of the power supply is given significant attention, while sizing and designing the power system.

Table 12.3 Clinic appliances and their power ratings

S/ no	Power consumption	Qty	Power (CME) watts	Power (EEME) watts	Total (watts)	Total (watts)	Daytime hours 7 a.m.–6 p.m.	Evening hours (6–10p.m.)	Night hours (10p.m.–7a.m.)	Total hours/day	Total energy (CME) (kWh/day)	Total energy (EEME) (kWh/day)
1	Refrigerator–vaccine (RV)	1	60	40	60	40	5	3	2	10	0.6	0.4
2	Refrigerator– nonmedical (RNM)	1	300	125	300	125	2	2	1	5	1.5	0.625
3	Centrifuge	2	242	242	484	484	4			4	1.936	1.936
4	Microscope	2	20	20	40	40	6			6	0.24	0.24
5	Blood chemical analyzer (BCA)	1	88	45	88	45	4			4	0.352	0.18
6	Hematology analyzer (HA)	1	230	230	230	230	4			4	0.92	0.92
7	CD4 Machine	1	200	200	200	200	4			4	0.8	0.8
8	Radio	1	30	15	30	15	10			10	0.3	0.15
9	Tube fluorescent lights (TFL)	4	40	18	160	72	8			8	1.28	0.576
10	Wall fan	5	65	65	325	325	8			8	2.6	2.6
11	Halogen lamp (security)	1	100	50	100	50	0	3	8	11	1.1	0.55
12	Desktop computer	1	230	65	230	65	4			4	0.92	0.26
	Total energy (kWh/day)										12.548	9.237
	% Energy reduction										26%	
	Oil equivalent of energy saved										0.0003	tonnes
	CO ₂ emission reduction										4.3043	kg/day

CME, Conventional medical equipment; EEME, energy efficient medical equipment.

- *Environmental health and sustainability:* It is expected that, energy supply to any health-care facility should not lead to environmental hazards. Environmental impact such as air pollution, water pollution, and noise pollution in any quantities that could further deteriorate the health of patients, affect the medical staff or people living at the health-facility premises, should be avoided. This can be achieved by making sure high penetration of renewable energy sources. This will ensure high value of renewable energy fraction. Consequently, reduction of GHG emission per kWh of power generated will lead to environmental sustainability. To this aim more priority should be given renewable energy sources than captive gasoline or diesel generator source in providing power supply to the rural health-care facilities.

A 24-h energy demand is required, so as to determine the sizes of the components. Because of the nonavailability of a typical load demand for RHC in Nigeria, load profile based on SARA as indicated by UNICEF for a standard rural health center is developed for the purpose of this study. This was centered on the estimates of the medical equipment, power ratings at different times of the day and night. It is assumed that, the power will vary across the hour of the day, and that the clinic is only operational between 8a.m. and 5p.m. daily. Essential appliances such as refrigerator, operated intermittently during the night. Two kinds of medical devices and appliances are modeled for the load-conventional (inefficient) and energy-efficient equipment. The existing devices in most RHC visited are conventional and obsolete technologies. The various appliances used in this study and the presumed distribution of the daily energy consumption by appliance are shown in [Table 12.3](#) and [Fig. 12.5A and B](#), respectively. The fan and the centrifuge consume bulk of the power during the daytime.

As shown in [Fig. 12.6](#), the peak load of 1.557 kW/day and 1.411 kW/day occur for both types on load between 12p.m. and 2p.m. To model the change in pattern of electricity usage during the year, a day-to-day variability of 10% and hour-to-hour random variability of 15% was specified in HOMER. The clinic utilizing conventional equipment will require 12.55 kWh/day to run its services, whereas the clinic deploying energy-efficient appliance and equipment will require 9.24 kW/day-26% less than the former. The oil equivalent of energy saved and the CO₂ avoided with use of energy efficient medical equipment (EEME) as against conventional medical equipment (CME) is 0.0003 tonnes/day and 4.3043 kg/day. The hourly load distribution analysis for pre-and post-DSM is given in [Tables 12.4 and 12.5](#).

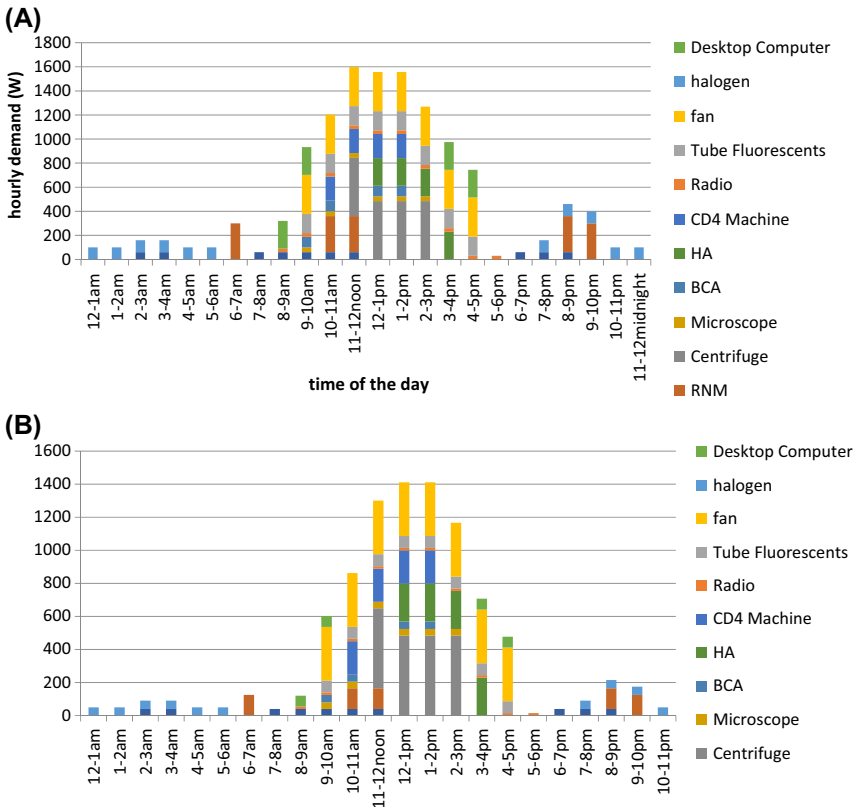


Figure 12.5 (A) Daily energy demand contributions of conventional appliances. (B) Daily energy demand contributions of energy-efficient appliances. *BCA*, blood chemical analyzer; *HA*, Hematology analyzer; *RNM*, Refrigerator-nonmedical.

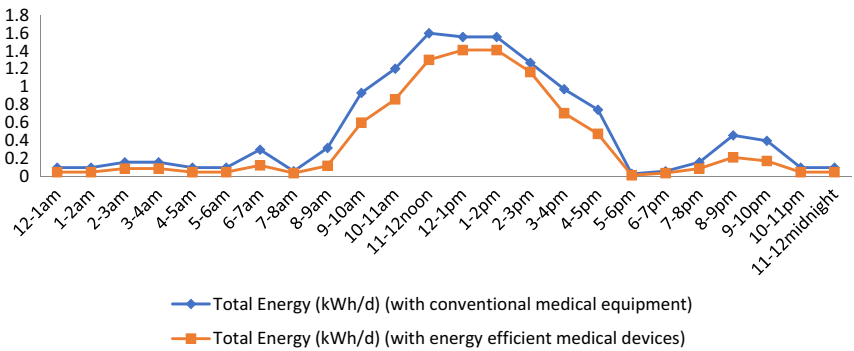


Figure 12.6 Electric load profile for both scenarios (conventional and energy-efficient devices).

Table 12.4 Hourly distribution of load demands without demand-side management

Time of the day	RV	RNM	Centrifuge	Microscope	BCA	HA	CD4 machine	Radio	Tube fluorescent	Fan	Halogen	Desktop computer	Total energy (Wh/d)
12–1a.m.											100		100
1–2a.m.											100		100
2–3a.m.	60										100		160
3–4a.m.	60										100		160
4–5a.m.											100		100
5–6a.m.											100		100
6–7a.m.		300											300
7–8a.m.	60												60
8–9a.m.	60							30				230	320
9–10a.m.	60			40	88			30	160	325		230	933
10–11a.m.	60	300		40	88		200	30	160	325			1203
11–12noon	60	300	484	40			200	30	160	325			1599
12–1p.m.			484	40	88	230	200	30	160	325			1557
1–2p.m.			484	40	88	230	200	30	160	325			1557
2–3p.m.			484	40		230		30	160	325			1269
3–4p.m.						230		30	160	325		230	975
4–5p.m.								30	160	325		230	745
5–6p.m.								30					30
6–7p.m.	60												60
7–8p.m.	60										100		160
8–9p.m.	60	300									100		460
9–10p.m.		300									100		400
10–11p.m.											100		100
11–12midnight											100		100
Total	600	1500	1936	240	352	920	800	300	1280	2600	1100	920	12548

BCA, blood chemical analyzer; HA, Hematology analyzer; RNM, Refrigerator-nonmedical; RV, refrigerator-vaccine.

Table 12.5 Hourly distribution of load demands with demand-side management

Time of the day	RV	RNM	Centrifuge	Microscope	BCA	HA	CD4 machine	Radio	Tube fluorescent	Fan	Halogen	Desktop computer	Total energy (Wh/d)
12–1 a.m.											50		50
1–2 a.m.											50		50
2–3 a.m.	40										50		90
3–4 a.m.	40										50		90
4–5 a.m.											50		50
5–6 a.m.											50		50
6–7 a.m.		125											125
7–8 a.m.	40												40
8–9 a.m.	40							15				65	120
9–10 a.m.	40			40	45			15	72	325		65	602
10–11 a.m.	40	125		40	45		200	15	72	325			862
11–12 noon	40	125	484	40			200	15	72	325			1301
12–1 p.m.			484	40	45	230	200	15	72	325			1411
1–2 p.m.			484	40	45	230	200	15	72	325			1411
2–3 p.m.			484	40		230		15	72	325			1166
3–4 p.m.						230		15	72	325		65	707
4–5 p.m.								15	72	325		65	477
5–6 p.m.								15					15
6–7 p.m.	40												40
7–8 p.m.	40										50		90
8–9 p.m.	40	125									50		215
9–10 p.m.		125									50		175
10–11 p.m.											50		50
11–12 midnight											50		50
Total	400	625	1936	240	180	920	800	150	576	2600	550	260	9237

BCA, blood chemical analyzer; HA, Hematology analyzer; RNM, Refrigerator-nonmedical; RV, refrigerator-vaccine.

Table 12.6 Assumption regarding component sizing and cost

Component parameter	Value	Component parameter	Value
PV		Converter	
Rated capacity	1 kW	Rated power	1 kW
Derating factor	80%	Efficiency	90%
Capital cost	\$4250	Capital cost	\$621.80
replacement cost	\$4200	Replacement cost	\$569
Operational life	20 years	O & M cost	\$3/year
Ground reflectance	20%	Operational life	15 years
Battery		Diesel	
Rating	4 V, 1900 Ah	Rated power	1 kW
Round-trip efficiency	85%	Capital cost	\$280
Min. state of charge	40%	Replacement cost	\$280
Capital cost	\$269	O & M cost	0.5\$/h
Replacement cost	\$260	Operational life	15000 h
O & M cost	\$5/year	Minimum load ratio	30%
Operational life	4 years		

O & M cost, operation and maintenance cost; *PV*, photovoltaic.

12.1.8.6.1.6 Component Data The initial selections of components are based on the load profile in Fig. 12.6. The details of components and other assumption regarding them are specified in Table 12.6. Prices are specified in US dollar. HOMER models two types of dispatch strategies—"load following," where the generator supplies exactly enough power to serve the load in the event of insufficient renewable energy and the "cycle charging," where the generators run at full load and excess electricity charges the batteries. In this study, both dispatch strategies were specified.

12.1.8.7 Emission Factors

An emission factor is a characteristic value that relates to the quantity of a pollutant released into the atmosphere with an activity associated with the release of that pollutant. These factors are usually calculated by dividing the weight of a pollutant by a unit weight, volume, distance, or interval of the activity emitting the pollutant. These factors are used to calculate emissions from different sources of air pollution.

These factors are averages of all reliable available data and are assumed to be typical for long-term means of the source category. The emission factor is used to compute the total emission from a source. Table 12.7 shows the state-by-state average emission factors for all the pollutants that HOMER

Table 12.7 Average emissions factors for the year 2000 for each us state

Serial number	State	Average grid emissions factors			SN	State	Average grid emissions factors			SN	State	Average grid emissions factors		
		CO ₂ g/kWh	SO ₂ g/kWh	NO _x g/kWh			CO ₂ g/kWh	SO ₂ g/kWh	NO _x g/kWh			CO ₂ g/kWh	SO ₂ g/kWh	NO _x g/kWh
1	Alabama	656	3.76	1.38	18	Kentucky	1011	5.7	2.41	35	North Dakota	1086	4.41	2.27
2	Alaska	586	0.61	2.21	19	Louisiana	629	1.6	1.15	36	Ohio	836	7.5	2.33
3	Arizona	533	0.74	1.06	20	Maine	297	0.96	0.65	37	Oklahoma	833	1.57	1.66
4	Arkansas	659	1.57	1.1	21	Maryland	623	4.58	1.58	38	Oregon	149	0.26	0.25
5	California	287	0.08	0.26	22	Massachusetts	587	2.53	0.91	39	Pennsylvania	560	4.32	1.23
6	Colorado	913	1.85	1.59	23	Michigan	710	3.2	1.52	40	Rhode Island	454	0.09	0.24
7	Connecticut	335	1.02	0.62	24	Minnesota	744	2.26	1.78	41	South Carolina	405	2	0.89
8	Delaware	894	5.93	1.59	25	Mississippi	597	3.2	1.55	42	South Dakota	378	1.25	1.61
9	District of Columbia	1205	6.18	2.36	26	Missouri	898	2.79	1.96	43	Tennessee	621	3.96	1.51
10	Florida	644	2.74	1.53	27	Montana	662	0.79	1.29	44	Texas	666	1.38	1.05
11	Georgia	641	3.87	1.43	28	Nebraska	702	1.95	1.42	45	Utah	950	0.71	2.01
12	Hawaii	779	2.08	2.38	29	Nevada	704	1.35	1.34	46	Vermont	26	0.02	0.14
13	Idaho	42	0.04	0.07	30	New Hampshire	321	3.12	0.64	47	Virginia	559	2.64	1.17
14	Illinois	503	2.24	1.23	31	New Jersey	332	0.96	0.62	48	Washington	130	0.72	0.25
15	Indiana	977	6.01	2.37	32	New Mexico	969	1.83	2.32	49	West Virginia	920	5.84	2.62
16	Iowa	894	3.13	1.84	33	New York	444	1.88	0.66	50	Wisconsin	799	3.01	1.7
17	Kansas	848	2.36	1.93	34	North Carolina	586	3.45	1.33	51	Wyoming	1044	1.69	1.84

From <https://www.epa.gov/energy>.

models. Prior to simulating the energy system, HOMER defines the emission factors (kg of pollutant emitted divided by the unit of fuel consumed) for each pollutant. Subsequently, it computes the annual emission of that pollutant by multiplying the emission factors by the total annual fuel consumption. Emissions factors for four of the six pollutants: carbon monoxide, unburned hydrocarbons, particulate matter, and nitrogen oxides are directly specified. Using these values and the carbon and sulfur content of the fuel, HOMER estimates the emissions factors for the two-remaining pollutants: carbon dioxide and sulfur dioxide. To achieve these, HOMER uses three primary assumptions following:

- Any carbon in the fuel that does not get emitted as carbon monoxide or unburned hydrocarbons get emitted as carbon dioxide.
- The carbon fraction of the unburned hydrocarbon emission is the same as that of the fuel.
- Any sulfur in the burned fuel that does not get emitted as particulate matter gets emitted as sulfur dioxide.

Eq. (12.1) is generally used in the estimation of the emission.

$$E = A_r \times E_f \times \left(1 - \frac{EF_\eta}{100}\right) \quad (12.1)$$

where E = emissions; A_r = activity rate; E_f = emission factor; and EF_η = overall emission reduction efficiency (%).

12.1.8.8 Results and Discussion

Systems constraints along with input parameters described in Table 12.3 were used in the simulations of the PV battery system to obtain the optimal configuration. Optimal system configuration is obtained by choosing suitable system components, depending on parameters such as: solar irradiance, diesel price, and maximum capacity shortage. The most viable system depends on the total net present cost (TNPC), as well as the hourly performance. This section presents the result obtained from the simulations, both in graphical and tabular forms.

12.1.9 System Configuration

Displayed in Table 12.8 is the optimal system architecture for the selected geopolitical zones, with both CME and EEME. It is worth noting that, during component sizing and optimization, HOMER prioritizes continuous satisfaction of load. It also makes sure, there is minimum diesel consumption, and the PV array is not oversized. In Table 12.8, for both case of

Table 12.8 System configuration for the six geopolitical zones

City	Gboko		Igbeti		Kabo	
Load type	EEME	CME	EEME	CME	EEME	CME
PV array (kW)	3	3	3	3	3	3
Generator (kW)	2	2	1	2	2	2
Number of batteries	2	3	2	3	2	3
Converter (kW)	2	2	2	2	2	2
Dispatch strategy	LF	CC	CC	CC	LF	CC
	Ihiala		Abadam		Okrika	
PV array (kW)	3	3	3	3	3	3
Generator (kW)	2	2	1	2	2	2
Number of batteries	3	3	2	3	3	3
Converter (kW)	2	2	2	2	2	2
Dispatch strategy	LF	LF	CC	CC	LF	LF

CC, Cycle charging; CME, conventional medical equipment; EEME, energy efficient medical equipment; LF, load following; PV, photovoltaic.

CME and EEME, the PV array size across the sampled locations is the same (3 kW). Except for Gboko and Abadam with a smaller size of diesel generator of 1 kW for EEME loads, all other locations require a 2 kW generator for both EEME and CME loads. For all locations, the number of batteries required with the use of CME is three each, whereas with the use of EEME; all locations returned two batteries each except for Ihiala and Okrika with three batteries each. The latter is because of the fact that, Ihiala and Okrika, receives the lowest average solar irradiance. The size of the converter for both categories of medical equipment for all locations is 2 kW.

12.1.10 Economic Analysis

Table 12.9 shows the economic analysis of the optimal configuration of the system in the six geopolitical zones. It gives the breakdown of the initial capital cost (ICC), operating cost, TNPC, and the levelized cost of energy (LCOE). The percentage reduction that accrues with the use of EEME instead of CME is also shown in Table 12.9. With 17% reduction, Igbeti and Abadam had the highest percentage reduction in TNPC and operating cost. Gboko recorded the least percentage difference of 15%. If installed, clinics in Igbeti will have the highest TNPC of \$17,611 and \$20,948 for EEME and CME, respectively. The initial cost of system installation using CME is the same across all locations that were considered (\$15,252),

Table 12.9 Economic analysis of optimal system architecture

City	Gboko			Igbeti			Kabo		
Load type	EEME	CME	% Reduction	EEME	CME	% Reduction	EEME	CME	% Reduction
Initial capital cost	14,983	15,252	2%	14,757	15,252	3%	14,983	15,252	2%
Operating cost	262	628	58%	198	584	66%	213	599	64%
Total net present cost	16,937	19,940	15%	16,238	19,611	17%	16,573	19,724	16%
Levelized cost of energy	0.672	0.585	−15%	0.645	0.575	−12%	0.658	0.579	−14%
	Ihiala			Abadam			Okrika		
Initial capital cost	15,252	15,252	0%	14,757	15,252	3%	15,252	15,252	0%
Operating cost	290	728	60%	200	585	66%	316	763	59%
Total net present cost	17,414	20,690	16%	16,249	19,621	17%	17,611	20,948	16%
Levelized cost of energy	0.691	0.607	−14%	0.645	0.576	−12%	0.699	0.615	−14%

CME, Conventional medical equipment; *EEME*, energy efficient medical equipment.

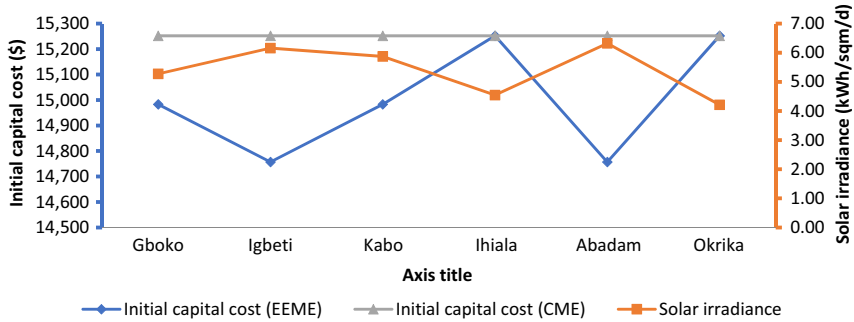
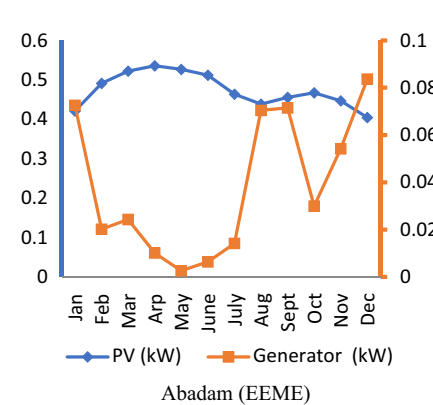
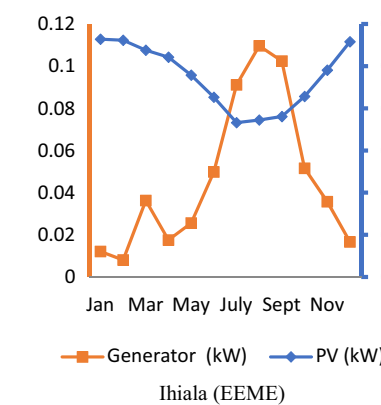
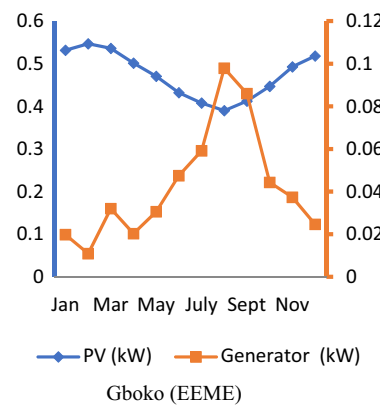
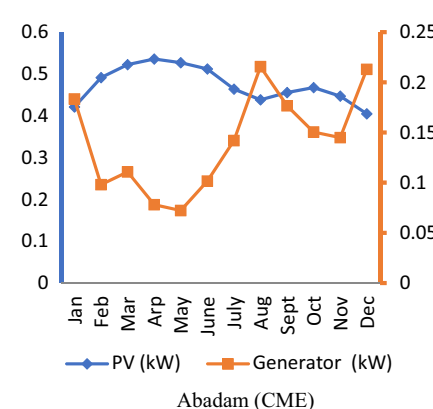
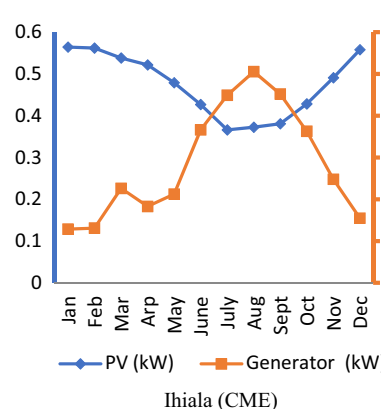
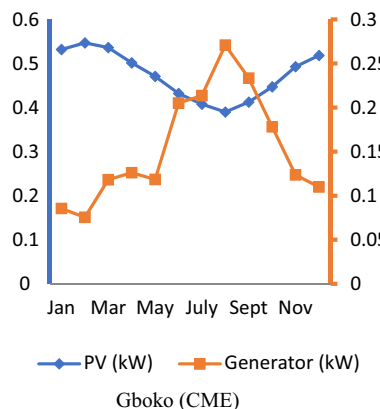


Figure 12.7 Relationship between initial capital cost for both energy efficient medical equipment (EEME) and conventional medical equipment (CME) and solar irradiance.

whereas that of the EEME varies directly. In the solar irradiance as could be seen in Fig. 12.7. At higher solar irradiance, the ICC is lower and high at lower, solar irradiance. The LCOE was higher for PV–DG battery system with EEME loads and lower for CME. In all scenarios, all capital cost for EEME and CME are close with just a maximum of 3% difference.

Fig. 12.8 shows the monthly contributions of the PV and diesel generator for the six locations across the six geopolitical zones. The contribution pattern of the PV array follows the same pattern for both types of loads across all sites except Igbeti. Generally, PV contribution falls to its lowest in the month of August, except in Igbeti, which experiences its lowest in the months of April and August. It can also be observed that, the diesel generator contribution peaks when the PV contribution is at its lowest across all locations.

Table 12.10 shows the breakdown of annual electricity production across all sites. Okrika recorded the highest annual electricity production of 4611 kWh/years and 5468 kWh/years, for EEME and CME, respectively. With the use of EEME, Okrika has the highest electricity production of 680 kWh/years, whereas Gboko produce the highest excess electricity of 1360 kWh/years with the use of CME. Unmet load and shortage capacity is mostly low and negligible as compared to the load served. The highest renewable energy fraction of 91.8% and 73.2% can be observed in Kobo. This is expected because it receives the highest solar irradiance out of all the locations considered. Okrika has the lowest renewable fraction of 86.3% and 71% for EEME and CME, respectively. This location receives the lowest average solar irradiance. Across all locations, the value of the renewable fraction for EEME is higher than, CME with the highest increment of 28% in Kobo and least in Ihiala (21%).



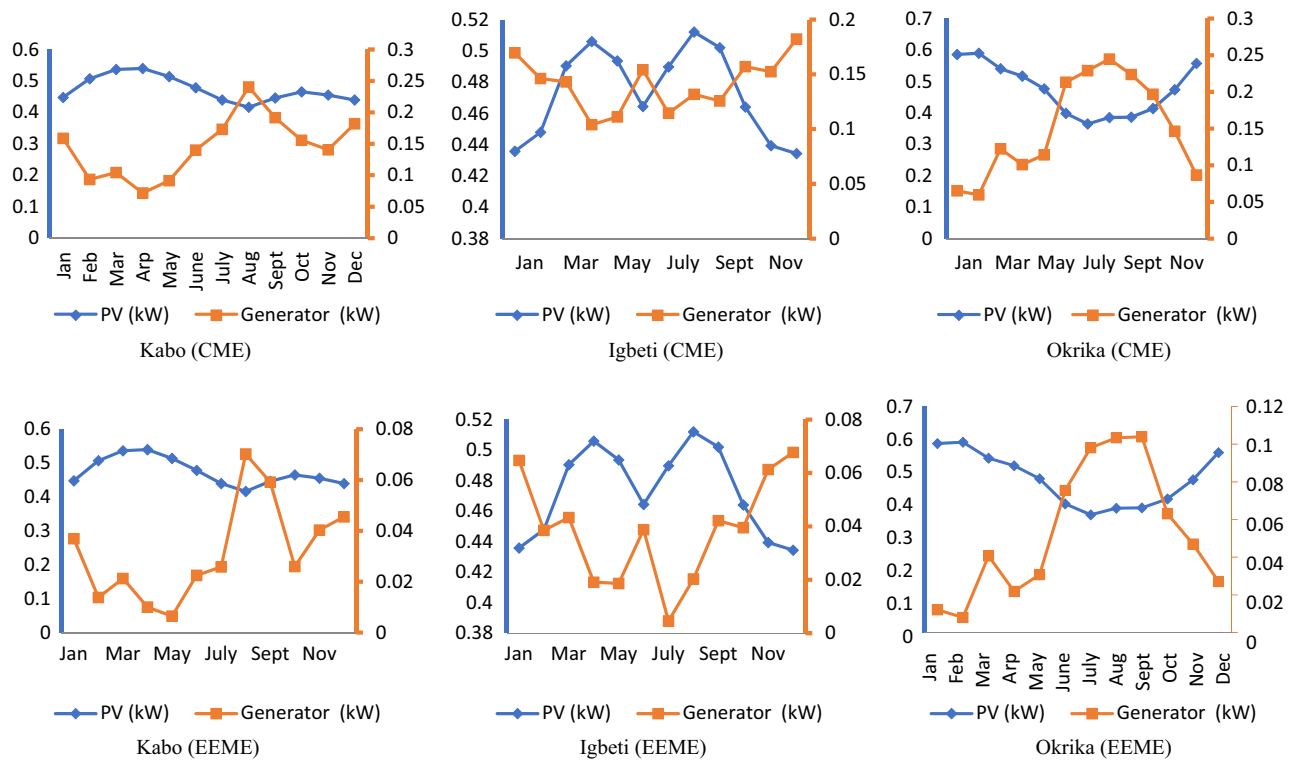


Figure 12.8 Monthly average electricity production. *CME*, Conventional medical equipment; *EEME*, energy efficient medical equipment; *PV*, photovoltaic.

Table 12.10 Energy production for optimal system

City	Gboko		Igbeti		Kabo	
Load type	EEME	CME	EEME	CME	EEME	CME
Annual electricity Production (kWh/year)	4522	4148	4482	5383	4425	5425
Excess electricity (kWh/year)	613	1360	545	36	518	53.6
Unmet load (kWh/year)	0.00000775	2.2	0.0427	0.000012	0.00000696	0.000011
Shortage capacity (kWh/year)	0.0185	0	1.33	0	0	0
Renewable fraction	0.889	0.702	0.901	0.729	0.918	0.732
	Ihiala		Abadam		Okrika	
Annual electricity production (kWh/year)	4556	5399	4485	5383	4611	5468
Excess electricity (kWh/year)	626	147	548	34.1	680	218
Unmet load kWh/year	0.00000771	0.49	1.24	0.0000128	0.00000753	0.598
Shortage capacity (kWh/year)	0.108	3.27	2.95	0	0.118	3.97
Renewable fraction	0.879	0.726	0.9	0.729	0.863	0.71

CME, Conventional medical equipment; *EEME*, energy efficient medical equipment.

12.1.11 Emission Results

The environmental benefit analysis of the proposed hybrid photovoltaic system is first considered in terms of the amount of fossil fuel consumed by the generator. This information is then employed to estimate the quantity of emissions produced by the generator. The emissions by the generator are assumed to be the quantity of emissions avoided by the solar PV system. As indicated in (U. S, 1998), various values of CO₂ emission factors are reported in the literature; 3.2, 3.15, and 3.0 kg CO₂/L of diesel, respectively. This work adopted an emission factor of 2.66 kg CO₂/L of diesel to evaluate the quantity of carbon dioxide. All other factors used by HOMER is given in [Appendices A.1](#). All emissions are estimated by HOMER software and results are given in [Table 12.11](#). Emissions are directly proportional to the quantity of diesel consumed by the generator. The diesel consumption will depend on the annual running hours, total load served annually, which also depends on whether the solar resource can adequately meet the load or not. [Table 12.12](#) shows the diesel consumption reduction that is achievable with the use of EEME as against CME. [Fig. 12.9A and B](#) show the relationship between CO₂ emission and diesel consumption for both CME and EEME. Ihiala consumed the highest liter of fuel and consequently the highest level of emission, whereas as expected, Kabo had the least fuel consumption as well as emission. There was a 72% reduction in Kabo, 74% in Igbeti and Abadam, whereas Okrika recorded the least reduction of 64%. The relationship between the running hours of diesel generator for both load types (EEME and CME) is shown in [Fig. 12.10](#). The RHC located in Okrika has the highest diesel generator running hours for both equipment types, whereas Abadam recorded the least diesel generator running hour.

12.1.12 Conclusion

Various aspects of DSM are very crucial in ensuring that, energy resources available to a country is efficiently used. So many benefits of DSM include: provision of relief to power grids and generation plants, mitigation of emergencies in electrical systems, minimization of blackouts to increase reliability of energy systems, reduction in energy prices, mitigation of emergencies in electrical systems, to reduce or partially eliminate investments in generation of energy, reduction of dependency on expensive imports, transmission and distribution networks, and reduction of environmental emissions.

Table 12.11 Emission for both conventional medical equipment (CME) and energy efficient medical equipment (EEME)

City	Gboko			Igbeti			Kabo		
Load type	EEME	CME	% Reduction	EEME	CME	% Reduction	EEME	CME	% Reduction
Carbon dioxide	488	1391	65%	328	1278	74%	364	1317	72%
Carbon monoxide	1.2	3.43	65%	0.81	3.16	74%	0.899	3.25	72%
Unburned hydrocarbons	0.133	0.38	65%	0.0898	0.35	74%	0.0996	0.36	72%
Particulate matter	0.0908	0.259	65%	0.0611	0.238	74%	0.0678	0.245	72%
Sulfur dioxide	0.98	2.79	65%	0.659	2.57	74%	0.732	2.64	72%
Nitrogen oxides	10.7	30.6	65%	7.23	28.2	74%	8.03	29	72%
	Ihiala			Abadam			Okrika		
Carbon dioxide	526	1586	67%	332	1281	74%	593	1669	64%
Carbon monoxide	1.3	3.91	67%	0.819	3.16	74%	1.46	4.12	65%
Unburned hydrocarbons	0.144	0.434	67%	0.0908	0.35	74%	0.162	0.456	64%
Particulate matter	0.0979	0.295	67%	0.0618	0.238	74%	0.11	0.311	65%
Sulfur dioxide	1.06	3.19	67%	0.667	2.57	74%	1.19	3.35	64%
Nitrogen oxides	11.6	34.9	67%	7.31	28.2	74%	13.1	36.8	64%

Table 12.12 Diesel fuel consumption analysis

Location	Gboko	Igbeti	Kabo	Ihiala	Abadam	Okrika	Base case
Fuel consumption (EEME)L/yr	185	125	138	200	126	225	20364
Fuel consumption (CME)L/yr	528	485	500	602	486	634	20364
% reduction	65%	74%	72%	67%	74%	65%	0

CME, Conventional medical equipment; EEME, energy efficient medical equipment.

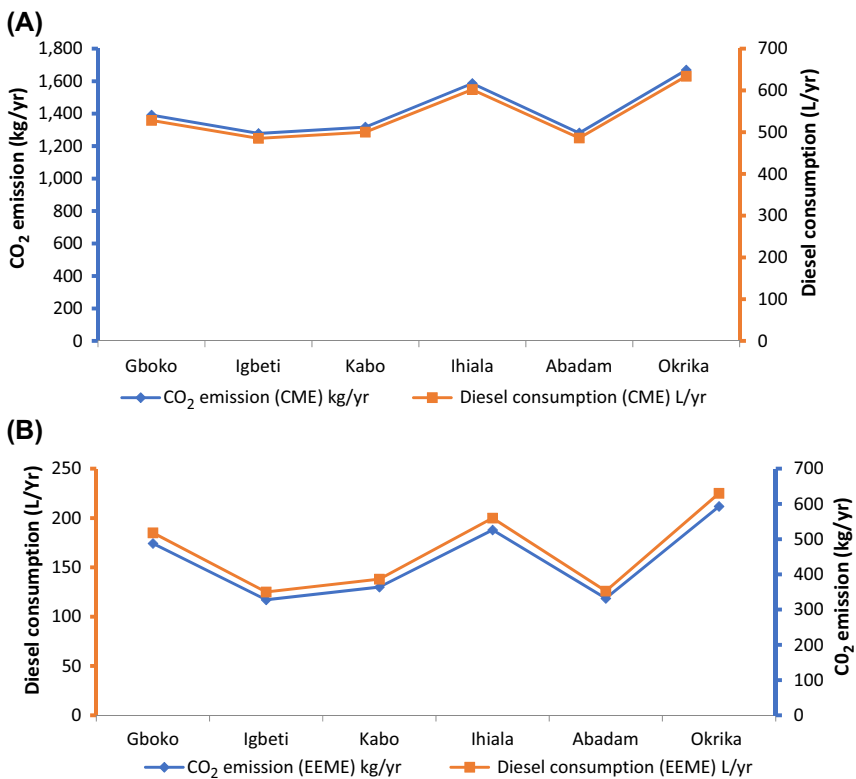


Figure 12.9 (A) The relationship between CO₂ emission and diesel consumption for conventional medical equipment (CME). (B) The relationship between CO₂ emission and diesel consumption for energy efficient medical equipment (EEME).

The technoeconomic and emission comparison of deploying energy efficiency as a DSM tool in sizing alternative energy for a typical health-care center has been presented in this chapter. In conclusion, this study validates the effectiveness of utilizing energy efficient-equipment as compared with

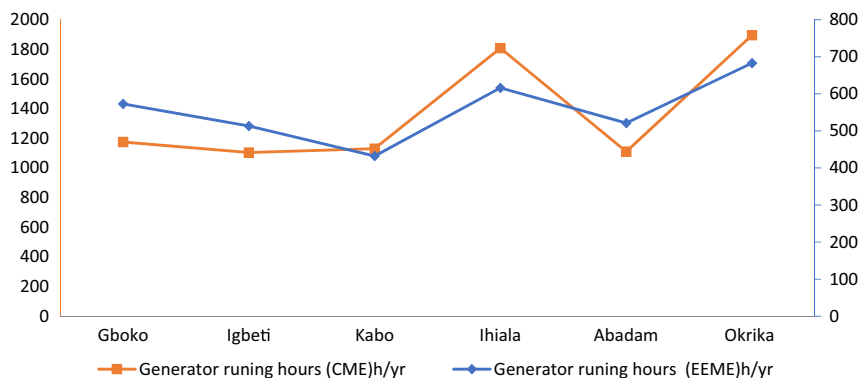


Figure 12.10 Generator running hours. *CME*, conventional medical equipment; *EEME*, energy efficient medical equipment.

conventional ones. It shows that, investments in more energy-efficient medical devices, though at higher costs, has the tendency to reduce the capital investment in hybrid renewable energy system for a rural health clinic, and as such, removes major barrier to the consumption of greener energy systems at lower costs over its life span.

For newly proposed clinics of similar status in rural communities of developing countries like the ones described in this study, a similar load profile is expected as the cautious selection of energy-efficient medical devices and energy conservation practices along with a hybrid PV/generator/battery system architecture would most possibly ensure the lowest NPC without compromising quality and reliability energy services delivery. The application of energy-efficient equipment is seen to increase the renewable energy penetration, across the six geopolitical zones in Nigeria. This in turn reduces the use operational hours of use of captive generators and consequently, the carbon footprint.

In terms of retrofitting, older health centers, the cost of procurement of energy-efficient equipment may initially appear expensive. Conversely, the NPC of the system over its life span makes investments in more energy-efficient devices reduce generator fuel costs considerably over time. Apart from this, cost of offsetting the effect of emission is also an advantage.

It is worth noting that, this model did not fully quantify the initial cost and maintenance costs of procuring newer, and more energy efficient medical equipment but only the approximate estimate. In future study, a search light can be beamed to explore these costs, the effect of inflation, carbon tax, as well as the variation in diesel fuel price, and solar irradiance so

as to create a robust cost–benefit and environmental assessment model. Furthermore, health centers with constrained budgets, and facing challenges, choosing between investing in hybrid energy system or efficient medical devices, models that fully consider both supply and demand side, management options can help generate a precise assessment of costs and benefits, based on the options available locally.

APPENDICES

A.1 Emission Factors

Carbon monoxide	6.5	g/L of fuel
Unburned hydrocarbons	0.72	g/L of fuel
Particulate matter	0.49	g/L of fuel
Portion of fuel sulfur converted to particulate matter	2.2	%
Nitrogen oxides	58	g/L of fuel

A.2 Destination of Fuel Carbon

Carbon dioxide	99.5%
Carbon monoxide	0.4
Unburned carbon	0.1
Total	100

A.3 Conversion Factor (Abolarin et al., 2013)

- 1 kW = 100 W
- 12,000 kWh = 1 tonne of oil equivalent
- 1 L = 2.68×10^{-3} tonnes of CO₂
- 1 kWh = 1.25×10^{-3} tonnes of CO₂

REFERENCES

Abolarin, S.M., Gbadegesin, A.O., Shitta, M.B., Yussuff, A., Eguma, C.A., Ehwerhemuepha, L., Adegbenro, O., 2013. A collective approach to reducing carbon dioxide emission: a case study of four University of Lagos Halls of residence. *Energy Build.* 61, 318–322.

Ahenkorah, A.K.O., Capacity Building in Energy Efficiency and Renewable Energy Regulation and Policy-Making in Africa, Ghana – Energy Efficiency Country Profile.

Akinbulire, T.O., Oluseyi, P.O., Babatunde, O.M., 2014. Techno-economic and environmental evaluation of demand side management techniques for rural electrification in Ibadan, Nigeria. *International Journal of Energy and Environmental Engineering* 5 (4), 375–385.

- Al-Karaghoul, A., Kazmerski, L., 2010. Optimization and life cycle cost of health clinic PV system for a rural area in southern Iraq using HOMER software. *Solar Energy* 84, 710–714.
- Bajpai, P., Dash, V., 2012. Hybrid renewable energy systems for power generation in stand-alone applications a review. *Renewable & Sustainable Energy Reviews* 16 (1), 2926–2939.
- Bekele, G., Palm, B., 2010. Feasibility study for a stand-alone-solar wind based hybrid energy system for application in Ethiopia. *Applied Energy* 87, 487–495.
- Benghanem, M., 2011. Optimization of tilt angle for solar panel: case study for Madinah, Saudi-Arabia. *Applied Energy* 88 (4), 1427–1433.
- Besarati, S.M., Padilla, R.V., Goswami, D.Y., Stefamagos, E., 2013. The potential of harnessing solar radiation in Iran: generating solar maps and viability study of PV power plants. *Renewable Energy* 53, 193–199.
- Course Module, Energy Efficiency and Demand Side Management. University of Warwick, REEEP.
- Demand-Side Management Sustainable Energy Regulation and Policymaking for Africa.
- Dihrab, S.S., Sopian, K., 2010. Electricity generation of hybrid PV/wind systems in Iraq. *Renewable Energy* 35 (6), 1303–1307.
- Dongellini, M., Marinosci, C., Morini, G.C., 2014. Energy audit of an industrial site: a case Study. *Energy Procedia* 45, 424–443.
- <https://www.epa.gov/energy>.
- Gellings, C.W., Parmenter, K.E., Energy Efficiency and Renewable Energy Handbook.
- Haney, A.B., Tooraj, J., Platchkov, L.M., Pollitt, M.G., 2010. Demand-Side Management Strategies and the Residential Sector: Lessons from International Experience.
- Hassan, K., Faitma, K., Mahmood, H.S., 2011. Feasibility of hybrid power generation over wind and solar standalone system. In: 5th Power Engineering and Optimization Conference (PENCO), 7, pp. 6–7.
- Hiendro, A., Kumianto, R., Rajagukguk, M., Simarajuntak, Y.M., 2013. Techno-economic analysis of photovoltaic/wind hybrid system for onshore remote area in Indonesia. *Energy* 59, 652–657.
- HOMER Energy LLC: Hybrid Optimization Model for Electric Renewable, 2009. <http://www.homerenergy.com/>.
- <https://image.slidesharecdn.com/presentazionecordoba-160319093812/95/residential-demand-response-operation-in-a-microgrid-8-638.jpg?cb=1458380410>.
- Jimenez, T., Olson, K., 1999. Renewable Energy for Rural Health Clinics.
- Lal, S., Raturi, A., 2012. Techno-economic analysis of a hybrid mini-grid system for Fiji Islands. *International Journal of Energy and Environmental Engineering* 3, 10.
- Lamba, M.K., Sanghi, A., 2015. Energy audit on academic building. *International Journal of Engineering Research and General Science* 3 (4).
- Martel, C.M., May 2000. Lessons in MRP Can Help Control Deregulated Energy Costs, 25 (5), p. 14.
- Nandi, S.K., Ghosh, H.R., 2010. Prospect of wind-PV battery hybrid power system as an alternative to grid extension in Bangledash. *Energy* 35, 3040–3047.
- Nwulu, N.I., Agboola, O.P., 2011. Utilizing renewable energy resources to solve Nigeria's electricity generation problem. *International Journal of Thermal and Environmental Engineering* 3 (1), 15–20.
- Ohumakin, O.S., 2010. Energy utilization and renewable sources in Nigeria. *Journal of Engineering and Applied Sciences* 5 (2), 171–177.
- Olatomiwa, L., Mekhilef, S., Huda, A., 2014. Optimal sizing of hybrid energy system for a remote telecom tower: a case study in Nigeria. In: IEEE Conference on Energy Conversion (CENCON), pp. 243–247.

- Olatomiwa, L., Mekhilef, S., Ohunakin, O.S., 2016. Hybrid renewable power supply for rural health clinics (RHC) in six geo-political zones of Nigeria. *Sustainable Energy Technologies and Assessments* 13, 1–12.
- Oluseyi, P.O., Babatunde, O.M., Babatunde, O.A., 2016. Assessment of energy consumption and carbon footprint from the hotel sector within Lagos, Nigeria. *Energy & Buildings* 118, 106–113. <http://dx.doi.org/10.1016/j.enbuild.2016.02.046>.
- Palensky, P., Dietrich, D., 2011. Demand side management: demand response, intelligent energy systems, and smart loads. *IEEE Transactions on Industrial Informatics* 7 (3), 381–388.
- Pitis (Femco), C.D., Livingstone (Anglo Gold Mining Motors), A., 2004. Energy efficient fans in underground auxiliary ventilation systems. In: Paper Presented at ICUE Conference (Cape Town, South Africa).
<http://www.poweringhealth.org/index.php/topics/technology/energyefficiency>.
- Rahman, S., Al-Hadhrani, M.L., 2010. Study of a solar PV-diesel battery hybrid power system for a remotely located population near Rafha Saudi-Arabia. *Energy* 36, 4986–4995.
- Saini, S., The Growing Need of Demand-Side Management, Energy Program, SangoGlobals
- Sameeullah, M., Kumar, J., Lal, K., Chander, J., 2014. Energy audit: a case study of hostel building. *International Journal of Research in Management, Science & Technology* 2 (2).
- Singh, H., Singh, M., Singh, G., 2012. Energy audit: a case study to reduce lighting cost. *Asian Journal of Computer Science and Information Technology* 2 (5), 119–122.
- Srinath, G., Uday Kumar, N., 2014. Energy audit as a tool for improving system efficiency in industrial sector. *International Journal of Engineering Research and Applications* 4 (6), 6–11. ISSN: 2248-9622.
- Van Alphen, K., Wilfred, G.J.H.M., Herkert, M.P., 2007. Renewable energy technologies in the Maldives – determining the potential. *Renewable & Sustainable Energy Reviews* 11, 1650–1674.
http://www.who.int/hia/green_economy/modern-energy-services/en/.
- Zhou, W., Lou, C., Li, Z., Lu, L., Yang, H., 2010. Current status of research on optimum sizing of stand-alone hybrid solar-wind power generation systems. *Applied Energy* 87, 380–389.

This page intentionally left blank

INDEX

“*Note:* Page numbers followed by “f” indicate figures and “t” indicate tables.”

A

Academic building

- climatic factors, 300–301
- commercial buildings, 295–296
- concrete and reinforced steel, 296–297
- construction materials, 302–303
- construction phase, 300, 302, 312–313
- construction projects, 295–296
- construction rate, 295–296
- cradle to grave study, 298
- data elucidation, 298
- data energy, 300
- data resources, 298–299
- demolition phase, 300, 312–313
- demolition process, 296
- direct environmental emissions, 299
- economic input-output (EIO)
 - method, 299
- electricity generation, 300–301, 301t
- elements and materials preservation, 296
- embodied energy, 300, 301t
 - externalities, 299
- energy consumption, 295–297
 - data, 300
- environmental assessment, 297
- environmental impacts, 296–297, 302
- environmental policy makers and
 - Government, 298
- financial factors, 297
- first floor layout, 303–304, 304f
- ground floor layout, 303–304, 303f
- heating and ventilation energy
 - requirements, 311–312
- heating, ventilation and air-conditioning (HVAC), 300–301
- human factors, 302–303
- indoor environment, 295–296
- input-output approach, 299
- Leontief inverse/total requirements
 - matrix, 300

- life cycle energy analysis, 296–297,
 - 312–313
- life cycle impact assessment, 298
- life cycle inventory analysis, 298
- maintenance phase, 300, 302,
 - 312–313
- manufacturing process, 295–296
- materials contribution, 309, 310f
- non-economic data, 299
- onsite construction process, 296–297
- operational energy, 300–302
- operational phase, 300, 312–313
- passive solar building design, 311–312
- quantitative analysis, 298
- residential buildings, 295–296
- scope and goal definition, 298
- secondary suppliers requirement, 299
- solid waste, 297
- THDC Institute of Hydropower
 - Engineering and Technology,
 - 300, 304–305, 305f
 - annual electricity consumption,
 - 305–306
 - climatic conditions, 305–306
 - construction phase, 306, 306f–307f
 - demolition, 307–308
 - green house gases emission, 309,
 - 309f–310f
 - life cycle energy (LCE),
 - 308, 308f
 - maintenance, 307–308
 - operational phase, 306–307
 - power generation capacity, 304–305
 - specifications, 304–305, 305t
 - total energy consumption, 305–306
- total lifecycle energy, 297
- total operational energy, 311, 311f
- total service life, 302
- truncation error, 298–299
- urban heat isolation effect, 311

- Additive decomposition, 7
- Air circulation and compressor
 - motors, 322
- Air pollutants
 - ammonium nitrate and fuel oil, 262–263
 - blasting, 264
 - bulk-explosive truck drive, 262–263
 - coalification, 265
 - coal washing/coal preparation, 265
 - custom-designed explosive mixtures, 262–263
 - drilling process, 262–263
 - environmental problems, 261–262
 - fly ash, 268
 - fugitive dust, 264
 - gaseous pollutants, 268–270
 - haul road dust, 264
 - nongaseous pollutants, 267–268
 - processes, 261–262, 263f
 - stoichiometry, 263–264
 - vegetation and topsoil removal, 262–263
 - ventilation air methane, 265
- Aluminum production
 - alumina refineries, 199
 - alumina refining, 206–207
 - and ingot casting, 210–213
 - anode effects, 207, 210–213
 - anthropogenic activities, 198
 - atmospheric carbon dioxide, annual
 - growth rate, 198, 199f
 - bauxite mining, 210–213
 - boundaries and calculation, 209–210
 - carbon emissions reduction, mitigation
 - strategies
 - climate change crisis, 215
 - emerging electrode technologies. *See* Emerging electrode technologies
 - end-of-life management, 215
 - energy efficiency, 215
 - innovation barriers, 215
 - interconnections, 215, 216f
 - long-term carbon emission reduction targets, 215
 - strict management system, 215
 - carbon equivalent, 210
 - carbon trading, 222–223
 - carbothermic reduction, 220–221, 220f
 - casting, 206–207
 - conversion factors, 210
 - direct energy, 207
 - direct on-site real time
 - measurement, 210
 - Eddy covariance/flux towers, 210
 - emission factors and models, 210
 - emission management, 207–208
 - energy consumption, 198–199
 - environmental problems
 - anode effects, 213–214
 - CO₂, 213
 - coal tar pitch, 214
 - fluorinated compounds, 214
 - polycyclic aromatic hydrocarbon (PAHs), 214
 - SO₂, 214
 - spent pot lining, 214
 - toxic emissions, 214–215
 - environmental profiles and pathways, 200–201
 - fifth assessment report (AR5), 197–198
 - fossil fuel combustion, 198
 - GHG effects, 197–198, 197f
 - GHGs concentration, 198–199
 - global annual production, 200–201, 201f
 - global warming effects, 197–198, 197f
 - global warming potential (GWP), 210–213
 - greenhouse gas emissions, 210–213, 211t
 - percentage contribution, 210–213, 212f
 - Greenhouse Gas Protocol-A Corporate Accounting and Reporting Standard, 208–209
 - Gulf of Cooperation Council and North America, 200–201
 - human sociocultural system, 213
 - indirect energy, 207
 - Industrial Revolution, 198–199
 - Intergovernmental Panel on Climate Change (IPCC), 197–198
 - guidelines, 208

ISO 14025, 208
 ISO 14064, 207
 ISO 14067, 208
 kaolinite reduction, 221–222,
 221f
 Kyoto Protocol, 206–207
 largest aluminum production countries,
 200–201, 200f
 life cycle assessment (LCA),
 200–201. *See also* Life cycle
 assessment (LCA)
 life cycle inventory (LCI)
 energy sources, 204–206
 inputs and outputs, 204–206,
 204t–205t
 treatment plant and red mud,
 204–206
 low-temperature reduction, ionic liquid,
 222
 mineral processing, 210–213
 mining, 206–207
 mitigation evaluation, 207–208
 multipolar electrolytic cell, 220
 National Oceanic and Atmospheric
 Administration (NOAA), 198
 oceans and glaciers,
 197–198
 processes, 210–213, 211t
 Product Category Rules, 208
 production chains, 206
 Publicly Available Specifications–2050,
 208
 recycling, 222
 smelting, 206–207, 210–213
 socioeconomic and environmental
 impacts, 213
 socioeconomic problems, 213
 system boundary setting and collection,
 208–209
 tiers/scopes, 209, 209f
 World Resource Institute and World
 Business Council on Sustainable
 Development, 207
 Ammonium hydroxide solution, 52
 Andalusian Construction Cost Database
 (ACCD), 233

B

Basic costs (BC), 236
 Bayer's process, 202
 Biomass-based energy system,
 143–144
 Biomass feedstocks, 143–144
 BLUE map scenario, 253, 253f
 Brazilian waste management outlook
 Brazilian aluminum recovery rate, 86
 Brazilian legislation, 84–85
 controlled disposal, 84–85
 door-to-door schedule, 86
 garbage collection, 86
 informal sector, 85–86
 plastic recycling, 86
 Rio de Janeiro panorama
 Brazilian Development Bank, 89
 commercial establishments,
 86–87
 Diagnostic of Solid Waste, 86–87
 emergency service, 86–87
 FERTILUB, 89
 GHG emissions, 89–90, 90f
 Municipal Act of Climate Changes,
 89–90
 municipal management, 89
 planning areas, 86, 87f
 population density, 86
 Program for Extension of Selective
 Collection, 89
 reforestation projects, 89
 residential waste, 86–87
 residential waste composition,
 88–89, 88f
 shopping malls, 86–87
 supermarkets, 86–87
 transfer stations and sanitary landfills
 locations, 87, 88f
 sanitary landfills, 84
 stakeholder group, 86
 sustainable development, 84–85
 urban waste disposal, 84
 waste final destination, types, 84, 85f
 Breakdown cost, 233
 British Standard Institute, 147
 Business model, 229

C

- Capital investment management, 322–323
- Carbon tax, 360–361
- Carbon trading, 222–223
- Carbothermic reduction, 220–221, 220f
- China's 5-year plan, 13
- Chinese emission factor, 33
- Chinese Government National Development and Reform Commission (NDRC), 119
- Chinese nonmetallic mineral product industry, 12–13
- Chinese research journal, 132
- Coal-based generation power plants, 142
- Coal combustion, 157
- Coal-fired power plants, 144–145
- Coal mining activities
 - agriculture forestry, 280–281
 - air pollutants
 - ammonium nitrate and fuel oil, 262–263
 - blasting, 264
 - bulk-explosive truck drive, 262–263
 - coalification, 265
 - coal washing/coal preparation, 265
 - custom-designed explosive mixtures, 262–263
 - drilling process, 262–263
 - environmental problems, 261–262
 - fly ash, 268
 - fugitive dust, 264
 - gaseous pollutants, 268–270
 - haul road dust, 264
 - nongaseous pollutants, 267–268
 - processes, 261–262, 263f
 - stoichiometry, 263–264
 - vegetation and topsoil removal, 262–263
 - ventilation air methane, 265
 - boundary, 276–277
 - carbon emissions reduction mitigation
 - carbon trading, 287–288
 - catalytic flow (CFRR), 286–287
 - catalytic monolith reactor (CMR), 286–287
 - concentrators, 287
 - cryogenic separation, 285
 - membrane separation, 286
 - methane emission mitigation and utilization techniques, 284–285
 - methanol and carbon black, 286
 - mine methane utilization, gas turbines, 287
 - power generation, methane, 286
 - pressure swing adsorption, 285
 - solvent adsorption, 285
 - thermal flow (TFR), 286–287
 - underground sequestration, 287
 - carbon footprint estimation, 278–279, 278f
 - case studies, 283–284
 - coal burning, 267
 - direct and indirect energy emissions, fossil fuel combustion, 281–282
 - direct GHG emissions, 277
 - energy source demand, 259
 - global energy demand, 259–260
 - operation, 260–261
 - primary energy demand worldwide, 259–260, 261f
 - strip mining, 260–261
 - total primary energy supply, 259–260, 260f
 - worldwide coal production and consumption, 259–260, 262f
 - equity share, 276–277
 - fuel combustion, 276, 279
 - fugitive emissions, 282–283
 - CH₄ and CO₂, 276
 - GHGs selection, 276
 - global warming, 270–271
 - greenhouse gas data collection, 279
 - direct on-site real time measurement, 279–280
 - emission factors and models, 280
 - indirect GHG emissions, 277
 - industrial processes and product use, 282
 - life cycle inventory (LCI)
 - bottom-up approach, 272
 - Caval Ridge Coal Mine Project, 273, 276t
 - decision-making, 271–272

- energy types, 273
 - environmental and social impact, 271–272
 - inputs and outputs, 273, 274t–275t
 - system boundaries, 272, 273f
 - mine fires, 266
 - net purchased electric and heating powers, 276
 - operational control, 277
 - organizational boundaries, 277
 - population growth, 259
 - torch combustion, 276
 - Coal tar pitch, 214
 - Commercial establishments waste, 90
 - Compressed air systems, 321
 - Confederation of Indian Industry (CII), 147
 - Construction and demolition wastes (CDW), 232–233
 - Core–shell nanoparticles, 52
 - Corrective maintenance, 231
 - Cost-benefit analysis, 326
 - Cost-management activities, 323
 - Cradle to gate stages, 115
 - Cyclohexane, 52
- D**
- Decision-making process, 48
 - Decomposition method
 - additive decomposition, 7
 - emission hierarchy, 5–6
 - energy consumption, 7
 - fossil fuel dependency, 6
 - index decomposition analysis (IDA), 6
 - indicators, 5–6
 - industrial production data, 7
 - Logarithmic Mean Divisia Index—index decomposition analysis (LMDI–IDA) formulation, 6–7
 - multiplicative approach, 7
 - policy making, 6
 - structural decomposition analysis, 6
 - time-series energy, 7
 - Demand-side management (DSM)
 - annual electricity production breakdown, 353, 356t
 - benefits, 357
 - carbon tax, 360–361
 - climate change, 318
 - CO₂ emission and diesel consumption, 357, 359f
 - conversion factor, 361
 - data requirements
 - component data, 336, 348, 348t
 - load data, 336–348
 - metrological (solar irradiance), 336–348, 337f
 - diesel consumption reduction, 357, 359t
 - diesel fuel price, 360–361
 - diesel generator, running hours, 357, 360f
 - economic analysis
 - optimal configuration, 351–353, 352t
 - electricity and heat demand, 317–318
 - electric renewables, hybrid optimization model, 334
 - emission factors, 361
 - air pollution, 348
 - emission estimation, 350
 - HOMER, 348–350
 - pollutants, 348–350
 - state-by-state average emission factors, 348–350, 349t
 - energy consumption, 318
 - energy demand reduction, 317–318
 - energy efficiency opportunities, 332t
 - air-conditioning units, 331
 - diesel/gasoline generators, 331
 - electrical power supply, 332–334
 - energy-efficient equipment, 331
 - energy star–rated equipment, 331
 - off grid/intermittent power sources, 331
 - power-consuming sectors, 331
 - sensitive laboratory equipment, 331
 - standard-efficiency models, 331–332
 - temperature sensitive drugs, 332–334
 - energy-efficient medical devices, 359–360
 - energy resources, 317
 - energy storage requirements, 336

Demand-side management (DSM)
 (*Continued*)
 environmental assessment model,
 360–361
 environmental benefit analysis, 357
 fossil fuel, 357
 fuel carbon destination, 361
 HOMER software and results, 357,
 358t
 hybrid PV/generator/battery system
 architecture, 360
 hybrid renewable energy system,
 359–360
 importance of, 318
 inflation effect, 360–361
 information dissemination
 benefits, 330
 financial analysis, 330–331
 load management programs, factors,
 330
 initial capital cost, 351–353, 353f
 long-terms planning, 318
 monthly contributions, PV and diesel
 generator, 353, 355f
 motivation
 cost-benefit analysis, 319
 costs reduction, 319
 energy commissions/agencies, 319
 energy efficiency, 319
 environmental and infrastructural
 development, 319
 implementation, 319
 power-generating stations, 319
 public energy utility companies, 319
 transmission and distribution network
 infrastructure, 319
 optimal system configuration, 350
 program design and delivery, 317
 reliability and efficiency, 336
 renewable energy access, 334–335
 resource planning, 317
 robust cost-benefit, 360–361
 site description, 335
 socioeconomic infrastructure, 318
 solar energy resources, 336
 solar irradiance, 360–361
 solar resource, 336

sustainability, definition, 318
 sustainable energy regulation, 318
 system configuration, 350–351,
 351t
 system installation cost, 351–353
 technoeconomic and emission,
 359–360
 total net present cost (TNPC), 350
 types, 317, 319–320
 electrification, 329
 energy reduction programs. *See*
 Energy reduction programs
 load management program. *See* Load
 management program
 productivity and environmental
 compliance, 328
 strategic load conservation, 329, 329f
 strategic load growth, 328, 329f
 Unmet load and shortage capacity, 353
 Direct environmental emissions, 299
 Domestic hot water (DHW), 242–243
 Domestic technical assumption (DTA),
 24–25
 Dry fly ash, 154

E

Ecoinvent database v3, 52
 Ecoinvent v2.2, 121, 132
 Economic input-output (EIO) method,
 299
 Electricity emission factor, 119
 Electronic induction printed circuit
 board assembly, 115
 Emerging electrode technologies
 anode design and composition,
 216–219
 carbon anodes, 216–219
 carbon cathode replacement, 219
 conventional and advanced methods,
 216–219, 217t–218t
 cryolite electrolyte, 215–216
 energy requirements, 216–219
 Hall–Héroult process, 215–216
 inert anode, 216–219
 titanium bromide, 219
 toxic waste, 219
 vertical electrode cells, 216–219

- “End-of-life” stage, system
 - boundary, 116
 - Energy and Resources Institute (TERI), 147
 - Energy auditing
 - continuous process, 324–325
 - cost-benefit analysis, 326
 - detailed audit, 326
 - dynamic model, 326
 - energy consumption activities, 324
 - energy-saving methods, 324
 - physically based model, 326
 - preliminary audit, 325
 - renewable energy technologies, 324–325
 - Energy reduction programs
 - automatic temperature controls, 320
 - compressed air systems, 321
 - efficient lighting, 322
 - energy auditing, 324–326
 - energy-efficient motors, 322
 - energy loss, 323–324
 - energy management
 - households, 323
 - practices, 322–323
 - households, 321
 - investments requirements, 321
 - lighting, 320
 - motors, 321
 - steaming and heating systems, 320
 - water treatment system, 320
 - Energy-saving tips. *See* Energy reduction programs
 - Energy system selection criteria
 - appliances, 344
 - clinic appliances, 339–342, 343t
 - daily energy capacity, 339–342
 - daily energy demand contributions, 344, 345f
 - electric load profile, 344, 345f
 - environmental health and sustainability, 344
 - evening peak hours’ supply, 342
 - gasoline/diesel generator source, 344
 - health-care facilities, 339–344
 - hourly distribution
 - with demand-side management, 344, 347t
 - without demand-side management, 344, 346t
 - load-conventional (inefficient) and energy-efficient equipment, 344
 - peak power capacity, 339
 - reliability, 342
 - supply duration, 342
 - Engineered nanomaterials (ENMs), 46
 - Engineered nanoparticles, 45–46
 - Enterprise Protocol, 169
 - Environmental input–output (EIO) analysis, 143
 - Enzyme immobilization, 46–47
 - European Union Emissions Trading Scheme (EU-ETS), 31–33
 - EUROSTAT, 247–248
 - Extended multiplier matrix decomposition, 23
- F**
- Fluorinated compounds, 214
 - Fossil fuel combustion, 198
 - Fourth Assessment Report, 1
 - Functional costs (FC), 236
- G**
- GHG Protocol Agricultural Guidance, 169
 - Green Bill of Materials (G-BOM) analyzer, 120–121
 - Green chemistry process, 47
 - Greenhouse Gas Protocol–A Corporate Accounting and Reporting Standard, 208–209
 - Gulf of Cooperation Council and North America, 200–201
- H**
- Hall–Hérault process, 215–216
 - Health clinics
 - classification, 337
 - high energy requirements, 338–339
 - low-energy requirements, 338

Health clinics (*Continued*)
 moderate energy requirements, 338
 United States Agency for International
 Development, 337
 Health post, 337
 High efficiency motors, 322
 Human sociocultural system, 213
 Hybrid Optimization Model for Electric
 Renewables (HOMER), 334
 Hydrofluorocarbons, 3–5

I

Impact assessment methodology, 56
 Index decomposition analysis (IDA),
 5–6, 15
 Indian power plant
 bioenergy maximum generation rate,
 143–144
 biomass-based energy system, 143–144
 biomass feedstocks, 143–144
 carbon dioxide emissions, raw material
 transportation, 150, 153t
 carbon dioxide production
 dry fly ash, 154
 emission factor, 154
 employees travel register, 153–154
 landfill waste, 154–155
 mill rejects, 154–155
 noncoking bituminous coal, 153
 service facilities energy
 requirement, 153
 wet ash, 154
 carbon trading and offsetting, 143
 climate change, 141
 coal-based generation power plants, 142
 coal combustion, 157
 coal-fired power plants, 144–145
 data sources, 148, 148t
 and research methodology, 143
 decision-making and identification,
 hotspots, 144–145
 direct and indirect emission, 156
 ecological resources, 142
 electricity demand, 142
 electricity generation, 143–144
 environmental input–output (EIO)
 analysis, 143
 environmental protection
 indicators, 141
 gaseous emissions, 141
 green electricity, 142–143
 input–output based approach, 143
 Intergovernmental Panel on Climate
 Change, 142
 life cycle assessment (LCA), 142–143
 life cycles stages, 141
 limitations, 156–157
 nonrenewable energy, 142, 157
 offsetting, 141–142
 power plant operation and service
 facilities, 149
 production components calculation,
 149–150, 151t–152t
 raw material stage, transportation,
 148–149
 reduction, 141–142
 renewable energy development
 program, 143–144
 research methodology
 boundaries selection, 145–146
 goal and scope definition, 145
 international standards, 145
 interpretation, 145
 life cycle impact assessment
 (LCIA), 145
 life cycle inventory (LCI), 145
 response strategies, 141–142
 scope and functional unit, 146
 supply chain, 143
 sustainable development goals,
 144–145
 system boundary
 activity data, 147
 auxiliary operations, 146
 cradle-to-grave approach, 146–147
 emission factors, 147
 organizational boundary, 146–147
 primary data, 147
 wastes transportation and
 disposal, 147
 system boundary problem, 142–143
 thermal efficiency, 142
 thermal power plant, 142, 144–145
 electricity generation process, 156

- greenhouse gases emissions, 155, 155f
- operation and service facilities, 156
- raw material transportation, 155–156
- top-down approach, 143
- total-generation capacity, 144–145
- waste materials disposal, transportation, 149
- wind and nuclear power plants, 142
- Induction cooker, 114f
- carbon emission calculation, 113
 - activity data, 120
 - cradle to gate assessment, 119
 - emission factor, 120
 - framework, 119, 120f
 - GHG emissions, 119–120
 - global warming potential, 120
 - Green Bill of Materials (G-BOM) analyzer, 120–121
 - impact assessment, 119–120
 - ISO/TS 14067:2013, 119
 - life cycle assessment (LCA), 119
 - manufacturing stage, 119
 - product carbon footprint (PCF) study, 119
 - raw material acquisition and manufacturing, 119–120
 - raw material stage, 119
 - sensitivity and contribution analysis, 119–120
- component (printed circuit boards), 137f
- cooking methods, 114
- cradle to gate stages, 113–114
- domestic models, 136f
- eco-friendly and low-carbon products, 113
- eco-product design, 135–136
- end-of-life stage, 113–114
- factory warehouse, 136f
- functional unit
 - allocation procedures, 116
 - cut-off criteria, 116
 - cut-offs, 116
 - data, 115, 115t
 - data quality, 115
 - electricity treatment, 119
 - electronic induction printed circuit board assembly, 115
 - geographical and time boundary, 116
 - manufacturing stage, 118–119
 - product category rule (PCR), 115
 - raw material stage, 117–118
 - system boundary, 116–117, 117f
 - transportation stage, 119
- greenhouse gas (GHG) emissions, 113
- life cycle impact assessment, 122, 123t–128t
- life cycle interpretation. *See* Life cycle interpretation
- life cycle inventory
 - manufacturing stage, 121–122, 121f
 - raw material stage, 121
 - transportation stage, 122
- manufacturing process, 137f–138f
- packaging materials, 137f, 139f
- product carbon footprint (PCF) analysis, 113
- product life cycle, 113–114
- quality testing process, 138f
- quantification and communication, 113–114
- sustainable consumption and production, 113
- Industrial Revolution, 198–199
- Industrial sectors, greenhouse gas (GHG) analyses
 - climate change, 1–2
 - CO₂ related emissions, 2–3, 4t
 - decomposition analyses methods, 3–5
 - decomposition method. *See* Decomposition method
 - emission reduction, 2
 - energy consumption, 2
 - energy efficiency, 5
 - environmental negotiations, 3
 - European Union (EU), 1–2
 - fossil fuels, 1
 - Fourth Assessment Report, 1
 - fuel types and sectors, 2–3
 - global warming, 1
 - hydrofluorocarbons, 3–5
 - index decomposition analysis (IDA), 5, 15

Industrial sectors, greenhouse gas (GHG)
 analyses (*Continued*)
 infrared radiation absorption, 1
 Kyoto Protocol, 1–3
 LEAP method, 3–5
 Logarithmic Mean Divisia Index
 (LMDI), 5, 15. *See also*
 Logarithmic Mean Divisia Index
 (LMDI)
 MARKA method, 3–5
 natural and socioeconomic systems, 3
 negative impacts, 3
 Organization for Economic
 Cooperation and Development
 (OECD), 2–3
 perfluorocarbons, 3–5
 policies, 2
 policymakers, 3–5
 reduction and mitigation approaches,
 3–5
 residential sector policy, 2
 sulfur hexafluoride,
 3–5
 thermal radiation, 1
 Third Assessment Report, 1
 Inorganic chemicals, 369
 Intergovernmental Panel on Climate
 Change, 142
 Intergovernmental Panel on Climate
 Change (IPCC), 173,
 197–198, 270
 guidelines, 208
 International Energy Agency's (IEA)
 Reference Scenario, 270
 International Federation of Wines and
 Spirits (FIVS), 168
 International Organization of Vine and
 Wine (OIV), 169
 International Wine Carbon Calculator
 (IWCC), 168
 International Wine Carbon
 Protocol, 169
 ISO 14025, 208
 ISO 14064, 207
 ISO 14067, 208
 Isopropanol (IPA), 52
 Italian Wine Carbon Calculator, 168

K

Kaolinite reduction, 221–222, 221f
 Kyoto Protocol
 aluminum production, 206–207
 Industrial sectors, greenhouse gas
 (GHG) analyses, 1–3
 Spanish construction sector, 21
 Spanish construction sector, extended
 carbon footprint, 26–27, 33
 Utility consumption, 237

L

Laccase immobilization, 56–57, 59–60
 Landfill waste, 154–155
 LEAP method, 3–5
 Leontief's multiplier matrix, 23
 Leontief's output multiplier, 24
 Life cycle assessment (LCA), 142–143.
See also Academic building
 aluminum scrap, 201
 carbon emissions, 201
 environmental management, 201
 induction cooker, 116
 magnetic nanoparticles (mNPs)
 characterization factors, 47
 cradle-to-gate approach, 50
 decision-making process, 48
 functional unit, 48–50, 49t
 ISO standards, 48
 octahedral PEI-coated mNPs,
 50–51
 oleic acid mNPs, 51
 polyacrylic acid-coated Fe₃O₄
 mNPs, 50
 polyethylenimine-coated mNPs,
 50–51
 production pathways, 48, 49f
 production protocols, 50
 semipilot scale, 50
 SiO₂-coated mNPs, Fe₃O₄
 preparation, 51–52
 spherical PEI-coated mNPs, 50–51
 natural resources, 201
 primary aluminum production
 anode production, 202
 Bayer's process, 202
 energy-intensive process, 202

- Hall—Hérault electrolytic process, 202
- impurities removal, 204
- net electrolytic reduction reactions, 202
- red mud, 202
- system boundary, 202, 203f
- raw materials extraction, 201
- secondary aluminum production, 204
- spanish construction sector, 20
- Life-cycle costs (LCC), 229–230
- Life cycle energy (LCE), 308, 308f
- Life cycle impact assessment (LCIA), 57, 145
- Life cycle interpretation (LCI)
 - induction cooker
 - cooker's carbon footprint, 128, 129t
 - database selection, value choices, 131–132
 - greenhouse gas emissions and removals, 128, 131t
 - limitations, 131
 - raw material stage, 128, 130f
 - sensitivity analysis. *See* Sensitivity analysis
 - uncertainty analysis, 132, 135t
 - printed circuit board (PCB), 372, 411, 421f, 421t, 422f
 - database selection, 423
 - greenhouse gas emissions and removals, 422, 422t
 - limitations, 422–423
 - sensitivity analysis, 423–426, 424t, 425f, 425t, 426f
 - uncertainty analysis, 426, 426t
- Life cycle inventory (LCI), 47–48, 118, 145
 - aluminum production
 - energy sources, 204–206
 - inputs and outputs, 204–206, 204t–205t
 - treatment plant and red mud, 204–206
 - coal mining activities
 - bottom-up approach, 272
 - Caval Ridge Coal Mine Project, 273, 276t
 - decision-making, 271–272
 - energy types, 273
 - environmental and social impact, 271–272
 - inputs and outputs, 273, 274t–275t
 - system boundaries, 272, 273f
- Ecoinvent database v3, 52
- environmental assessment, 52
- manufacturing stage
 - absorbent towers, 411
 - activity data, 374
 - consumables packaging, 384, 399t–400t
 - consumables transportation, 384, 401t–409t
 - consumables usage, 384, 385t–398t
 - electricity consumption, 374, 383t
 - emission factor, 374
 - internal transportation tools, 384, 384t
 - liquid wastes, 411, 412t
 - process flow, 374, 382f
 - solid waste management, 384, 410t
 - water consumption, 382, 383t
- octahedral polyethylenimine (PEI)-coated mNPs, 52, 53t
- oleic acid-coated mNPs, 52, 54t
- on-site measurements, 52
- polyacrylic acid (PAA)-coated Fe_3O_4 , 52, 53t
- raw material stage
 - database selection, 374
 - data sources, 374
 - transportation of, 374, 379t–381t
 - weight and emission factor, 374, 378t
 - weight, materials used, and emission factors, 374, 375t–377t
- SiO_2 -coated mNPs, Fe_3O_4 , 52, 55t
- SiO_2 -coated mNPs thin shell, Fe_3O_4 , 52, 55t–56t
- spherical polyethylenimine (PEI)-coated mNPs, 52, 54t
- transportation stage, 411, 413t
- wastewater treatment process, 52
- Load management program
 - load control, 328
 - load leveling
 - base load generation, 326–328

Load management program (*Continued*)
 forms, 327f
 load shifting, 328
 peak clipping, 327
 valley filling, 327
 tariff incentives and penalties, 328

Logarithmic Mean Divisia Index (LMDI)
 carbon intensity, 7–8
 early oil crisis
 CO₂ factors, 8
 Divisia method, 8
 economic growth/development,
 8–9
 Organization for Economic
 Cooperation and Development
 (OECD) countries, 8
 results, 8, 9t
 factors, 7–8
 greenhouse crisis solution
 Australian sector, 13
 China's 5-year plan, 13
 Chinese nonmetallic mineral product
 industry, 12–13
 decomposition results, 10–13,
 12t–14t
 energy efficiency, 13–15
 energy intensity, 10, 13
 factors, total emission, 10, 11t
 ferrous metals pressing, 10
 fuel shift, 10
 heat and electricity carbon emission
 coefficients, 10
 industrial activity, 10
 industrial structural shift, 10
 nonmetal mineral products and
 smelting, 10
 raw chemical materials and products,
 10
 Taiwan's decomposition results,
 10–12, 12t
 Taiwan's industrial emission,
 10–12

Logistic chain, 83f
 stages, 82
 transfer stations, 82
 treatment and decomposition, 82
 waste demand region, 82

M

MaClar method, 236

Magnetic nanoparticles (mNPs), 46
 biomedical applications, 46
 biotechnological applications,
 46–47
 chemical coprecipitation, 46
 coating materials, 46
 decision-making process, 48
 end-of-life stage, 47
 engineered nanomaterials (ENMs), 46
 engineered nanoparticles,
 45–46
 environmental results, 58t
 characterization, 57
 classification, 57
 energy consumption, 59
 environmental profiles, 59–60, 59f
 laccase immobilization, 56–57,
 59–60
 life cycle impact assessment (LCIA), 57
 magnetic separation stage, 59
 oleic acid-coated mNPs production,
 64–67, 66f–67f
 polyacrylic acid (PAA)-coated Fe₃O₄
 mNPs production, 60–61,
 60f–61f
 polyethylenimine (PEI)-coated mNPs
 production, 62–63, 62f–63f
 ReCiPe midpoint methodology, 57
 redispersion stage, 59
 SiO₂-coated mNPs, Fe₃O₄
 production, 67–71, 68f–71f
 spherical PEI-coated mNPs
 production, 63–64, 64f–65f
 superparamagnetic characteristics, 57
 transmission electron microscopy, 57
 washing stage, 59
 enzymatic cascade reaction,
 46–47
 enzyme immobilization, 46–47
 green chemistry process, 47
 health and environmental risks, 47
 impact assessment methodology, 56
 inorganic/organic protective coatings, 46
 life cycle assessment (LCA), 47. *See also*
 Life cycle assessment (LCA)

- life cycle inventory (LCI) analysis, 47–48
 - Ecoinvent database v3, 52
 - environmental assessment, 52
 - octahedral polyethylenimine (PEI)-coated mNPs, 52, 53t
 - oleic acid-coated mNPs, 52, 54t
 - on-site measurements, 52
 - polyacrylic acid (PAA)-coated Fe_3O_4 , 52, 53t
 - SiO_2 -coated mNPs, Fe_3O_4 , 52, 55t
 - SiO_2 -coated mNPs thin shell, Fe_3O_4 , 52, 55t–56t
 - spherical polyethylenimine (PEI)-coated mNPs, 52, 54t
 - wastewater treatment process, 52
 - lysine amino groups, 46–47
 - magnetic core, 46
 - microemulsion, 46
 - nanomaterials, 45
 - nanoscience development, 47
 - nano-sized water droplets, 46
 - nanotechnology, 45
 - oleic acid, 48
 - production process, 47
 - relative surface area and quantum effects, 45
 - surfactant molecules, 46
 - synthesis, 48
 - total life cycle environmental impacts, 47–48
 - unit immobilization yield, 72–73, 72t, 73f, 74t
- MARKA method, 3–5
- Massart method, 50
- Mass balance, 149
- Mill rejects, 154–155
- Ministry of Environment and GHG Program, 147
- Multiplier decomposition analysis, 37–38, 37f
- Multipolar electrolytic cell, 220
- Multiregional input–output models (MRIO), 24–25
- Municipal solid waste (MSW)
 - recyclable waste
 - anaerobic composting, 84
 - atmospheric pollutant emissions, 93–94
 - atmospheric pollutants emissions, 81
 - BAU scenario, 92, 102
 - benefits, 81
 - biogenic carbon, 102
 - boundaries, 95, 96f
 - Brazilian commercialized diesel, 102
 - Brazilian electric energy mix data, 97–98
 - Brazilian municipalities, 80
 - Brazilian waste management outlook
 - See Brazilian waste management outlook
 - Brazil Recycle Program, 80–81
 - business-as-usual (BAU) CF, 82
 - chemical and physical modification, 83–84
 - CO_2eq emission factors, 98, 99t–100t
 - composting process, 102
 - composting unit, 84
 - controlled disposal rates, 79–80
 - conversion factors, 95
 - Cooperpires facility, 95
 - cut-off approach, 97
 - diesel consumption, 93–94
 - diesel upstream emissions, conversion factors, 97
 - direct emissions, 97
 - domestic and commercial sewage, 81
 - dry and wet waste, 91
 - emission factors, 98, 101f, 101t
 - emissions inventory, 81
 - Environment Ministry, 80–81
 - EURO3 specifications, 93–94
 - facilities location, 93, 94f
 - GHG emission factors, 101
 - Global Warming Potential (GWP), 95
 - Global Waste Management Outlook Report, 79
 - gravimetric composition coefficients, 103, 103t–104t
 - greenhouse gases (GHG), 80
 - GWP100, 98
 - household waste, 80

Municipal solid waste (MSW) (*Continued*)

- Intergovernmental Panel on Climate Change (IPCC), 80
- International Solid Waste Association, 79
- leachate percolation, 80
- life cycle GHG emissions, 95
- logistic chain, 83f. *See also* Logistic chain
- manual/mechanical technology, 83–84
- municipal solid waste (MSW), 80
- National Energy Balance, 97
- National Policy for Solid Waste (NPSW), 80
- optimization route
 - software, 102
- organic fraction, 83
- private company (PC) characteristics, 90–91
- ReCiPe H Midpoint characterization method, 98
- reduction costs, 80–81
- sanitary landfills, 81
- selective collection regions, 92, 93f
- software ORD, 93
- sorted/unsorted materials, 97
- sorting unit, 93
- sorting units, 83–84
- spatial planning, 92
- transfer station, 94
- transport data, 104, 105t–110t
- types, 92, 92t
- uncontrolled disposal, 79–80
- waste amounts, 95, 95t
- waste decomposition, 80
- waste disposal, 79–80
- waste generators, 83
- waste management, 80
- waste reuse rates, 80
- waste trucks, 101
- wet and dry waste, 83
- wet fraction, 93
- wet waste, 98–101
- system boundaries, 232

N

- Nanoparticles (NPs)
 - classification, 45–46
 - polyacrylic acid (PAA), 48
 - polyethylenimine (PEI), 48
 - silica-coated mNPs, 48
- National Oceanic and Atmospheric Administration (NOAA), 198
- Net present cost (npc), 334
- Noncoking bituminous coal, 153

O

- Oleic acid-coated mNPs production
 - chemical requirements, 65
 - coprecipitation method, 64–65
 - environmental hotspot, 65
 - global environmental profile, 65, 66f
 - magnetic NPs formation, 65, 66f
 - oleic acid, 65–67, 67f
 - wastewater stream, 64–65
 - wastewater treatment plant (WWTP), 65
- Organic chemicals, 369
- Organizational budget, 322–323
- Organizational nature, 322–323
- Organization for Economic Cooperation and Development (OECD), 2–3
- ORTEC Routing and Dispatch (ORD), 91
- Oxidative precipitation, 51

P

- Packaging methods/materials, 117
- Paper materials, 118
- PAS 2050: 2011 guidelines, 147
- Perfluorocarbons, 3–5
- Personal electronic product. *See* Induction cooker
- Plastic materials, 118
- Policymaking training manual, 322
- Polyacrylic acid-coated Fe₃O₄ mNPs, 50
- Polyacrylic acid (PAA)-coated Fe₃O₄ mNPs production
 - environmental results, 60
 - chemical requirements, 61
 - electricity requirements, 60–61, 61f

- environmental hotspot, 61
 - global environmental profile, 60, 60f
 - Polycyclic aromatic hydrocarbon (PAHs), 214
 - Polyethylenimine (PEI)-coated mNPs
 - production
 - environmental results, 62
 - deionized water requirements, 62
 - electricity requirements, 63
 - environmental hotspot, 62–63, 63f
 - global environmental profile, 62, 62f
 - potassium nitrate consumption, 63
 - wastewater treatment plant (WWTP), 62
 - Polyoxyethylene(5)nonylphenyl ether, 52
 - PRé Consultants SimaPro 8.1
 - software, 187
 - Predictive maintenance, 231
 - Preventative maintenance, 231
 - Printed circuit board (PCB)
 - allocation procedures, 368
 - carbon emission calculation
 - cradle-to-gate assessment, 372
 - emission database, 373
 - framework, 372, 373f
 - G-BOM analyzer, 373
 - GHG emissions and removals, 372
 - goal and scope definition, 372
 - ISO/TS 14067:2013, 372
 - LCA, 372
 - life cycle impact assessment (LCIA), 372
 - life cycle interpretation (LCI), 372, 411, 421f, 421t, 422f
 - life cycle inventory (LCI), 372.
 - See also* Life cycle inventory (LCI)
 - product carbon footprint (PCF)
 - analysis, 411, 414t–420t
 - climate change, 365
 - cutoff, 368
 - cutoff criteria, 368
 - data, 366–367, 367t
 - data quality, 368
 - distribution stage, 365–366
 - drilling needles and milling cutters, 427t–428t
 - electricity consumption, 426–427
 - electricity treatment, 372
 - electronic components, 365
 - end-of-life stage, 365–366
 - factory manufacturing line, 428f–429f
 - factory wastewater treatment facility, 429f–430f
 - functional unit, 366
 - geographical and time boundary, 368
 - global warming potential (GWP), 365
 - intermediate products, 365
 - life cycle assessment (LCA), 365
 - low-carbon products, 365
 - manufacturing stage, 365–366
 - bag production process, 370
 - energy consumption data, 371
 - hazardous liquids, 371
 - sewage wastewater, 371
 - sludge generation, 371
 - solid waste, 371
 - product carbon footprint (PCF), 365
 - product life cycle, 365–366
 - product system and function(s), 366, 367f
 - raw material stage, 365–366, 369–370
 - sewage treatment, 428
 - small-scale products, 365
 - system boundary, 368, 369f
 - transportation stage, 372
 - use stage, 365–366
 - Producer Responsibility criterion, 21
 - Product category rule (PCR), 115, 170, 208
 - Product end-of-life treatment policy, 116
 - Product life cycle, 115
 - Product Protocol, 169
 - Proton sponge mechanism, 50–51
 - Publicly Available Specification (PAS), 168
- ## R
- ReCiPe midpoint methodology, 56–57
 - Recycling, 222
 - Red wines
 - carbon footprint *vs.* water footprint (WF), 187, 189, 189f–190f

Red wines (*Continued*)

- distribution, end-of-life scenario, 187, 188t
 - functional unit data, 187, 188t
 - ISO 14067, 182f
 - core module, 182–185, 184t
 - cradle-to-cradle approach, 181
 - cradle-to-grave approach, 181
 - cropped surface basis, 181–182
 - diesel fuel, 182
 - distribution phase, 182
 - downstream module, 182–185, 184t
 - ecoInvent 3.0 database, 181
 - PRé Consultants SimaPro 8.0 software, 181
 - sustainability plan, 181
 - total CF and contribution, 183–185, 183t
 - upstream module, 181, 183–185, 184t
 - upstream phase, 182–183, 183f
 - vineyard management, 181
 - phases contribution, 189, 190f
 - studied product data, 187, 188t
 - upstream, core, and downstream contributions, 187, 189f
- Reheat regenerative ranking cycle, 149
- Renewable energy development program, 143–144
- Residential sector policy, 2
- Residential waste, 90
- Restaurant waste, 90
- Reverse microemulsion method, 51
- Rural health-care centers (RHC). *See* Demand-side management (DSM)

S

Sensitivity analysis

- manufacturing stage
 - electricity usage, 132, 134t, 135f
 - emission factor database selection, 132
- material stage
 - integrated circuits, 132, 133t, 134f
 - printed circuit boards, 132, 133t, 134f
- utility consumption, 253–256, 254f

Service Availability and Readiness

- Assessment (SARA), 339, 340t–341t, 344
- Simple costs (SC), 236
- SiO₂-coated mNPs, Fe₃O₄ preparation, 51–52
- environmental results, 69, 70f
 - cyclohexane, 68
 - deionized water, 67
 - environmental burdens, 68, 69f
 - mechanical agitation, 68
 - reverse microemulsion, 68
 - silica coating stage, 67–68, 68f
 - silica thin shell, 52
 - thin silica coating
 - chemicals requirements, 71, 71f
 - cyclohexane, 69–71
 - environmental profile, 69–71, 70f
 - pilot plant, 71
- SO₂, 214
- Social Accounting Matrix (SAM), 20
- additive decomposition analysis, 21
- Spanish construction sector
- autonomous demand, 30–31
 - booming economic process, 39
 - characteristics, 30–31
 - construction sector emission multipliers
 - domestic emission multipliers, 34–36, 36f
 - domestic-induced multipliers, 37–38
 - domestic multiplier/output multiplier, 37–38
 - electricity mix, 36–37
 - energy and pollution intensive inputs, 37–38
 - energy cleanliness strategy, 36–37
 - environmental efficiency, 34–36
 - fossil energy source multipliers, 36–37
 - heating systems, 36–37
 - high-induced effects, 38
 - imported multiplier, 37–38
 - income distribution, 37–38
 - international production layers, 37–38

- multiplier decomposition analysis, 37–38, 37f
- national energy mix, 34–36
- positive electricity, 34–36
- production process, 37–38
- total domestic efficiency, 37–38
- consumer responsibility criterion, 20
- databases, 28
- demand emissions-intensive inputs, 28–30
- domestic emissions, 30
- economic and population growth, 28
- economic growth, 40
- emissions analysis, 21
- energy and environmental policy, 40–41
- energy demand, 19–20
- energy efficiency, 19–20
- energy preservation, 19
- environmental legislation, 39–40
- environmental policy improvements, 30
- European Parliament
 - recommendations, 20
- extended carbon footprint, 28–30, 29f, 38
 - autonomous final demand, 25–26
 - average emission factor, 33
 - carbon leakage, 33–34
 - Chinese emission factor, 33
 - circular effects matrix, 24
 - construction sector, direct emissions, 31, 32t
 - consumer responsibility, 27, 33
 - design mitigation policies, 33–34
 - direct emissions, 24–26
 - direct method, 22
 - domestic carbon, 33
 - domestic demand, 27
 - domestic emission multiplier matrix, 22
 - domestic emissions, 26
 - domestic-induced emissions, 25–26
 - domestic technical assumption (DTA), 24–25
 - domestic total emissions, 31–33
 - dragging effect, 34
 - economic crisis and stagnation, 31–33
 - embodied emissions, 31–33
 - emission factors, 23–24
 - endogenous and exogenous components, 26
 - energy goods consumption, 25–26
 - environmental costs, 33
 - environmental impact, 26
 - European Union Emissions Trading Scheme (EU-ETS), 31–33
 - exhaustive control, 24
 - extended multiplier matrix
 - decomposition, 23
 - household consumption
 - endogenization, 23
 - incentivize environmental efficiency, 31–33
 - indirect emissions, 24–25
 - indirect method, 22
 - indirect multipliers matrix, 23–24
 - induced emissions estimation, 34, 35f
 - industrial and hotel and restaurant sectors, 34
 - input–output models, 21–22
 - Irish construction sector, 31
 - Kyoto Protocol, 26–27, 33
 - Leontief's multiplier matrix, 23
 - Leontief's output multiplier, 24
 - matrix multipliers, 22
 - metallurgy/nonmetallic minerals, 31–33
 - multiregional input–output models (MRIO), 24–25
 - national extraction sector, 31–33
 - negative effect, 34
 - producer responsibility expression, 26–27
 - responsibility criterion, 24–25
 - sectorial and households' direct and indirect emissions, 26
 - stock variations, 26
 - Stone's additive decomposition, 23
 - total emission multiplier matrix, 24–25
 - total emissions, 22
 - total virtual carbon, 27
 - vertical specialization processes, 27

Spanish construction sector (*Continued*)

- financial markets, 40
- fossil energy sources, 40–41
- heating systems, 19–20
- income-generated expenditure, 39
- input–output analysis, 38
- input–output life-cycle assessment model (IO-LCA), 20
 - advantage, 20–21
- Kyoto Protocol, 21, 40–41
- life cycle assessment (LCA), 20
- light installations, 19–20
- limitations, 38
- policy implementation, 28
- process-based LCA, 20–21
- Producer Responsibility criterion, 21
- production chain emissions, 20
- production process, 20
- regional governments, 30–31
- sectorial reallocation, 28–30
- Social Accounting Matrix (SAM), 20
 - additive decomposition analysis, 21
 - total domestic emissions, 39–40
- Spent pot lining, 214
- Sustainable energy regulation, 322
- Swiss ecoinvent data version 2.2, 369
- Spherical PEI-coated mNPs
 - production, 63
 - ammonium hydroxide, 63
 - deionized water consumption, 64
 - electricity requirements, 64, 65f
 - global environmental profile, 63, 64f
 - heating process, 64
 - octahedral PEI-coated mNPs, 63
- Stone's additive decomposition, 23
- Structural decomposition analysis, 6
- Sulfur hexafluoride, 3–5

T

Tetraethyl orthosilicate (TEOS), 52

THDC Institute of Hydropower Engineering and Technology, 300, 304–305, 305f

- annual electricity consumption, 305–306
- climatic conditions, 305–306
- construction phase, 306, 306f–307f

- demolition, 307–308
- green house gases emission, 309, 309f–310f
- life cycle energy (LCE), 308, 308f
- maintenance, 307–308
- operational phase, 306–307
- power generation capacity, 304–305
- specifications, 304–305, 305t
- total energy consumption, 305–306

Thermal power plant, 142, 144–145

- electricity generation process, 156
- greenhouse gases emissions, 155, 155f
- operation and service facilities, 156
- raw material transportation, 155–156

Thermal radiation, 1

Third Assessment Report, 1

Total net present cost (TNPC), 350

U

United States Agency for International Development, 337

Unmet load, 342

“Use” stage, system boundary, 116

Utility consumption

- BLUE map scenario, 253, 253f
- business model, 229
- cleaning tasks, 234t–235t
 - Andalusian Construction Cost Database (ACCD), 233
 - basic costs (BC), 236
 - breakdown cost, 233
 - construction process, 236–237
 - constructive element, 236–237, 238t–240t
 - cost structure, 236, 236f
 - functional costs (FC), 236
 - MaClar method, 236
 - product/cleaning tool, 233
 - simple costs (SC), 236
 - task periodicity, coding, 237, 241t
 - task type, coding, 237, 241t
- cleaning tasks branch, 250, 251t
- construction phase, 230
- discount rates, 253
- ecological footprint, 230
- electrical machinery, 251
- electricity, 241–242

- energy demand, 250
 - environmental analysis, 230
 - environmental indicators, 230
 - facility manager (FM), 229–230
 - food consumption, 251–252
 - fuel, 242–243, 243t
 - global warming potential, 237
 - Hernando Colón university Hall of
 - Residence, 248, 249f
 - anodized aluminum frames, 249–250
 - first floor, 249, 249f
 - ground floor, 249
 - heating system, 250
 - impact driver, 251–252, 252f
 - Kyoto Protocol, 237
 - life-cycle costs (LCC), 229–230
 - long-term scenarios
 - BLUE map scenario, 248
 - International Energy Agency, 248
 - use-and-maintenance phase, 248
 - machinery, 246
 - maintenance and renovation, 229–231
 - manpower
 - average daily calorie consumption, 246–247
 - emission factor, 247–248
 - EUROSTAT, 247–248
 - food consumption, 246–247, 247t
 - impact sources, 246
 - metabolic rate, 246–247, 247t
 - manpower and machinery, 230–231
 - materials
 - average return distance, 244
 - cleaning products, 244
 - construction phase, 245
 - cradle-to-gate analysis, 244–245
 - domestic cleaning kit, 244
 - emission factor, 244–246
 - environmental impact, 244–245
 - fuel emission factor, 245, 245t
 - manufacturing, 244
 - recycling and energy recovery, 245
 - transportation, 244
 - transport vehicle, 244
 - waste, 244
 - methodology flowchart, 237, 242f
 - MSW generation, 251–252
 - open and free-access database, 229–230
 - operation and maintenance costs, 229–230
 - periodic cleaning, 230–231
 - propane and drinking water
 - consumption, 250
 - resource consumption, 237, 241
 - sensitivity analysis, 253–256, 254f
 - system boundaries, 232f
 - cleaning, 231
 - construction and demolition wastes (CDW), 232–233
 - construction phase, 232–233
 - corrective maintenance, 231
 - finishes and installations
 - renovation, 231
 - food consumption, 232
 - maintenance, 231
 - mobility, 232
 - municipal solid waste (MSW), 232
 - predictive maintenance, 231
 - preventative maintenance, 231
 - rehabilitated building, 231
 - transversal boundaries, 232
 - UNE-EN 15978 standard, 231
 - use-and-maintenance phase, 231
 - utility consumption, 231
 - tertiary buildings, 229–230
 - total results, 252–253, 252t
 - UNE-EN 15978:2012 standard, 250
 - use-and-maintenance phase, 230–231, 252–253
 - use branch, 250, 250t
 - water, 243–244
- ## V
- VIVA Sustainable Wine
 - CO₂ offset contribution, 179–180, 179f
 - environmental and socioeconomic performance, 178
 - hybrid approach, 179
 - indicators, 178
 - Italian Ministry for the Environment, 178
 - label and smartphone application, 178, 179f

VIVA Sustainable Wine (*Continued*)

Red #6 details, 180, 180f

Red #7 details, 180, 180f

vinification phase, 180

W

Waste collection operation, 90

Waste treatment transportation routes, 118

Wet ash, 154

Wind and nuclear power plants, 142

Wine industry

agricultural land, 162

beyond ISO 14067

carbon footprint *vs.* water footprint
(WF) (red wine), 187, 189,
189f–190fcarbon footprint *vs.* water footprint
(WF) (white wine), 187, 190fdistribution (red wine) end-of-life
scenario, 187, 188t

evaluation procedure, 185

functional unit (red wine) data,
187, 188t

life cycle, 185, 186f

phases contribution (red wine),
189, 190fPRé Consultants SimaPro 8.1
software, 187

process site-specific data, 187

recursive approach, 185

studied product (red wine) data,
187, 188t

total production data, 187, 187t

upstream, core, and downstream
contributions (red wine), 187, 189f

water footprint (WF), definition, 185

core processes, 170

crop production, 162

downstream processes, 171

economic production,
161, 191

emission factor, 172

emission inventory, 171–172

emission quantification,
171–172environmental footprint indicators,
169–170Environmental Labels and Declarations,
170equivalent carbon dioxide (CO₂eq)
emissions, 171

European Union (EU), 163

food sector, 161

functional unit (FU), 173

global warming potential, 173, 173t

Intergovernmental Panel on Climate
Change, 173

ISO 14064

crop reconversion process, 175

diesel and biodiesel fuels, 175

direct emissions, 176, 177f

electric energy consumption
reduction, 176

energywares production, 176

environmental impact, 175

environmental sustainability, 175

first-generation biodiesel, 175

greenhouse gas emissions,
organization, 176, 176f

indirect emissions, 175–176, 177f

land surface basis, 176–178, 177f

operational boundaries, 175

organization boundaries, 175

product-oriented approach, 176–178

Umbrian agricultural company, 175

uncertainty assessment, 176

ISO 14067, red wines, 182f

core module, 182–185, 184t

cradle-to-cradle approach, 181

cradle-to-grave approach, 181

cropped surface basis, 181–182

diesel fuel, 182

distribution phase, 182

downstream module, 182–185, 184t

ecoInvent 3.0 database, 181

PRé Consultants SimaPro 8.0
software, 181

sustainability plan, 181

total CF and contribution,
183–185, 183tupstream module, 181, 183–185,
184t

upstream phase, 182–183, 183f

vineyard management, 181

- land area distribution, 162, 162f
- life cycle assessment (LCA) approach, 169–170
- life cycle stages, 170–171
- New World countries, 163
- organization-oriented study, 169–170
- primary data, 172
- principles, 171
- Product Category Rules (PCR), 170
- production process, 161
- product-oriented approach, 192
- protocols and guidelines
 - activity-based approach, 168
 - British Standards Institute, 168
 - business-to-consumer assessments, 169
 - Enterprise Protocol, 169
 - environmental awareness, 167
 - GHG Protocol Agricultural Guidance, 169
 - International Federation of Wines and Spirits (FIVS), 168
 - International Organization of Vine and Wine (OIV), 169
 - International Wine Carbon Calculator (IWCC), 168
 - International Wine Carbon Protocol, 169
 - Italian Wine Carbon Calculator, 168
 - national agencies, 168
 - Product Protocol, 169
 - Publicly Available Specification (PAS), 168
 - sustainability principles, 167
- scientific literature
 - air-conditioning systems, 166
 - allocation choices, 167
 - cradle to grave and cradle to gate, 163–164
 - data quality, 167
 - diesel production and consumption, 165–166
 - end-of-life phases, 163–164
 - energy consumption, 166
 - gate-to-gate approach, 163–164
 - glass bottle production, 166
 - global warming potential (GWP), 167
 - grapevines treatment, 165–166
 - Italian red wine, 166
 - kgCO₂eq/bottle, 164–165, 165f
 - model transportation, 163–164
 - packaging process, 164–165
 - pesticides and fertilizers, 165–166
 - production process phases, 163–164
 - resources consumption, 165–166
 - spirit packages, 166
 - storage and consumption phase, 166–167
 - system boundaries, 163–164
 - third-party logistic company, 167
 - transportation and distribution phase, 163–164
 - transport modes/choices, 167
 - vineyard-planting phase, 165
 - viticulture activities, 164–166
- secondary data, 172
- system boundaries, 171–173, 172f, 174f
- total direct and indirect environmental impacts, 161, 169–170
- upstream processes, 170
- VIVA Sustainable Wine
 - CO₂ offset contribution, 179–180, 179f
 - environmental and socioeconomic performance, 178
 - hybrid approach, 179
 - indicators, 178
 - Italian Ministry for the Environment, 178
 - label and smartphone application, 178, 179f
 - Red #6 details, 180, 180f
 - Red #7 details, 180, 180f
 - vinification phase, 180
- wine production data, 163, 164t
- world wine production trend, 162, 163f
- World Resource Institute and World Business Council on Sustainable Development, 207
- World Resource Institute (WRI)
 - India, 147

This page intentionally left blank

Environmental Carbon Footprints

Industrial Case Studies

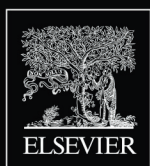
Case studies are the most flexible of all research designs, allowing the researcher to retain the holistic characteristics of real-life events, while investigating empirical events. *Environmental Carbon Footprints: Industrial Case Studies* provides a wide range of industrial case studies beginning with the textiles, energy systems, and conventional and biofuels.

Each footprint case study is associated with the background information, scientific consensus and reason behind its invention, methodological framework, assessment checklist, calculation tool/technique, applications, and challenges and limitations. More importantly, application of each indicator/framework in various industrial sectors and their associated challenges, futuristic views are worthwhile to learn.

Key Features

- Includes case studies from a various industries such as textiles, energy systems, and conventional and biofuels.
- Provides calculation tool/technique, applications, and challenges and limitations for determining carbon footprints on industry by industry bases.
- Each case study provides the background information, scientific consensus, and reason behind its invention.

Dr. Subramanian Senthilkannan Muthu is currently working for Lidl Hong Kong as a Sustainability Manager, based out of Hong Kong. He has gained his PhD from The Hong Kong Polytechnic University. He is a renowned expert in the areas of Environmental Sustainability in Textiles & Clothing Supply Chain, Product Life Cycle Assessment (LCA) and Product Carbon Footprint Assessment (PCF) in various industrial sectors. He has published more than 75 research publications, written numerous book chapters and authored/edited multiple books in the areas of Carbon Footprint, Recycling, Environmental Assessment, Environmental Sustainability, etc. (over 40 books to his credit)



Butterworth-Heinemann

An imprint of Elsevier
elsevier.com/books-and-journals

ENGINEERING

ISBN 978-0-12-812849-7



9 780128 128497