Green Energy and Technology

Oktoviano Gandhi
Dipti Srinivasan *Editors*

Sustainable Energy Solutions for Remote Areas in the Tropics

Springer

Green Energy and Technology

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Preface

My first encounter with the energy problems in the remote tropics was in early 2016, at the start of my Ph.D. journey under Prof. Dipti Srinivasan. At the time, I joined a community project organised by the Indonesian Students' Association in Singapore to an Indonesian island called Geranting. The island is located merely 30 km away from mainland Singapore, a global financial centre and one of the most prosperous countries in the world, but the difference in the level of development of the two islands could not be starker.

There are about 300 families in Geranting Island, and most of them are fishermen. The residents relied on an old diesel generator for five hours of electricity per day. When the diesel generator breaks down—a common occurrence—the residents resort to hazardous kerosene lamps for lighting. The island had actually received grants from the government in the forms of solar home systems for each house and communal solar PV systems for the local school and for water desalination. Nevertheless, without the transfer of knowledge to the community and proper maintenance, the systems quickly broke down and were abandoned.

After the community project in Geranting, a group of friends and I came back to the island to repair the PV system at the local school and decided to try and solve more of these problems. We discovered that this is the case not just in Geranting, but in many islands and communities across Indonesia, and across the developing economies. It is obvious that the technologies to solve the problems are already available, but without proper implementation, the situation will not improve.

Throughout my Ph.D. and rural electrification journey, I have encountered and learned from numerous people who have the same vision and passion to solve these energy problems as sustainably as possible. Their advice, which comes from their wealth of experience, has definitely helped me in the discovery and implementation of sustainable energy solutions in the remote tropics.

When the opportunity arises to put the lessons I have learnt, combined with Prof. Dipti's expertise in renewable energy and energy systems, into a book, we immediately contacted the experts whom I have encountered, as well as those whose works have been instrumental in the sustainable energy sector. Many of them have agreed to become authors and shared their lessons learnt from their own journey in their respective chapters.

The lessons from these experts are now more important than ever. As we are faced with the “dual challenge” of meeting rising energy demand and emitting a decreasing amount of carbon, we need to collaborate and combine all our efforts, knowledge, and expertise to come up with, implement, and scale the solutions.

Working with such diverse groups of authors, from academia, industry, government, and non-profit sector—all of whom are experts in their chosen fields—has been very enriching both personally and professionally. I would like to thank the authors who have been committed in writing their respective chapters, particularly Christoph Luerssen, who has contributed immensely to the book since the ideation stage.

Singapore Oktoviano Gandhi

My interest has always been renewable energy in all its forms and its relation to sustainable development. Although sustainable energy was not a popular term even twenty years ago, the concept was widely discussed due to the fact that almost all developing economies that have grown in the past fifty years have done so either using non-renewable resources or by making formerly sustainable ecosystems, such as natural forests, unsustainable in the long run through industrial exploitation, and other activities. Furthermore, this development corresponds to nearly one for one increase in the use of energy.

Today, people use more energy than ever from a variety of sources for a multitude of tasks, which undoubtedly make our lives better. While Asia has an abundance of natural energy resources, the main challenge has been to balance the energy demand against sustainable practices. In 2008, I started offering a graduate-level course to provide the students with a thorough understanding of analysis and management strategies for promoting the advancement and use of economically and environmentally sustainable electrical energy systems. The course covered distributed generation and renewable energy sources and strategies for supply and demand-side management for efficient resource utilisation, as well as issues related to the environmental impact of electrical energy generation. My encounters with these disciplines provided much inspiration and conceptual linkages that enhance the potential for smart energy technologies to reduce or shift energy demand.

The last few years have seen a rapid increase in community-led sustainable energy projects around the developing world, capitalising on alternative energy initiatives taken by the governments and moving towards a sustainable low-carbon economy. These initiatives have included both energy generation and conservation projects, combined with micro-generation technologies and energy efficiency improvement programmes. In this book, rather than providing a typical overview of sustainability projects, various experts in the field provide an interesting account of projects to illustrate how smart initiatives are potentially transforming everyday practice. Our hope is that this book will speak to the engineers and economists who are designing, building, and making the case for sustainable development in remote communities with little or no access to grid electricity. Towards this end, this book draws on experience from a wide range of fields to reconceptualise and extend the possibilities for sustainable development in remote regions. We hope to showcase innovations for sustainability transitions that have been successfully implemented as local projects and disseminate best practices to encourage innovation diffusion.

Singapore Dipti Srinivasan

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Editors and Contributors

About the Editors

Oktoviano Gandhi obtained a master of physics degree from the University of Oxford, UK, in 2015, and a Ph.D. from the National University of Singapore (NUS) in 2019. He is currently a research fellow at the Solar Energy Research Institute of Singapore (SERIS), NUS. On the research front, he has worked on the engineering aspects of solar cells and modules, solar energy integration in power systems, all the way to analysing policies' impact on energy intensity. His scientific works have resulted in more than twenty international publications. Oktoviano has also held positions in many top universities across the world, namely Yonsei University in South Korea, University of Sao Paulo in Brazil, and Tsinghua University in China.

Through Alva Energi, a company that he co-founded, he is channelling his expertise in solar energy, rural electrification, electricity grid planning, and energy policy to promote renewable energy development in Indonesia. His works and achievements have been recognised internationally: he was selected to be part of Global Young Scientists Summit, Leader of Tomorrow at St. Gallen Symposium, One Young World Ambassador, and BP Advancing Energy Scholar. Most recently, Okto was featured in Vanity Fair 2020 Global Goals List, representing SDG7: Ensure access to affordable, reliable, sustainable and modern energy for all.

Dipti Srinivasan is a professor in the department of electrical and computer engineering (ECE) at the National University of Singapore (NUS), where she also heads the Centre for Green Energy Management and Smart Grid (GEMS). Her recent research projects are in the broad areas of optimisation and control, wind and solar power prediction, electricity price prediction, deep learning, and development of multi-agent systems for system operation and control. Her current research focuses on the development of novel computational intelligence-based models and methodologies to aid the integration of the new smart grid technologies into the existing infrastructure so that the power grid can effectively utilise pervasive renewable energy generation and demand-side management programs, while accommodating stochastic load demand. She has published more than 350 publications which have been highly cited.

She is a fellow of IEEE and was awarded the IEEE PES Outstanding Engineer award in 2010. She is an associate editor of IEEE Transactions on Smart Grid, IEEE Transactions on Sustainable Energy, IEEE Transactions on Evolutionary Computation, IEEE Transaction on Neural Networks and Learning Systems, and IEEE Computational Intelligence magazine. At the ECE department of NUS, she teaches courses in the areas of sustainable energy systems, smart grid, and computational intelligence methods. She is the recipient of the NUS Annual Teaching Excellence Award and Engineering Educator Award.

Contributors

Andrea Eras-Almeida is a Ph.D. researcher at Instituto de Energía Solar at Universidad Politécnica de Madrid (UPM). Her research focuses on off-grid renewable solutions on vulnerable contexts such as small islands, rural areas, and refugee camps. She is a member of the UPM Platform on Refugees. She has ten years of professional background in the energy sector. Among other positions, she has been Head of the Energy Planning Department at Electrical Company ELECGALAPAGOS (Ecuador) and also she worked in the UN Development Program as Energy Advisor. In Reiner Lemoine Institut, she has been Guest Researcher at the Off-Grid Research Unit. She holds an electrical engineering degree from Universidad de Cuenca (Ecuador), a master’s degree in Renewable Energy and Environment by UPM, and a master’s degree in Economic Development and Public Policies by Universidad Autónoma de Madrid. She is committed to energy transition based on holistic solutions for resilient energy supply. Currently, she is involved in energy research projects in Africa and Latin America.

Paul Bertheau is an expert in island energy supply and has been a member of the Off-Grid Systems team at the Reiner Lemoine Institute since 2012. He holds an international master's degree in Global Change Management and is currently doing his PhD at the Europa-University of Flensburg and the Reiner Lemoine Institute. His research focuses on sustainable electrification options for small islands in the Philippines. He has led several research projects, including market potential studies for renewable energy on islands and feasibility studies for specific renewable technologies and renewable energy projects. In this context, he has worked with partners from the public and private sectors and gained practical work experience in Africa, Asia, and the Pacific.

Dr. Philipp Blechinger is an international expert in renewable energies and rural electrification. He holds a Ph.D. in engineering from the TU Berlin. Currently, he is Head of unit Off-Grid Systems at Reiner Lemoine Institut. Here he managed and conducted a wide range of international projects on energy access and island energy supply. Examples include the rural electrification planning for Nigeria and the support to the Department of Energy of the Philippines to improve electrification efforts. Apart from that he continuously publishes and shares research results on conferences and in scientific journals (>50) acting as reviewer and co-editor as well. He is also a visiting scholar of the Renewable and Appropriate Energy Lab (RAEL) at UC Berkeley and a selected member of the Arab-German Young Academy of Sciences and Humanities (AGYA). During his fieldwork, he visited many Caribbean countries: Barbados, Grenada, Jamaica, St. Kitts & Nevis, St. Vincent & the Grenadines, and Trinidad & Tobago. In addition, he worked on the Cook Islands, the Philippines, in Tanzania, Nigeria, and Zambia.

David Cheong is the vice dean in the School of Design and Environment, National University of Singapore (NUS). In addition, he is the co-director (Centre for Integrated Building Energy and Sustainability in the Tropics) in the Department of Building, NUS. Dr. Cheong is also a fellow of the International Society of Indoor Air Quality and Climate. His research interest is in the area of indoor air quality, ventilation and energy efficiency in buildings as well as the migration of pollutants into buildings. He has more than 200 publications in international journals and conferences. He serves on several local technical committees and is a reviewer of numerous research projects for the Engineering and Physical Sciences Research Council (EPSRC) in the UK and Research Grants Council of Hong Kong.

Walter Commerell has been a professor for Energy Storage at THU, Ulm University of Applied Sciences since 2007. He is a member of the institutes “Energy and Drive Technology” and “Vehicle Systems Technology”. His research areas are energy storage and energy management in stationary and mobile systems. He initiated and manages the “International Energy Competence Network” (IECN). Professor Dr. Commerell is a member of the Association Simulation (ASIM) and speaker of the department “Simulation of Technical Systems” and member of the German Society for Solar Energy and the International Solar Energy Society.

Since 2010, he is the director of the “Steinbeis Transfer Centre System Design”, where he together with a group of engineers work on industrial projects. Since 2000, he has been in the Supervisory Board of Phocos AG, where markets solutions for off-grid systems are designed and sold. Before joining the university as a professor, he worked for T-Systems for several years as a project centre team leader model-based design, and he was CEO of VIAx Solutions Ltd.

He received his Dipl. Ing. (FH) in industrial electronics with a focus on renewable energies in 1988 and his doctorate after working in industry in 2001.

Alvin B. Culaba is an academician of the National Academy of Science and Technology, Philippines and a university fellow and professor of mechanical engineering at De La Salle University Manila, Philippines. A pioneer in the area of life-cycle assessment (LCA), he was the first to apply the LCA methodology to sustainability analysis of manufacturing processes and has developed streamlined LCA approaches to different energy applications. His various energy studies were the basis for the crafting of the Philippines twin energy bills, namely the Biofuels Act of 2006 and the Renewable Energy Act of 2008. He led a technical team that developed and commissioned a community-based micro-hydro power (MHP) system in an off-grid area in the northern Philippines. He is actively engaged in the country’s energy sector since 1988 and has been the Philippines energy adviser and expert panel member on the energy of the Congressional Commission on Science, Technology and Engineering. He was also a past president of the National Research Council of the Philippines, the Philippine-American Academy of Science and Engineering, and the Philippine Association for the Advancement of Science and Technology. A multi-awarded scientist, teacher, and science administrator, he holds a Ph.D. in mechanical engineering at the University of Portsmouth, UK, and is listed in the Who's Who in Philippine Engineering.

Tika Diagnestya is a social justice advocate and a management consulting analyst at Accenture. As a management consultant, She helps her clients to grow and sustain their business for a better global economy and to improve economic injustice. Her project ranges from sustainability to digital issues.

Her journey to reduce economic inequality started when she went to Tanzania for her foremost volunteer abroad in 2013. Since then, She has helped to rebuild low-income houses in a rural area within the USA before returning to Indonesia. In 2018, she and her co-founder won an award to launch Masak Bersih (MASIH). MASIH, in its first few years, aims to distribute 500 clean cook stoves to the rural areas of Indonesia.

She had internship experiences in a government agency and a multilateral organisation with a specific interest in macroeconomics and economic development. After graduating with a B.A. degree in Economics from New York University, She worked for a year as an investment analyst with an Indonesian government agency hoping to make a change for the country's economy.

Patrick Dolle is currently working as a project coordinator in the Department for International Cooperation at Physikalisch-Technische Bundesanstalt (PTB), the German Metrology Institute. Among other projects, he is working in Indonesia on a project to strengthen quality infrastructure for photovoltaics. The project aims to support the quality assurance services for photovoltaics systems in Indonesia. He has an academic background in environmental and forest sciences, as well as in international cooperation and sustainable development. He has worked for several research institutes like the Bern University of Applied Sciences in Switzerland and the Forest Research Institute (FVA) in Baden-Württemberg, Germany.

Raluca Dumitrescu is the head of ME Consult, the consulting arm of MicroEnergy International. She is a rural electrification expert with extensive experience in countries in Africa, South Asia, and Latin America. She has participated in numerous feasibility studies on solar home systems and mini-grid and in the design of various intervention measures to intensify and improve the productive use of solar energy, particularly in unconnected rural areas, combined with an assessment of end-user financing for energy access (microfinance models, PAYG, and A-B-C). She is familiar with the local context of Tanzania and has worked extensively on previous projects in the country and region. In addition, she also has expertise in financial due diligence, strategy development, and business models, including risk analysis and market analysis. Currently, She is a doctoral candidate at the Technical University Berlin on the topic of "Community-Based Intelligent Rural Electrification—Swarm Electrification".

Sebastian Groh is a 2013 Stanford Ignite Fellow from Stanford Graduate School of Business and holds a Ph.D. from Aalborg University and the Postgraduate School MicroEnergy Systems at the TU Berlin where he wrote his doctoral thesis on the role of energy in development processes, energy poverty and technical innovations, with a special focus on Bangladesh. He published a book and multiple journal articles on the topic of decentralized electrification in the Global South.

He started his career and received his DNA at MicroEnergy International, a Berlin-based consultancy firm working on microfinance and decentralized energy. In 2014, He founded SOLshare, acting as its CEO since then. He is also an associate professor in the Business School of BRAC University in Dhaka, Bangladesh. On behalf of SOLshare, he received numerous awards, among them Tech Pioneer '18 by the World Economic Forum and best energy start-up in the world by Free Electrons. SOLshare also received the prestigious UN DESA Powering the Future We Want USD 1M Energy Grant, along with Grameen Shakti. He became

Ashoka Fellow in 2018, and UBS Global Visionary in 2019, as well as received the 2019 Unilever Young Entrepreneurs Award.

Martha M. Hoffmann is a researcher in the Research Unit Off-Grid Systems at the Reiner Lemoine Institut (Berlin, Germany). She conducts research on the simulation and optimization of sector-coupled local energy systems in the scope of the H2020 project E-LAND. She was enroled in the master's degree in Renewable Energy Systems at TU Berlin. In the context of her work, she wrote her final thesis examining the future operation options of micro grids interconnecting with weak national grids. For this, she developed off-gridders, a simulation and optimization tool for electric energy systems away from or connected to a central electricity grid, based on the Open Energy Modelling Framework (oemof). She holds a bachelor's degree in Energy and Process Engineering from TU Berlin. After conducting a student research project dealing with swarm grids, she spent three months in India for an internship at Oorja Development Solutions Limited, during which she worked on electrification with micro grids.

Swee-Sum Lam, Ph.D., Ph.D., CA, CFA, is an associate professor of finance at the NUS Business School and the director of the Asia Centre for Social Entrepreneurship and Philanthropy (ACSEP). She is an accountant by training, having earned her doctorate degree in finance from the University of Washington. Prior to joining NUS, Associate Professor Lam has had diverse work experience in corporate banking, corporate finance, and real estate. Since assuming the directorship of ACSEP in 2011, she has curated the addition of six new modules—on leadership, entrepreneurship, investing and consulting at the intersection of the business and social sectors—to both the BBA and MBA curricula at the NUS Business School. To build leadership in the people, public and private sectors, she seeded the Social Impact Prize Awards and Scholarships in Social Entrepreneurship and Philanthropy for both BBA and MBA students. She also oversaw the launch of the ACSEP Case Series on Social Entrepreneurship and

Philanthropy to advance impactful practices through formal education and executive training. In addition, she introduced the ACSEP Working Paper Series on Social Entrepreneurship and Philanthropy to foster thought leadership with the desired outcome being the reallocation of scarce resources to those who can deliver impact for social good.

Licheng Liu received his B.Eng. in engineering science from the National University of Singapore in 2010 and was subsequently awarded the NRF Clean Energy Scholarship, issued by the Singapore Economic Development Board, to pursue a Ph.D. degree in Advanced Photovoltaic at the Solar Energy Research Institute of Singapore in the National University of Singapore. Upon conferment of his Ph.D. degree in 2014, he started working closely with various governmental bodies, as the deputy head of the National Solarisation Centre, to promote solar energy as a reliable and sustainable alternative source of energy for Singapore. He kick-started the SolarNova project and was a vital contributor to the Floating PV Test Bed project. Thereafter, he moved on to the Independent Power Producer (IPP) business at Saferay, where he was in charge of the operations and maintenance, as well as the asset management for a fleet of utility-scale solar power plants that the company developed and built in Japan. Currently, he is focusing on the project development and project financing aspects of the IPP business, where he performs due diligence on legal, technical, financial, and tax-related topics, evaluates the profitability with financial models, and carries out a risk assessment and mitigation for potential projects.

Christoph Luerssen is currently a final-year Ph.D. candidate at the National University of Singapore (NUS) conducting his research on energy storage for solar-powered cooling applications at the Solar Energy Research Institute of Singapore (SERIS). His research interests also include product development and system design for rural electrification as well as the exploration of ways to enable clean energy transition in developing economies.

Prior to his Ph.D. studies, he pursued a bachelor's degree in Energy Systems Technology at Ulm University of Applied Sciences in Germany while working part-time as a development engineer for Fosera, a solar home system manufacturer. He started his professional career with an apprenticeship as a hands-on Mechatronics Technician and continues to enjoy applied work.

Christoph co-founded Alva Energi, an Indonesian renewable energy company, where he serves as the CTO and aims to contribute to the clean energy transition in Indonesia, which is well aligned with his passion: developing and implementing various types of solar energy solutions.

Isidro A. Marfori III is a licensed mechanical engineer and an assistant professor of mechanical at De La Salle University Manila, Philippines. He finished his M.Sc. in mechanical engineering at De La Salle University and has been awarded outstanding thesis for his thesis titled “Design and optimisation of a propeller-type micro-hydro turbine using computational fluid dynamics”. Ingko, as he is fondly called by his colleagues and friends, has been involved in the design and implementation of micro-hydro power (MHP) systems in the country since 2004. His expertise and knowledge in MHPs have contributed to the drafting of policies related to local MHP standards, technology deployment, and studies on MHP turbines and controllers. He received the Pillar of Excellence Award in Community Engagement in 2015 for his significant and impactful work on community-based MHPs. An expert in advanced computer-aided design and simulation, he is currently undertaking research on optimality and sustainability of community-based MHP system operations and cost competitiveness.

Daniel Philipp has more than 17 years of experience in energy engineering and economics, strategic business development, technology design, clean energy technologies (CET) implementation, testing of standards for CETs, supervision of CET installation and testing, as well as monitoring and impact evaluation. Since 1995, he has been involved with microcredits for developing aid policy. In 2002/2003, he conducted research in cooperation with the Technical University Berlin on the enterprise Grameen Shakti (GS) in Bangladesh, together with GS's loan officers on how green microloans can be disbursed for SHS. Ever since, he has tried to replicate through different technical assistance programs the Bangladeshi model of linking CETs with affordable financing in countries such as the Philippines, Peru, Tanzania, Burkina Faso, Senegal, Ghana, and Ethiopia. He possesses a deep understanding of the complexity of the supply chains of CETs in different socioeconomic and cultural contexts. He has been involved in technical and financial due diligence of PAYG companies in West and East Africa. He has conceptualised the swarm electrification (Peer-to-Peer Networks of CETs) approach and is currently coordinating the development and market distribution of swarm energy products and services.

Thomas Reindl is the deputy CEO of the Solar Energy Research Institute of Singapore (SERIS) and the principal research fellow at the National University of Singapore (NUS). He started with photovoltaics (PV) in 1992 at the SIEMENS Corporate R&D Labs. After holding several management positions at SIEMENS and running one of the leading German PV systems integration companies as a chief operating officer, he joined SERIS in 2010 and soon became the director of the Solar Energy System cluster. During his time at SERIS, he won public research grants in excess of SGD 20 million, founded two spin-off companies and authored strategic scientific papers such as the "PV Roadmap for Singapore". He holds a master in chemistry, a Ph.D. in Natural Sciences and an MBA from INSEAD, all awarded with highest honours. His research interests are high-performance PV and embedded systems, techno-economic road-mapping, and the reliable integration of renewable energies into power systems. He is also the principal investigator of the "Floating PV test bed" project in Singapore.

Chandra Sekhar is a tenured professor and co-director (Centre for Integrated Building Energy and Sustainability in the Tropics) in the Department of Building, National University of Singapore. He was the programme director (M.Sc. in Building Performance and Sustainability) for 17 years until 2019. His research interests include thermal comfort, ventilation/IAQ, energy efficient HVAC systems, smart buildings, and building energy analysis with more than 250 publications in international journals and conferences. He is a co-inventor and holds three US and other patents. He is a fellow of ASHRAE and ISIAQ.

In addition, he has also been recognised through several other awards, including Uichi Inouyi Memorial Asian International Award from SHASE, Japan (2019); Environmental Health Award (2014), Exceptional Service Award (2013), and Distinguished Service Award (2010) from ASHRAE; SPRING Singapore Merit Award (2012), ASEAN Energy Award (2011), and The Enterprise Challenge (TEC) Award of the Singapore Prime Minister's Office (2004). He has been an ASHRAE Distinguished Lecturer since 2006 and is regularly invited as a speaker around the world. He currently serves as Director-at-Large on the ASHRAE Board of Directors. He is active in Standards and Technical committees in ASHRAE and is also actively involved in local standardization activities in Singapore.

Amalia Suryani has an overall twelve years of experience in the energy and environment sector. She started her career as a fuel price and subsidy analyst in the Indonesian Ministry of Energy and Mineral Resources. In 2010, she joined the Clinton Foundation as an energy efficiency analyst, supporting the Jakarta government in implementing energy efficiency measures for buildings and streetlighting. From 2011 to 2018, She worked for German Agency for International Development Cooperation (GIZ) as a renewable energy advisor in the Energising Development (EnDev) project. EnDev is a global partnership promoting sustainable access to modern, clean, and affordable energy services. She acted as the project's team leader for three years, managing the support programme for photovoltaic mini-grids and micro-hydro power plants. She holds a master's degree in Environmental and Energy Management from the University of Twente in the Netherlands and is currently pursuing her second master's degree in Sustainable Development Studies at Universität Leipzig, Germany.

Xiang Ru Amy Tan is a research associate at the Asia Centre for Social Entrepreneurship and Philanthropy (ACSEP) in the NUS Business School. She holds a master of social science (Sociology) from NUS, and her research interests include food and preventive health care, ageing, and community-enabling in the urban environment. She is experienced in conducting ethnographic and mixed methods social research. She has been involved in various social research projects in the past, such as examining the rise of singlehood, delayed marriages; landscape study on the state of home and community care for seniors in Singapore; strategic philanthropy in funding public goods. She is deeply interested in using impact evaluation methods to build research capabilities in the social sector, and she has also written on social impact measurement in the growing impact investing sector.

Christian von Hirschhausen is a professor for Economic and Infrastructure Policy at Berlin University of Technology and research director for International Industrial and Infrastructure Policy at the German Institute for Economic Research (DIW Berlin). He holds M.A. (Economics) from the University of Colorado at Boulder (1988), Diplom-Ingenieur (Industrial Engineering) from TU Berlin University of Technology, Ph.D. (Doctor in Industrial Economics) from the Ecole des Mines de Paris (1995), and Habilitation (venia legendi) in Economics from TU Berlin University of Technology (2002). Previously, he has held position at Dresden University of Technology. His research focuses on environmental, energy and resource economics, infrastructure and network economics, applied industrial economics, and political and institutional economics. He is the editor-in-chief of EEEP (*Energy and Environmental Economics and Policy*) and has published extensively on issues of the low-carbon energy transformation in Germany, Europe, and globally. His recent works are on electrification and network economics.

Jackie Yap Chee Wei was born in Ipoh, the state of Perak, Malaysia, in 1992. He received the B.S. degree in mechanical engineering from the University of National Energy (UNITEN), Putrajaya campus, Malaysia, in 2015. His research areas include renewable energy and entrepreneurship. From 2015 onwards, he has been the founder and chief executive officer of HiGi Energy Corporation, a company established to eradicate water hyacinth disaster across 52 countries by turning water hyacinth and other agricultural wastes into cooking fuels. He has extensive experience in business model innovation and community development in the sustainable cooking industry.

He is associated with the U.S. Department of States for the Global Innovation through Science and Technology (GIST) fellowship. He is also associated with Techtown, an entrepreneurial hub based in Detroit, Michigan, USA. He is a consultant in the For-Purpose Enterprise (FPE), a non-profit organisation to provide consultancy service to start-ups and corporations with sustainability-related initiatives within the organisation.

Dazhi Yang received his B.Eng., M.Sc., and Ph.D. degrees in electrical engineering from the National University of Singapore, Singapore, in 2009, 2012, and 2015, respectively. He is currently a research scientist with the Singapore Institute of Manufacturing Technology, Agency for Science, Technology and Research, Singapore. His research interests include solar forecasting, data science, and spatio-temporal statistics. He is a subject editor of *Solar Energy*, for the area of Solar Resources and Meteorology.

Abbreviations

AC	Alternating current
BNI	Beam normal irradiance
BTI	Beam-tilted irradiance
CAPEX	Capital expenditure
CFC	Chlorofluorocarbon
CFL	Compact fluorescent lamp
CHP	Combined heat and power
COP	Coefficients of performance
CSR	Corporate social responsibility
CSS	Control Systems Society
DC	Direct current
DHI	Diffuse Horizontal Irradiance
DRC	Democratic Republic of Congo
DRE	Decentralized renewable energy
DSCR	Debt service coverage ratio
DTI	Diffuse-tilted irradiance
EPC	Engineering, procurement and construction
ESMAP	Energy Sector Management Assistant Program
EYA	Energy Yield Assessment
FAO	Food and Agriculture Organization
FCU	Fan coil unit
FIT	Feed-in tariff
GADM	Global Administrative Areas
GDP	Gross domestic product
GHG	Greenhouse gas
GHI	Global horizontal irradiance
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit (German Society for International Cooperation)
GS	Grameen Shakti (Village Energy)
GTI	Global-tilted irradiance

HCD	Human-centred design
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HOMER	Hybrid Optimisation of Multiple Energy Resources
HVDC	High-voltage direct current
ICT	Information Communication Technology
IDCOL	Infrastructure Development Company Limited
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineer
ILK	Institut für Luft- und Kältetechnik (Institute of Air Handling and Refrigeration)
IMF	International Monetary Fund
IoT	Internet of things
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IT	Information Technology
KYC	Know your customer
LCA	Life-cycle assessment
LCOE	Levelised cost of electricity
LED	Light-emitting diode
LGU	Local Government Unit
LPG	Liquefied petroleum gas
LVDC	Low-voltage direct current
MBE	Mean bias error
MFI	Microfinance Institution
MHP	Micro-hydro power
MKP	Misi Kami Peduli (Mission: We Care)
MOA	Memorandum of Agreement
MPPT	Maximum power point tracking
MSE	Mean square error
MTF	Multi-tier Framework
NAMRIA	National Mapping and Resource Information Authority
NASA	National Aeronautics and Space Administration
NGO	Non-Governmental Organisation
NUS	National University of Singapore
O&M	Operations and maintenance
ODP	Ozone depletion potential
OECD	Organisation for Economic Cooperation and Development
OPEX	Operational expenditure
P2P	Peer-to-peer
PAYG	Pay-as-you-go
PCM	Phase change material
PLN	Perusahaan Listrik Negara (National Electricity Company of Indonesia)

PPA	Power purchase agreement
PU	Polyurethane
PV	Photovoltaic
QI	Quality Infrastructure
R&D	Research and Development
RE	Renewable energy
RLI	Reiner Lemoine Institute
RMSE	Root mean square error
SDG	Sustainable Development Goal
SHS	Solar home system
SPT	Simplified planning tool for hybrid systems
SPV	Special purpose vehicle
SROI	Social return on investment
TV	Television
UHI	Urban heat island
UN	United Nations
UNEP	United Nations Environment Programme
VRF	Variable refrigerant flow
VSD	Variable speed drive
WACC	Weighted average cost of capital
WHO	World Health Organization
YDD	Yayasan Dian Desa (Dian Desa Foundation)

Introduction

Oktoviano Gandhi and Dipti Srinivasan

Climate change is probably the most difficult and important challenge of this century. If left unsolved, it has the potential to end humanity as we know it. The world has experienced approximately 0.6 °C increase in temperature as of 2014 compared to the periods of 1950–1980 [1] and is predicted to suffer from a 3.5 °C increase in temperature by the end of the century should the business-as-usual activities continue [2]. So far, the temperature increase shows no sign of stopping: July 2019 was recorded as the hottest July globally since 1880, at 0.95 °C above the twentieth century average [3]. Even a mere 2 °C increase in temperature would cause sea level to rise by 56 cm by 2100—submerging many low-lying islands and countries—and increase the frequency of extreme weather conditions throughout the world, among other severe and irreversible effects [4, 5]. At 3.5 °C increase, the consequences are much worse.

The problem of climate change has been worsening due to the increasing use of energy in both the developed and developing countries. The world energy consumption has increased by approximately 40% from 2010 to 2017 and is predicted to increase by more than 25% by 2040 even in the International Energy Agency (IEA)'s "New Policies" scenario [6]. Under this scenario, the CO_2 emissions in 2040 would be 35.9 gigatonnes, up 10% from the 2017 value. Meanwhile, the United Nations Environment Programme (UNEP) warned that CO_2 emissions need to peak by 2020 and decrease drastically if we were to stay within a 2 °C temperature increase by 2100 [2].

The increase in the final energy consumption can be largely attributed to the expanding economy of countries with large population like India, China, and Indonesia, particularly in the form of increasing electricity demand for industrial motors,

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as well as for space cooling and household appliances in urban areas [6]. The equipment does not only consume energy when used but also has to be manufactured using energy. Approximately, half of the increase in primary energy demand would be fulfilled by fossil fuel generation [6], which emits greenhouse gases, among other pollutants.

While the energy consumption of the urban dwellers continues to increase unabated, there remains large portion of the population which still does not have access to energy, especially in the form of electricity. These communities are usually located in remote areas (or islands) in the developing world, most of which lie along the Earth's tropical belt. These remote communities too experience a growth in their purchasing power, albeit at a slower rate than their urban counterparts. And, they too need to increase their electricity consumption (often from 0) to improve their livelihood, such as to have lighting in the evening, to have access to fresh food and working vaccines, among other basic needs.

Yet, if the remote communities obtain their energy sources in the same way as most of humanity before them did, i.e. by burning fossil fuels for electricity and cutting wood from the forest for cooking, the problem of climate change will be exacerbated. Ironically, these remote communities are also the most vulnerable to the consequences of climate change. Therefore, there needs to be sustainable energy solutions for the remote communities to improve their livelihood, while protecting the world's environment.

That is precisely the aim of this book, to not only provide an overview of the types of problems that exist in the remote tropics but also the details of what the solutions can be, accounts on how they have been applied in real life by experts in the field, as well as their impacts and how these solutions can be made more sustainable, not only for the environment but also for the communities. This book is targeted towards people who want to make a real difference in the world, by solving one of the world's most challenging problems at any scale—one community, an island, a country, or even a whole continent. These people can be existing energy practitioners in the rural areas, academics, policy makers, or even students who are embarking on a learning journey about energy and sustainable development. These people most definitely include you, who have picked up this book to learn about the defining challenge of our time and how to solve it.

1 The Remote Tropics

The tropics are the region around the equator, between $\pm$ 23°27′ latitude as shown in Fig. 1, characterised by warm weather (averaging 25–28 °C) all year round. Unlike the temperate and the subpolar regions, the tropics only experience two seasons: wet and dry seasons—some areas even experience only one hot season. It is home to about a third of the world's population.

The tropics are also home to the world's largest tropical rainforests, one of the key ingredients in keeping our Earth's temperature to stay within a 2 °C increase.

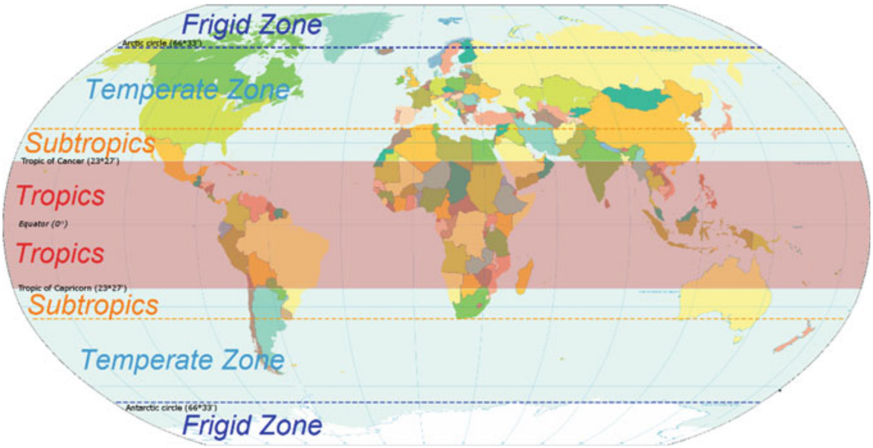

Fig. 1 World map with tropical region marked in crimson. Picture by Genetics4good/CC BY-SA 3.0

Unfortunately, the forest land keeps on decreasing due to corporate logging and mining activities, as well as deforestation by locals to obtain wood for cooking fuel and construction.

The countries that lie along the tropics are generally less affluent compared to its temperate counterparts, as can be seen in Fig. 2. Almost all tropical countries fall under the International Monetary Fund (IMF)'s category of "emerging and developing economies" [7]. As of 2019, they possess an average gross domestic product

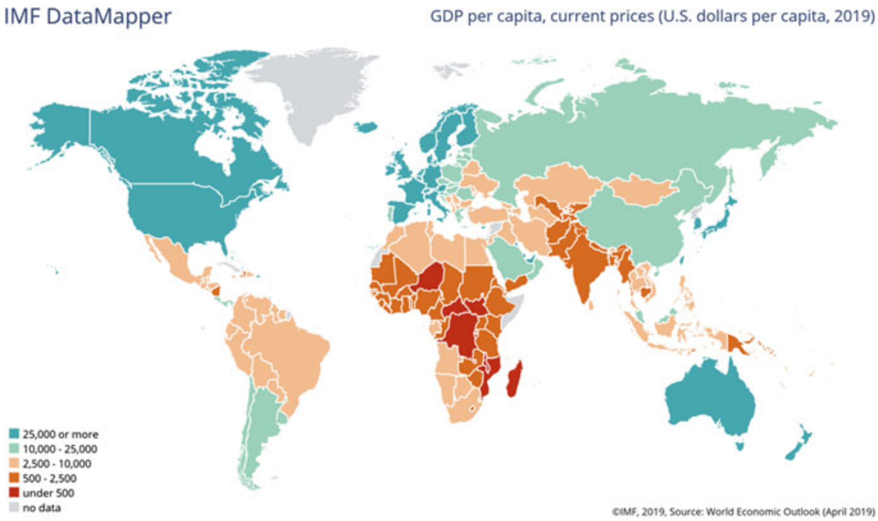

Fig. 2 Annual GDP per capita of countries around the world. *Source* IMF [7]

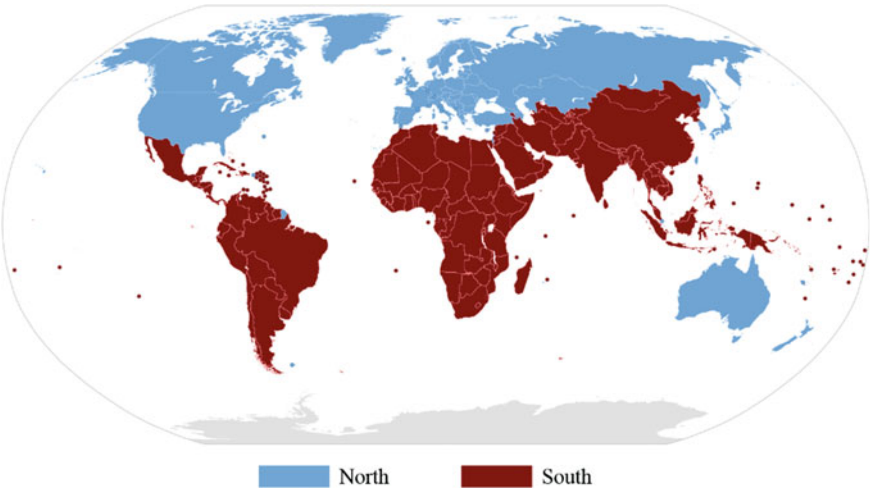

Fig. 3 Global North and Global South categorisation

(GDP) per capita of 5420 USD/year, compared to an average of 48,610 USD/year in "advanced economies" category and the world average of 11,570 USD/year [7].

These developing economies are also categorised as the Global South, as opposed to the Global North term for the developed economies as shown in Fig. 3. These terms are used to replace the less subtle terms of "first world" and "third world" countries.

Along with the income disparity, the development in the tropical countries tends to lag that in the temperate countries. This includes access to clean water, electricity, cooling, and transportation, among other indicators. Within these tropical countries, there is also a disparity in the level of development between the urban and the rural residents. The urban residents in the developing economies may enjoy almost as many amenities as those in the developed economies. However, this is not the case in the rural areas. For example, in the island of Sumba, one of the > 17,000 islands in Indonesia, more than half of its 750,000 people are off-grid, meaning that they have no access to electricity [8]. Many villagers, therefore, have to rely on dim light from hazardous kerosene lamps to carry out activities after sunset—limiting their productivity, deteriorating their health, and increasing the risk of fire.

The problems cannot be solved using the same solutions that have been used to push the development in the now-developed countries, considering the remoteness, the level of income of the remote communities and their countries, as well as the different climate, as elaborated in detail in the subsequent chapters of this book.

The remoteness brings about many challenges, such as higher transportation costs, as well as a lack of qualified manpower and specialised equipment. More importantly, each of the remote communities has its own traditions and social structures. As such, any solution must be community-centric for it to work and be sustainable.

Fortunately, more sustainable solutions are also becoming possible, mainly through the rapid advance in technologies, especially the information communication technology (ICT) and the renewable energy technologies that may allow the emerging economies to leapfrog the third industrial revolution and catch up with the developed economies. Moreover, the tropical regions also receive more consistent and higher amount of sunlight, compared to most of the developed countries. This makes the advances in solar photovoltaic (PV) technology and its consequent decrease in price particularly beneficial for the remote tropics.

2 Scope and Outline of the Book

This book is divided into two parts: Part I: ***The Energy Problems and Solutions in the Remote Tropics*** and Part II: ***Tools Enabling the Solutions and Future Development***.

Each chapter in the first part of the book covers a different type of energy problems that exist in remote tropical areas, the existing solutions and their impacts, the challenges encountered in implementing the solutions, and how to make these solutions even more sustainable. The experiences do not only cover the technical aspects of the technology but also the community and business aspects, which are rarely combined in a single book or chapter. After understanding the various problems and solutions presented in Part I, the second part of the book outlines the tools that can facilitate the deployment of the solutions elaborated in Part I.

Our intention is to make this book as a reference and a case study, where the readers who are interested in a particular problem can directly go to that chapter. Nevertheless, others who are more curious to discover the different problems and solutions, and/or are trying to find out what problems they would like to solve, are welcome to read the book cover to cover.

Although the use of energy for cooking is addressed in Chap. "Sustainable Cooking: Beyond the Cooking Problem with the Lens of Human-Centred Design", this book places more emphasis on energy in the form of electricity, especially that supplied by PV. The rationale for the focus on electricity is because the recent rapid advances in technologies, such as PV and batteries, have been in the electricity sector. It is undeniable that the transport sector in the remote areas is also in need of sustainable solutions; however, the solutions available are still emerging and there are not enough accounts to provide definitive case studies on the topic. PV is the main topic of this book because of its modularity, rapidly decreasing cost, and low carbon footprint, which make it a suitable candidate for sustainable energy solutions for the remote tropics. Compared to other renewable energy sources, such as wind and geothermal, solar energy is more widely and uniformly available in the tropics and can be implemented at smaller scales.

The context and case studies given in the different chapters are mostly about the remote Southeast Asia, as it is the world's fastest-growing region and the third-largest population (also the world's largest region if combined with South Asia), as well as because the editors' and authors' experiences are mostly in this region.

That being said, examples from other countries have also been drawn, such as that from Bangladesh in Chap. "Swarm Electrification: From Solar Home Systems to the National Grid and Back Again?". Through the case studies, the readers can appreciate what it takes to make energy solutions sustainable. The lessons from this book are also applicable in other remote areas in the tropics such as large parts of the African and the South American continent.

Some of the authors have chosen to use different terms to refer to the same or similar concepts, such as the use of mini-grid in Chap. "The Sustainability Dilemma of Solar Photovoltaic Mini-Grids for Rural Electrification" versus microgrid in Chaps. "Solar-Powered Cooling for the Remote Tropics and Assessment of Micro Grid Potential in Southeast Asia Based on the Application of Geospatial and Micro Grid Simulation and Planning Tools". The authors' choice of words has been maintained to illustrate the diversity of the terms used in the literature.

The rest of the chapters are structured as follows.

Part I: **The Energy Problems and Solutions in the Remote Tropics**

Chapter "Sustainable Cooking: Beyond the Cooking Problem with the Lens of Human-Centred Design" explains the severity of the cooking problem in many developing countries and how it exacerbates poverty, gender inequality, and health problems. Using Indonesia as a case study, the authors elaborate the available cookstoves, the stakeholders, and the existing programmes pushing sustainable cooking forward. Human-centred design processes are walked through to identify how to solve the cooking problem more sustainably.

Chapter "Solar-Powered Cooling for the Remote Tropics" compares and contrasts the cooling needs in the tropics to those in other climates. After underlining the importance of cooling, the chapter offers detailed technical descriptions of the various available solutions for each of the cooling problems in the tropics. It notes that most of the solutions are still in pilot stage. As such, more implementation cases and business models need to be developed to address the urgent needs of cooling in remote tropics.

Chapters "Swarm Electrification: From Solar Home Systems to the National Grid and Back Again?, The Sustainability Dilemma of Solar Photovoltaic Mini-Grids for Rural Electrification, and Micro-Hydro Power System" cover the problems of electricity access and how they can be solved through solar home systems (SHS) (Chap. "Swarm Electrification: From Solar Home Systems to the National Grid and Back Again?)", PV mini-grid (Chap. "The Sustainability Dilemma of Solar Photovoltaic Mini-Grids for Rural Electrification"), and micro-hydro power (MHP) system (Chap. "Micro-Hydro Power System").

Chapter Swarm Electrification: From Solar Home Systems to the National Grid and Back Again? elucidates how SHS can not only serve the off-grid population but also those who have access, albeit intermittent, to electricity. Furthermore, the authors also show the possibility and the pathway how SHS can be interconnected with and provide services to the wider electricity grid.

Chapter "The Sustainability Dilemma of Solar Photovoltaic Mini-Grids for Rural Electrification" gives insights on the details of PV mini-grids implementation based on the authors' on-the-ground experiences in Indonesia. Challenges and controversies surrounding PV mini-grids are discussed and potential solutions are elaborated.

Chapter "Micro-Hydro Power System" gives a comprehensive account of both the technical and social aspects of running successful MHP projects in remote areas with a detailed case study of the implementation of MHP in the remote Philippines.

Part II: **Tools Enabling the Solutions and Future Development**

Chapter "Assessment of Micro Grid Potential in Southeast Asia Based on the Application of Geospatial and Micro Grid Simulation and Planning Tools" gives insights how geospatial analysis and simulation tools can locate islands with microgrid potential and subsequently determine the microgrid feasibility. On top of comparing the state-of-the-art tools for microgrid planning, the chapter also sheds light on the common microgrid parameters through detailed case studies, thereby allowing readers to use them as reference for their own projects.

Chapter "Solar Project Financing, Bankability, and Resource Assessment" talks about the bankability of PV project and identifies questions that still need to be answered to further develop off-grid PV financing. The chapter then instructs how to obtain irradiance data from freely available sources and convert them to inputs required for a PV project, as well as how to handle uncertainty in the data.

Chapter "Understanding Social Impact and How to Measure it" emphasises the importance of impact evaluation and of including it since the project planning stage by identifying what data need to be collected from which groups. The procedure to apply the impact evaluation methodologies has been detailed for a rural electrification case study.

Chapter "The Grid of the Future" reassesses the current electrical grid development and contrasts it with the needs of the rural tropics. Subsequently, the chapter proposes a blueprint for the future grid consisting of smart grid cells, as well as the economic and technical pathways towards achieving it.

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The Energy Problems and Solutions in the Remote Tropics

Sustainable Cooking: Beyond the Cooking Problem with the Lens of Human-Centred Design

Tika Diagnestya and Jackie Chee Wei Yap

Abstract Many remote communities still rely on wood, charcoal, or biomass for cooking. This is unthinkable in the developed world considering how these traditional forms of cooking are exacerbating gender inequality, education gap, and even causing premature deaths through the indoor air pollution. These severe negative impacts resulting from open-fire cooking constitute the infamous cooking problem. Yet, many people, both in the developed and developing countries, still lack awareness of the problem and its urgency. This is one of the factors why people have not transitioned to clean cookstoves, despite their availability in the developing market. This chapter elaborates on the cooking problem and its impacts on the remote communities and the society. Subsequently, some of the technologies that can and have been replacing traditional cookstoves are listed. Realising that simply having the technology is not enough, this chapter provides a detailed discussion on what could be done in order to transition the biomass cookstove users to use clean cookstove sustainably through human-centred design perspective for the case of Indonesia.

Keywords Clean cookstoves · Human-centred design · Poverty · Sustainability · Sustainable cooking

1 Introduction

In this era of Industry 4.0, there are still approximately 60% of the developing country households—more than 2.85 billion people—who still rely on wood, charcoal, animal dung, and crop waste, to cook [1]. This reality is unimaginable in the developed countries such as the USA, where there are ~780,000 unit shipments of electric/gas cooking appliances in the USA alone in 2017 [2]. But even before comparing the

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disparity between the developed and the developing countries, let us investigate the disparity within the developing countries. The developing countries themselves can be categorised into the rural and urban areas. The average fuelwood reliance in the rural and urban regions of South Asia and Southeast Asia in 2013 is approximately 79.5% and 28.5%, respectively [1]. In most of the urban areas of developing countries, households have easy access to various relatively clean fuels and clean cookstoves. Although access to clean fuels or alternatives (such as liquefied petroleum gas (LPG)) may also be available in the rural regions—albeit to a lesser extent—most households do not adopt them for their primary cooking fuel. Such a gap in the solid fuel utilisation between rural and urban areas is closely related to the income inequalities [3], and the widening of the rural-urban income gap is a self-perpetuating process.

Numerous regions in Indonesia still use wood as their primary fuel source [4]. There can be many reasons why rural households have not transitioned to cleaner cooking stoves and fuels, such as financial barrier and low health awareness. In Sub-Saharan Africa, 82% of the population depend on solid fuels for their primary cooking needs [1]. The widespread use of solid fuels is probably because they are often freely available in these rural areas. Another instance is India; at the global scale, 30% of the world biomass consumers are residing in India [5]. Being the second most populated country in the world, the number of people who need to adopt cleaner cooking in India is massive and the country's development towards sustainable cooking is crucial.

The impacts of biomass cookstoves are more than just poverty. The World Health Organisation (WHO) Bulletin reported that biomass smoke contains carbon monoxide, nitrous oxides, and other particles which could damage human health as they could affect the lungs directly [6]. This adversely affects the user of biomass cookstoves who directly breathe in the toxic smoke while cooking. Furthermore, most of the time, not only the users of biomass cookstoves breathe the smoke. In most places in developing countries, the users of biomass cookstoves are the mothers. While a mother is cooking with biomass cookstoves, her children usually also come along to the kitchen. According to WHO [6], "there is consistent evidence that indoor air pollution increases the risk of chronic obstructive pulmonary disease and of acute respiratory infections in childhood, the most important cause of death among children under 5 years of age in developing countries". Another sobering point: In Indonesia alone, the toxic smoke and other indoor pollution have led to about 165,000 premature deaths every year [7]. Yet, many of these households still feel that early symptoms of respiratory illnesses are not dangerous.

Transforming these households towards cleaner cooking (both clean fuels and clean stoves) is not easy. It takes more than the government and NGO initiatives to develop sustainable clean cooking. For example, in India and Indonesia, the government has given away clean cookstoves such as LPG stoves to the solid fuel-based stoves users. From 2007 to 2012, the Indonesian government distributed ~54 million (equivalent to ~21% of Indonesia population in 2012) LPG starter kits [8] through a kerosene-to-LPG conversion programme called "Zero Kero" in order to make households convert from traditional cookstoves to clean cookstoves (see Fig. 1). Yet in 2016, there were still about 40% of households in Indonesia who still use traditional

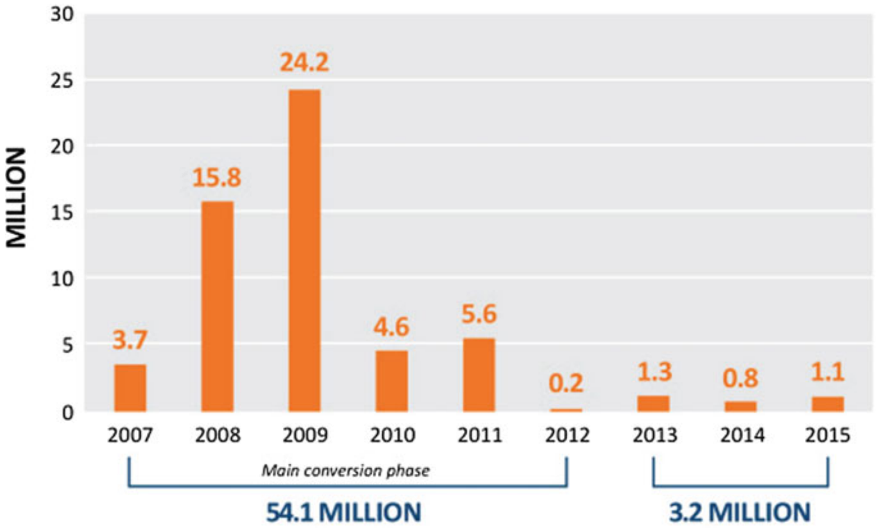

Fig. 1 Number of free LPG starter kits distributed from 2007 to 2015 as part of the kerosene-to-LPG conversion programme in Indonesia [8]

biomass fuels as one of their cooking options [9]. Some of these households use both LPG and biomass fuels for cooking in a household. From interviews conducted by Masak Bersih (MASIH)[1] in Indonesia, rural households prefer their traditional stoves (e.g. wood-fuel stoves) over the LPG stoves for various reasons, such as fear of gas explosion, expensive fuel price, and different taste of food cooked with the clean stove. This case shows how solely distributing LPG has had a small impact on the transformation towards sustainable cooking with clean cookstoves.

Thus, in this chapter, the cooking problem and what can be done to solve it are discussed. The chapter is divided into three main sections: Sect. 2 discusses the cooking problem at a deeper level; Sect. 3 gives an overview of the technologies available in the Indonesian market; and Sect. 4 elaborates the use case of human-centred design (HCD) in Indonesia, including some lessons learned from the existing solutions. Although the examples have been given for the case of Indonesia, the principles and findings from this chapter can be applied to solve the cooking problems in other countries or regions.

[1]Masak Bersih (MASIH), or Clean Cooking in English, is a social enterprise that focuses on clean cooking problem in rural Indonesia. MASIH aims to educate these rural communities on the benefits of shifting away from open wood burning and provide affordable financing options to purchase clean cookstoves that can reduce the impact of wood burning or that utilise alternative fuel options: https://d-prize.org/winners/profiles/2018/11/29/masih.

2 The Cooking Problem

Food is one of the most important elements of life; without food, people will become hungry, fall sick, and eventually die. The importance of food then leads us to the role of cooking.

Cooking is not a major problem in wealthy countries, where people barely give their quiet gas stoves or electric cookers a second thought. This leads to a lack of social awareness, which makes cooking problem look less sexy than others. Moreover, the ignorance of this cooking problem is not limited to the developed countries; in the developing countries, many of the victims do not know of the harm caused by the cooking problem either. “Millions of families need clean cooking solutions, and many of them do not even know that they face a problem”, said Rida Mulyana, Director General of New Renewable Energy and Energy Conversion Directorate at the Ministry of Energy and Mineral Resources of Indonesia [10]. This chapter is written to raise awareness about the importance of cooking problem.

The severity of cooking problem does not just affect the individuals, but also the whole economy. Energy Sector Management Assistance Programme (ESMAP) and Global Alliance for Clean Cookstoves estimated the global economic value of the negative externalities from the cooking problem to be over $120 billion annually “against a scenario of shifting all solid fuel users to high performing ICSs [Improved Clean Stoves]” [1]. It seems that an easy solution can be provided by giving free ICSs in order to shift all the solid fuel users. Yet, this cooking problem is not as easy as it seems; giving away free clean cookstoves does not solve the problem either.

According to the 180-page World Bank report published in 2014, “Three decades of efforts to promote both modern fuels and improved biomass stoves have seen only sporadic success [11]”. It implies that the cookstove users—mostly the women—still feel more comfortable with the traditional cooking methods as they have been embedded in their respective cultures. Hence, it is difficult for solid fuels users to become clean cookstoves users. Some programmes have given stoves for free and even made the women to commit in writing that they will use and not sell the stoves. However, when the auditor came, the women were using the stoves as chairs [12].

After giving some thoughts to the depth and breadth of the cooking problem, now we may think that this problem seems very hard to tackle, where shall we start? Let us dive into the following parts to understand more of the problem.

2.1 Poverty Premium: Fairness?

One of the phenomena many failed to see on the surface of cooking problem is the poverty premium in energy. The poverty premium is the phenomenon where people at the lower tier of income group pay a higher price per unit for the same types of fuel [1]. This is a vicious cycle of poverty which we must eradicate. In a study done by the International Energy Agency (IEA), there are correlations between the shares of biomass in household energy demand with the level of economic development. In Thailand, biomass accounts for 33% of household energy consumption when the per-capita income averages $2490; On the other hand, in Tanzania, with per-capita income of only $320, the share of solid fuel is a whopping 95% of household energy consumption [13]. The poverty premium in energy can be quite extreme: in 2012, the average real cost of solid fuel in Sub-Saharan Africa region exceeded the price of LPG [1]. Solving this issue requires actions from the policy makers, to prevent the poor from getting poorer.

In recent years, there has been heated discussion around the "fairness" of consumer energy markets. While "fairness" is a rational ideal, the market mechanism needs to be regulated to achieve it. Again, we ask ourselves, don't the people at the bottom of the pyramid know about the poverty premium since they have been trapped in the cycle of poverty? Unfortunately, there are other challenges. In a focus group discussion in a remote Thai village done by Warm Heart, a Thailand-based NGO, a woman mentioned, "Oh, we know all about bad smoke, but smoke is the only thing that keeps the mosquitos away. We have a choice: die now from disease, or later from smoke. We think later is better" [14].

Even though the "cooking problem" seems simple, it is only because the related issues—which threaten human lives and economic development—were not considered. To solve these issues, we need to understand all the factors affecting the households' energy preferences, such as "age, gender, education, occupation, religion, lifestyle, household size, device characteristics, and environment awareness" [15]. If we could fly a man to the moon, the authors believe that with persistence, we could tackle this cooking problem, and humanity could collectively march forward.

2.2 Women: The Victims of Time Poverty

After touching on the issue of energy poverty in the previous subsection, in this subsection, we would like to extend it to "time poverty". There are different roles for men and women, especially so in the remote regions of Southeast Asia. This applies to their household system and culture as well; the two genders have different needs, different motivations, and face different constraints. In the context of daily cooking, according to the World Bank, women generally spent more time in cooking preparation as well as in firewood collection [1].

More than one billion women, including their daughters, globally, rely on "free" solid fuels for cooking and heating [16]. The fuel used is not "free", but only non-monetized; the fuel collection process consumed arduous hours from the women. While it is perceived as "free", solid fuel may be far more expensive than modern clean cooking fuels, when the cost of time is considered [16].

There is a huge amount of time lost due to the solid fuel collection and preparation of food using the traditional cooking method. It is estimated that 60 million person years are lost annually as opportunity cost, and researchers have concluded that up to half of this time could be utilised in a more productive manner, such as farming activities and other income-generating endeavours [1]. If this time could be used for economic development, it could contribute to an increase of USD 5–30 billion for the annual household income [1].

The time lost to fuel collection, preparation, as well as the conventional solid fuel cooking, causes "time poverty", as it restricts the women's participation in income-generating activities such as farming and sewing. The time poverty is not only economically constraining but is also reducing the opportunities for women's self-actualisation. Imagine how meaningful the time available—which can be spent on childcare, education, and leisure—is to a modern female mother living in the city.

To make matters worse, many women in the rural areas do not even have access to basic financial services which we take for granted. Historically, women invest up to 90% of their income on their families [17]. Therefore, if we could invest in women's education instead of letting them stuck in the time poverty of fuel collection and cooking preparation, we could effectively solve the cooking problem and improve the opportunities for the future generation.

3 The Available Cookstoves in Indonesia

The United Nations, through the Global Alliance for Clean Cookstoves, have defined some general features that clean cookstoves should have in order to achieve the goal of reducing health damages, environmental threats, and other risks caused by usage of non-commercial biomass. Clean cookstoves must significantly reduce pollutant emissions and fuel usage, and in the case of industrial production, they should also meet international standards for performances and safety. Additionally, the stoves must meet social, material, economic, and behavioural needs of users.

Clean cookstoves can be classified according to different criteria; for instance, the Global Alliance for Clean Cookstoves identifies seven main possible categories, which are: (i) traditional ones, (ii) ones with rocket-type combustion chamber, (iii) gasifiers, (iv) charcoal burning, (v) liquid/gas fuelled, (vi) fan-assisted, and (vii) wood burning with chimneys [1]. Generally, the stoves which present the highest performances are the ones fuelled by liquids or gases, while, among the models that utilise wood or charcoal, the highest performing are the gasifiers.

Given the many types of clean cookstoves available in the world, below are some of the examples of the most common types of clean cookstoves available in Indonesia. These clean cookstoves are gathered through an in-depth interview in March 2018 by MASIH Team with Yayasan Dian Desa (YDD)[2] (translated as light of the village foundation). The scope of the interview was about the World Bank's sustainable cooking programme in Indonesia [4], *Tungku Sehat Hemat Energi* (translated as healthy and energy-saving cookstoves) in 2012. For this programme, YDD has helped

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[2]Yayasan Dian Desa is also the home to the Indonesia Clean Cookstoves Alliance, whose working principle is to spread the use of appropriate technology to provide sustainable solutions for development throughout Indonesia: http://www.diandesa.org/.

Fig. 2 Various clean cookstoves that have been evaluated by Yayasan Dian Desa

evaluate the clean cookstoves—partly shown in Fig. 2—according to the World Bank's standards. They tested the submitted stoves from around the world, which included but were not limited to the stoves listed below. The stoves were tested against standards relating to fuel efficiency, carbon monoxide (CO), and PM 2.5 emissions as well as for their suitability to be deployed in Yogyakarta province, Indonesia, the target area of the programme.

3.1 Traditional Chimney-Installed Stoves

The traditional chimney-installed stoves are the same traditional cookstoves that most people in Yogyakarta have been using. However, for the smoke to be less severe inside the house, a chimney is installed. The users do not need to learn how to use a new cookstove and the chimney makes the cooking experience cleaner. The stoves use regular size wood, the same as what has been used before. Figure 3 is an example of a cookstove with installed chimney.

Fig. 3 Traditional chimney-installed cookstove in Yogyakarta area, Indonesia. *Source* Masak Bersih

3.2 Traditional Charcoal-Based Clean Cookstoves

The traditional charcoal-based clean cookstoves, also known as *Anglo Supra* in Java, are clean cookstoves derived from the traditional stoves design. The main source of fuel used is charcoal as shown in Fig. 4. According to YDD, Anglo Supra cookstove is not a good fit for the Yogyakarta area because of the difficulty and the cost of obtaining charcoal. Moreover, since temperature is almost constant all year round, there is no need for slow radiative cooking, except for cooking satay (traditional Indonesian meat skewer).

3.3 Traditional Wood-Based Clean Cookstoves

Wood-fuel-based cookstove is another commonly used cookstove in Indonesia. One of them is called *Keren Super*. *Keren Super* is the improved and clean version of the traditional *Keren* stoves that have been used for a long time. However, for the World

Fig. 4 Anglo Supra in use in Yogyakarta area with one of the small–medium enterprise users. *Source* Indonesia Stove Alliance (Indonesia Stove Alliance was established in early 2013 to respond to the need for clean-cooking solutions for the households in Indonesia that use biomass

Bank programme, YDD also mentioned that the *Keren Super* cookstove is not a popular cookstove choice in Yogyakarta province. One of the reasons is because *Keren Super* is a one-hole clean cookstove, whereas the villagers have a tradition of making Javanese sugar (*Gula Jawa*) using multiple cook holes to make the evaporating and oxidising process faster. An effort to change the villagers' behaviour is necessary for the villagers to use this type of cookstoves. An example of *Keren Super* can be seen in Fig. 5.

3.4 Modern Wood-Based Clean Cookstoves

Modern wood-based clean cookstoves are generally coated with zinc and are more efficient in producing fire. The cookstoves use smaller wood pieces as fuel than what the traditional wood-based cookstoves use. Due to the small size of the cookstoves (see Fig. 6 for two brands of modern wood-based clean cookstoves), the cookstoves' users need to cut the wood into small pieces before putting them into the stoves. Unlike charcoal, there is plenty of small wood for sale in the programme's target area and many other parts of Indonesia. The cookstoves themselves are also lightweight compared with the other two clean cookstoves previously mentioned.

Fig. 5 *Keren Super* cookstove in use for demonstration purposes

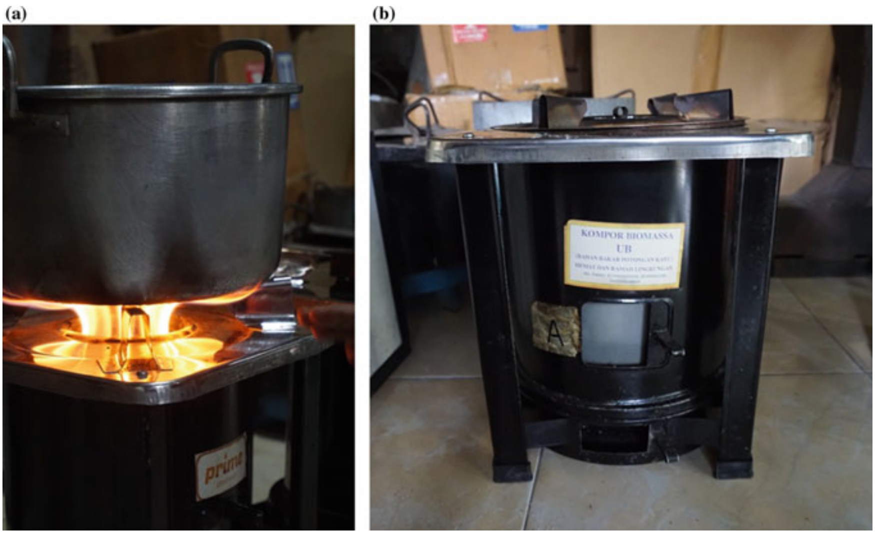

Fig. 6 **a** PRIME and **b** UB wood-fuel cookstoves during cooking demonstration

3.5 Modern Pellet-Based Clean Cookstoves

Similar to the wood cookstove, pellet cookstove is another more modern type of cookstove. These cookstoves have a similar appearance as the modern wood-based clean cookstoves, as seen in Fig. 7, but use small pellet and/or dry coconut shell as the source of fuel instead. For small pellet, cookstove users usually have to buy them, which also creates job creation in the area. Unfortunately, there are not many pellet-based clean cookstove users in Indonesia yet.

There are also users, mostly farmers, who use dry coconut shell as the source of fuel for this type of clean cookstoves. This is despite the time required to dry the coconut since wet coconut shell cannot light up the cookstove. Since these cookstoves are not yet widespread, many farmers still do not recognise the use of dry coconut shells and throw them away as waste.

The cookstoves above are just some illustrations of the available technologies. Other solutions include electric fuel solutions, renewable fuel cooking solutions, and improved biomass cookstoves, which are not explained in this subsection. Interested readers may refer to Global Alliance for Clean Cookstoves [1] for other types of cooking solutions. As stated earlier, the technology is not the main barrier to solve the cooking problem; therefore, more emphasis is placed on the human-centred design solution, discussed in the next section.

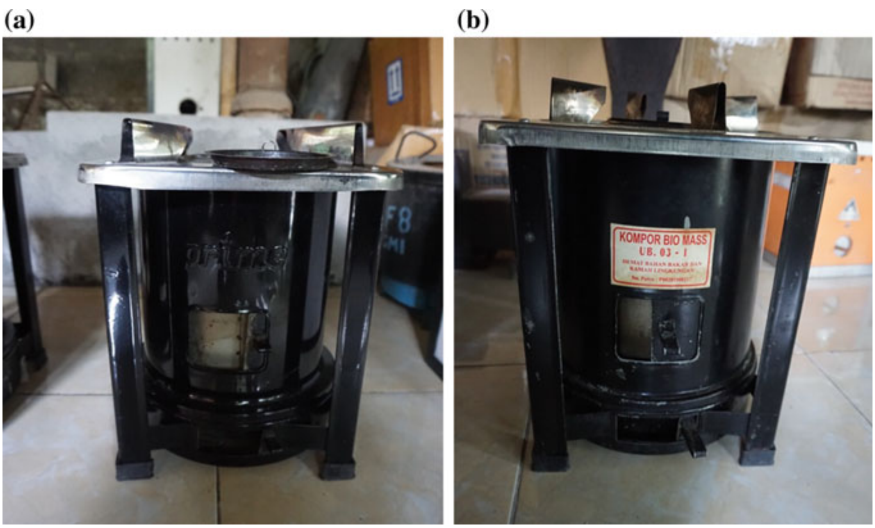

Fig. 7 **a** PRIME and **b** UB pellet-fuel cookstoves during cooking demonstration

4 Lenses of Human-Centred Design Solutions from an Indonesian Case Study

There have been several solutions to the cooking problem in the developing and developed countries. However, in transitioning from traditional cooking to sustainable clean cooking, there are many steps to take; only focusing on the final solution is not going to solve the cooking problem. Thus, it is imperative to conduct human-centred design to understand better the appropriate approach in solving the cooking problem. Human-centred design (HCD)—formulated by IDEO.org [18]—is an approach to problem solving by tailoring the solutions to suit the people whom the solutions are designed for. Before going into the details on HCD, below is an overview of the stakeholders of the clean cookstoves sector in Indonesia, which might be similar to other countries.

4.1 Clean Cookstoves Stakeholders in Indonesia

Users

The first main stakeholder is the users. The users are the one who perform the cooking activity, typically the mother/wife in the family. Users are highly impacted by the cooking problem.

Passive Users

Passive users are the one who do not cook but are located near the cooking areas. They are also impacted by the smoke from the cooking activity. Most of the time, passive users are the children in the households who play in the kitchen while their mother is cooking.

Consumers

The consumers of the clean cookstove business model can be different from the users. In the business model, the consumers are the buyers of the cookstoves, who can also be the fathers in the households.

Opinion Leaders

Opinion leaders are those who have an influential voice in a village/area. Opinion leaders can also be consumers and users at the same time. Opinion leaders can be village leaders or trusted elderly in the village.

Market Aggregators

Market aggregators are the distributors of the stoves. In Indonesia, market aggregators can be different from the producers and can sell cookstoves from more than one producer.

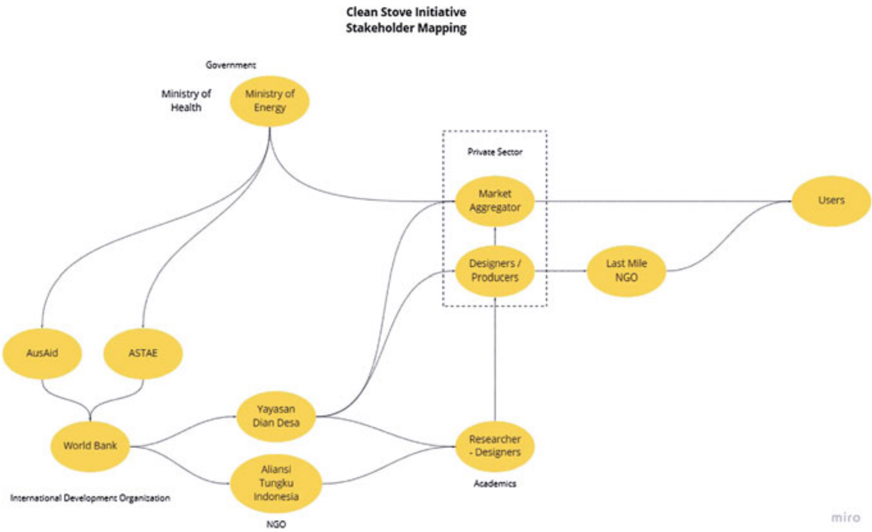

Fig. 8 Clean cookstove stakeholder mapping in Indonesia

Producers

Producers of the cookstoves are the ones who produce and test the cookstoves. In most cases, the producers only sell the stoves and not the fuel.

Public Sectors

Public sectors such as the government and non-profit organisations play a major role in defining the business model for the sustainable cooking industry. Some of the major roles are the education about the cooking problem, determining the price of the cookstoves and fuel, and implementing the public policy to encourage the transition towards sustainable cooking.

A detailed relationship of the stakeholders in Indonesia can be seen in Fig. 8. Note that the figure is not exhaustive even though it has mapped most of the stakeholders found during the HCD research conducted by MASIH. More stakeholders not mentioned in the figure, as well as other changes, might appear in the future.

4.2 Human-Centred Design for Clean Cookstoves Sector in Indonesia

In applying HCD to achieve better solution to the cooking problem in Indonesia, the following phases have been carried out by MASIH. The following subsections will walk the readers through the whole HCD process conducted by the author. Although there is room for improvements to the approach, many insights can still be obtained.

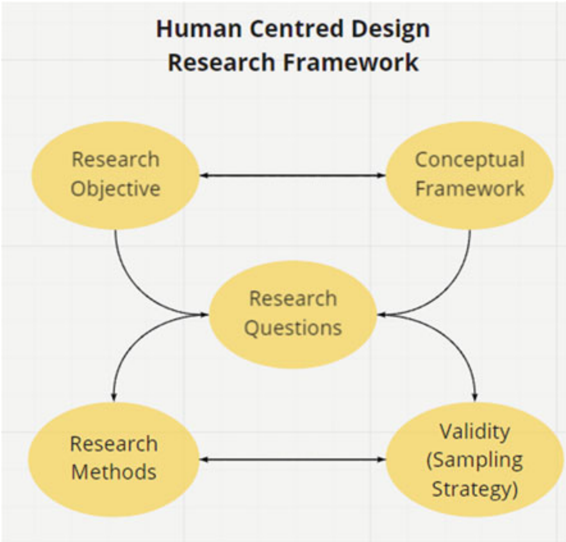

Fig. 9 Human-centred design research framework

4.2.1 Inspiration: Defining the Hypothesis

An example of the HCD research framework can be seen in Fig. 9. The insights of the HCD come from answering the research questions, which in turn are derived from the research objective, the conceptual framework, the research methods, and validity (sampling strategy). All the aspects are correlated with one another to answer the research questions.

In determining the research questions, iteration process is key. While iterating, we always need to keep in mind our objective, conceptual framework, methods, and sampling strategy. The conceptual framework can be started by analysing what has been done through desktop research and in-depth interviews. Through the desktop research, we found some key clean cookstoves initiatives which had been done in Indonesia, such as the initiative by World Bank, which was supported by the Indonesian Ministry of Energy and Mineral Resources, Asia Sustainable and Alternative Energy Programme (ASTAE), and Australian Aid. The authors hypothesised that there are four key issues in the programme, which are the cultural acceptability, affordability, availability, and accessibility (illustrated in Fig. 10).

These four key issues became one of the hypotheses to be tested on the HCD. Are these four key issues the reason why people do not transition to clean cookstoves? Or are there other reasons why there are still so many people who do not use clean cookstoves? After deriving these hypotheses from the desktop research, the research objectives can be developed further as outlined in Table 1.

Fig. 10 Four key issues of the World Bank's clean cookstove initiative in Indonesia

Table 1 Detailed objectives and hypotheses of the HCD

Objective	Hypothesis
To understand the challenges of clean cooking behaviour in Indonesia	Users do not believe that their normal behaviour is unhealthy
	Educating about negative health impact is not useful
	Clean cookstoves require the users to spend money that they do not have
To understand previous and existing initiatives' success and challenges	Challenges: a. Difficulty in ensuring sustainable use and convincing the users to buy b. Bad agent communication to deal with local issues c. Lack of availability of low-cost/free substitutes d. Stove was not designed for users' needs
	Success: a. Demos were very helpful in convincing the users that cookstoves worked b. Clean cookstoves that required little or no change in behaviour are the ones that are still used c. Creating a sense of community from the clean cookstoves users is important d. Targeting users that will benefit economically from using clean cookstoves is effective

4.2.2 Pre-immersion Phase: In-Depth Interviews

As one of the objectives of the HCD is to understand the success and challenges of previous initiatives, in-depth interviews with the key stakeholders of the previous initiative need to be done. In this case, the interview was conducted with *Yayasan Dian Desa* (YDD) on the World Bank's project in helping Indonesia transition towards clean cooking. The project sets a challenge for cookstove producers in Indonesia to produce a healthy energy-saving stove (*Tungku Sehat Hemat Energi/TSHE)*—where World Bank asked YDD to evaluate the effectiveness of these TSHE. YDD's evaluation was based on several standards and indicators, such as the energy-saving aspect. The project was carried out over a year, where market aggregators distribute cookstoves in Yogyakarta province, some areas in Central Java, as well as areas in East Nusa Tenggara.

The challenges of the project that were uncovered through the in-depth interview are:

Education

The majority of people in Indonesia do not know the negative health impacts of biomass cooking or indoor air pollution. The lack of education regarding the health impact leads to challenges in communicating and socialising the project goal to the community. In fact, there is generally a lack of health and hygiene education in most of the rural areas. Furthermore, the majority of the traditional cookstoves users also do not know the potential cost savings that they can obtain by using clean cookstoves.

Price

The price of LPG is only subsidised in Java island. Indonesia government's subsidised LPG and kerosene-to-LPG conversion programme in 2014 have raised awareness about clean cookstoves. However, maintaining those users to keep using LPG is tough due to unstable and high prices of LPG outside Java.

After conversion to clean cookstoves, only a small percentage of users continue to cook with the clean cookstoves. One of the highly probable reasons is the low price of the stoves. As the stoves were given out at subsidised prices or even for free, many people took it for granted and end up not using the stoves at all.

Culture

Another possible reason why user does not use the clean cookstoves after the programme is due to a lack of understanding how to use the stoves. Some of the users find the clean cookstoves difficult to use as they are only familiar with the traditional or biomass stoves.

In helping the users and consumers transition to clean cookstoves, each region needs a personalised approach. In Indonesia, different areas have different cultures, beliefs, traditions, and even types of food to cook. Thus, the different factors in each area need to be considered to ensure sustainable clean cookstoves conversion.

Other than challenges, our objective is also to learn from the successes of the World Bank project. The following are the lessons learned from the project:

Start small and expand

Understanding the customers and the relevant stakeholders will help in achieving the goal of the project. The Indonesia Cookstoves Alliance (*Aliansi Tungku Indonesia*) has the credential and the relevant network in the clean cookstoves industry. First, target a small group of customers and focus in getting them to convert to clean cookstoves. It is easier to expand the customer base after a successful pilot.

Localise the solution

Every area has its own characteristic of cooking and food preferences. Each user needs to learn how to use the new cookstove to make them feel comfortable and continue using the cookstove. As such, every location needs its own approach.

4.2.3 Immersion and Ideation: Getting to Know and Insights

After completing one of the HCD objectives, we need to tackle the other objective: to further understand the challenges of clean cooking behaviour in Indonesia. In order to accomplish this objective, an initial immersion HCD method from IDEO was applied. In this initial phase, we need to immerse ourselves in some beneficiaries' lives surrounding the traditional and clean cookstoves ecosystem and to learn directly from these beneficiaries and to deeply understand their needs.

The beneficiaries are around the Yogyakarta project area. The immersion experience included several profiles of beneficiaries:

- Business owners who use clean cookstoves
- Business owners who do not use clean cookstoves
- Households who use both traditional and clean cookstoves
- Households who do not use clean cookstoves.

The findings gathered during the immersion phase are then synthesised at the HCD ideation phase. From this process, insights regarding the users' experience, as well as answers to the questions, such as why some people transition to clean cookstoves and why some people do not, were obtained. The following are the key insights concluded through the immersion and ideation phase:

More-than-one-hole stove

Almost all the portable clean cookstoves available only have one hole. In Java island, most people cook with two-hole stoves. People care about saving their time during cooking and wood collecting, and that is why people want more than one hole.

Thus, some users chose to install chimney (see Fig. 3) in order to reduce the indoor air pollution, rather than using the portable clean cookstoves. That way, the users can still use the traditional cookstoves and have less smoke in the kitchen.

During the immersion phase, it was found that there are more chimney cookstove users than the portable clean cookstove users. This might be due to the ease of use in using chimney cookstove; the users of traditional stoves do not need to learn how to use a new stove.

Convenience of the cookstove and of the fuel

The driver to use LPG, when it is available and affordable, is the convenience that cannot be attained using other cooking fuels. With the LPG stove, users are able to turn on and off the stove easily, even to start the fire prior to cooking. Meanwhile, the cookstoves which use wood fuel, pellet, and other types of fuel are not as convenient.

However, there are still some who are reluctant to change to LPG stove. Some of the reasons found during the immersion phase are pride, tradition, safety, and cost. In Indonesia, some people use traditional cookstoves with pride because of its long-lived tradition from one generation to the next. There is also a safety issue, since there are several instances where LPG stoves cause fire in households.

Since wood is available for free, some villagers prefer to use wood as their main cooking fuel. The collection of the wood is not considered as a burden to them even though it may take half a day to collect enough wood. In many places in Java, where there is abundance of wood around the villages, the preference for wood-fuelled cookstoves is even more prevalent.

Cleanliness might be more important than health

Even though health deterioration from indoor air pollution is a serious negative externality, many people do not consider this as a reason to transition to clean cookstove. Some of the users are more concerned about their kitchen becoming dirty because of the smoke and their body becoming smelly because of the cooking. They are concerned about how their kitchen, including the kitchen ceiling, turns darker or black.

Approach using familiarity

In order to introduce a new concept of clean cookstove to the society, the idea is more welcomed when introduced and supported by the villagers' group. In villages, there are usually group of farmers, group of females or religious groups, who usually meet regularly. These meetings have been the best approach to introduce the clean cookstoves. In most cases, endorsement from the opinion leaders or from people that are trusted in the village can lead to faster social acceptance of and transition towards clean cookstoves.

Another point to consider in introducing the clean cookstoves is the feature of the cookstoves themselves. It is found that as long as the method of using the clean cookstove is familiar to the users, they will continue to use the cookstove. This is why installing the chimney has been more sustainable than the portable clean cookstoves.

Based on the insights obtained in the ideation stage, solutions that are more suitable for the beneficiaries can be thought of and prototyped.

5 Conclusion

Cooking problem is a problem that caused more than poverty, but also gender inequality and health issues. Although it is and has been a serious problem in developing countries, the awareness of this problem is still low. This might be because the impact of the problem is indirect. However, the severity of the impact and of the problem is high.

Despite the availability of clean cookstoves in the developing countries, the cooking problem remains unsolved. There are still many challenges in making the traditional cookstove users to transition to clean cookstoves. The technology available for sustainable cooking is not limited to portable stoves; it has been found that installing chimney to existing cookstoves can be more effective in reducing indoor air pollution due to ease of acceptance by the users.

Based on the existing problems and solutions, a human-centred design (HCD) was done for the case of Indonesia to enrich the understanding on the cooking problem and on how to move towards sustainable cooking. Through the inspiration and pre-immersion phases, we have gained insights to be tested in the later phase of HCD. Subsequently, the immersion phase is about understanding and empathising with the traditional cookstove users at a deeper level.

After doing the immersion phase, the ideation phase is where the researchers need to make sense of what have been learned, identify opportunities for the design, and prototype possible solutions (if applicable). The main learnings are willingness to adopt more-than-one-hole cookstove, the importance of convenience of the cookstove and fuel, cleanliness is a bigger concern than health, and familiarity approach.

The last phase of the HCD is the prototype phase. Objective of the prototype or implementation phase is to bring the solution to life, and eventually, to market—where we have kept the very people we are looking to serve at the heart of the process.

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Solar-Powered Cooling for the Remote Tropics

Christoph Luerssen, Chandra Sekhar, David Cheong and Thomas Reindl

Abstract Cooling is a necessity in the remote tropics to ensure access to safe vaccines, a functioning food supply chain, and thermal comfort in crucial medical facilities, as well as during extreme heat events. However, the operation of standard electrically powered cooling equipment remains a challenge in those areas due to unreliable electricity grids, if they are even present. Therefore, solar-powered cooling is a promising option, as it can operate independently from the grid. The solutions include solar-powered refrigerators for domestic and commercial use as well as vaccine storage, solar-powered cold storages and ice makers to serve the first mile of the food supply chain, and solar-powered air conditioners to cope with heat waves. Despite the variety and complexity of the system configurations and products, the technology is ready to be implemented. Nevertheless, a wide implementation has not yet been achieved due to a lack of viable business models. However, locally adapted business models, in combination with suitable system configurations/products, have the potential to create large impact in various parts of the remote tropics.

Keywords Air conditioner · Cold storage · Cooling · Ice maker · Off-grid · PV-powered cooling · Refrigerator · Remote

1 The Need for Cooling

Cooling has become a part of all our daily lives and is used in a wide variety of applications; in some situations, we feel and appreciate it, while in others it happens

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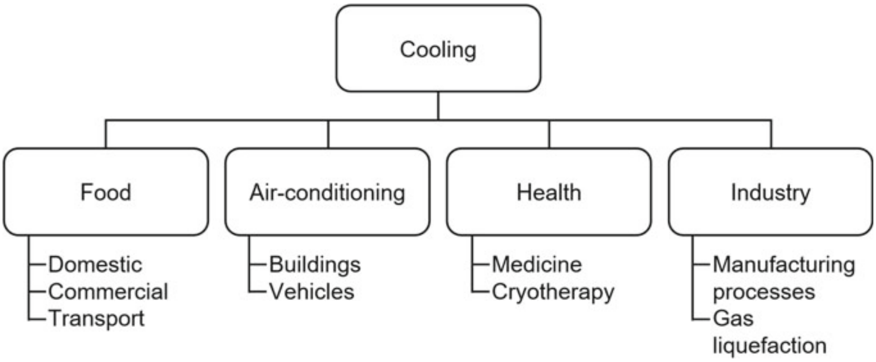

Fig. 1 Cooling applications sorted into four categories: food conservation, air conditioning, health, and industry

in the background. For example, cooling is used for conservation of food along the supply chain, including domestic refrigeration of food. It is also used for air conditioning of buildings and vehicles as well as for industrial processes. Another indispensable use of cooling is to ensure the preservation of medicine, especially vaccines. The multifarious applications of cooling are listed in Fig. 1. In recent years, cooling has become even more important with increasing world population, globally rising temperatures, and a globally growing middle class.

The world population has reached 7.7 billion in 2019 and is predicted to reach 10.9 billion by 2100, with the major population growth in hot climates (hot-humid and hot-dry, as listed in Fig. 5) [1]. The population growth is particularly high in the areas that are already suffering from low food quality and food supply shortage due to underdeveloped food supply chains. The lack of access to cooling in the supply chain (and in households) causes high food wastage in those areas. The Food and Agriculture Organization (FAO) of the United Nations (UN) [2] suggests that the worldwide food wastage (good quality food that is discarded at retail and consumption stages) and food loss (food that spoils before it reaches the consumer) along the supply chain is approximately one-third of the total food production. In the tropics, i.e. hot (and humid) climate, fruit and vegetables have a very short shelf-time if not cooled. In rural areas, where farms and food production hubs are located, cooling is often unavailable due to the lack of access to electricity and high investment required for cooling equipment. Therefore, providing cooling for food conservation is of key importance in times of growing world population. Food wastage is no longer acceptable when food demand is growing.

In addition to the need of cooling in order to feed the world population, global warming makes cooling a necessity to survive extreme heat waves in certain parts of the world. Temperatures exceeding 40 °C put the most vulnerable part of the population, newborns and elderly, at risk. In May 2018, at least 65 people died due to extreme heat in Pakistan [3]. Similarly, in India, over 4000 heat deaths were reported from 2013 to 2016 [4]. While people in tropical areas suffer the most, heat waves also become a concern in Europe where temperature records of 42.6 °C in France and

41.5 °C in Germany were measured in July 2019 [5]. Furthermore, air conditioning is indispensable for health institutions, such as hospitals and elderly homes.

Additionally, the growing middle class, especially in countries such as India, China, and Indonesia, who can afford refrigerators and air conditioners will cause a drastic increase in global energy consumption. Sustainable Energy for All recently described the situation in four categories and determined their population size. The data obtained from the report “Chilling Prospects: Providing Sustainable Cooling for All” from “Sustainable Energy for All” [6] was listed in Fig. 2.

According to the report [6], **The Rural Poor** are mostly farmers without access to a cold chain for their harvest, which leads to low quality products; thus, the products cannot be sold at higher prices. They live in poverty and do not have access to electricity. Moreover, spoiled vaccines cause health risks. **The Slum Dwellers** may have intermittent access to electricity, which causes food spoilage, even though they may own a refrigerator, which consequently also leads to high food poisoning risk. Fortunately, access to safe vaccines is mostly guaranteed, due to the proximity to the city. **The Carbon Captives** are on the edge of being able to afford the cheapest air conditioner, which is typically the least energy-efficient choice. Due to the large size of the group, it poses a serious risk for increase in greenhouse gas emissions. **The**

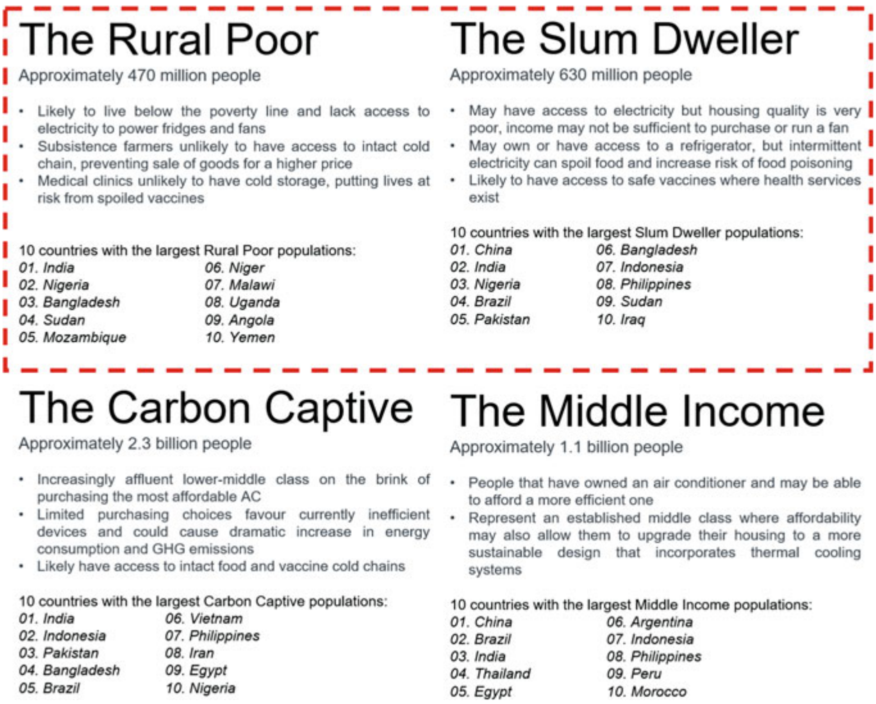

Fig. 2 Categorisation of the main population groups that are going to adopt cooling devices and their size as well as their global location; adopted from “Chilling Prospects: Providing Sustainable Cooling for All” from “Sustainable Energy for All” [6]

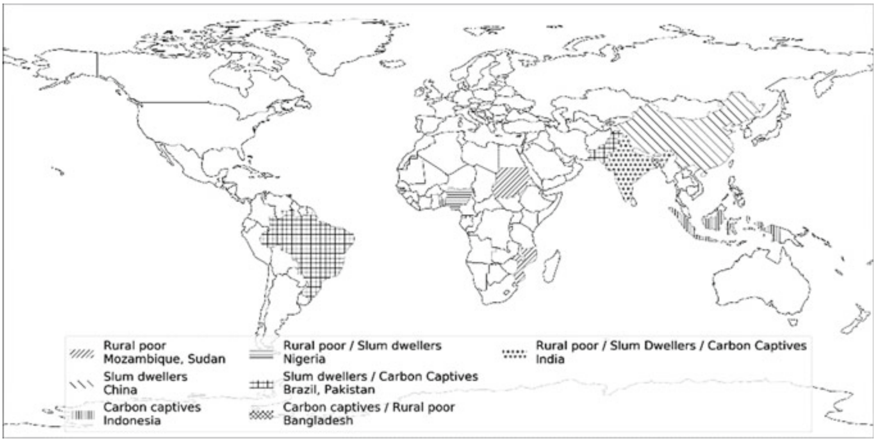

Fig. 3 Geographical distribution of the countries affected by high demand for cooling equipment using the four categories, **The Rural Poor**, **The Slum Dwellers**, **The Carbon Captives** and **The Middle Class**. For each country only the largest groups are indicated Adopted from "Chilling Prospects: Providing Sustainable Cooling for All" from "Sustainable Energy for All" [6]

Middle Income are in a better position; they are able to replace their air conditioner with a more efficient model and keep the operation hours short. Moreover, they may be able to improve their houses to minimise the usage of air conditioning further. The geographical distribution of the categories is shown via world map in Fig. 3, where the most affected countries are indicated. For each country, only the largest groups are highlighted. It can be seen that nearly all are close to the equator, which means that those countries experience tropical or sub-tropical climate. As this book targets the remote tropics, special attention is paid to the **The Rural Poor**, while **The Slum Dwellers** (framed in red in Fig. 2) are also discussed. Together, they make up 1.1 billon people.

Nevertheless, **The Carbon Captives** and **The Middle Income** are 3.3 billion people combined. The reason why the carbon captive and the lower middle-class categories are so massive is that the economy in the affected countries is growing. The economic growth is caused by increasing manufacturing, production, and other industries. The factories/companies move to those countries for more "favourable" price of labour, commodities, and electricity. This industrial growth requires machines that often need to be cooled as well. Therefore, energy-efficient cooling for manufacturing is also important.

Although the developed world is not the topic of this book; however, to give an overview of the "cooling problem" and for comparison with the rural tropics, the development of the cooling demand in the developed world shall be covered briefly. The developed world gained access to refrigerators a long time ago. Moreover, the growth of industry and manufacturing occurred much earlier. Cooling of buildings was not necessary, because of moderate temperatures in mostly temperate climates. In order to supply the unavoidable cooling needs in temperate climates, namely food conservation and cooling in the industry, efficiently, energy efficiency classes for refrigerators have been implemented and energy efficiency efforts have been conducted in the industry.

This could decrease the overall cooling demand. However, the use of air conditioners for cooling of buildings has increased significantly in the recent years. This may be due to a few hot summers in a row, or increasing advertisement from air conditioning companies, or increased thermal comfort demand from the people. Nevertheless, the use of cooling systems in new buildings is especially notable. Those cooling systems are incorporated at the planning stage. This does not have anything to do with a few hot summers, but with a change of architecture style. Windows are getting larger and larger, and sometimes even entire glass facades. and glass towers are built. It is obvious that those greenhouse-like buildings cannot provide thermal comfort for people without utilisation of cooling systems: the solar heat gain through the large glass areas is simply too big.

The narrative about the developed countries in temperate climates has served to show that energy-efficient cooling equipment technology is not the Holy Grail by itself, and energy-intensive cooling needs to be avoided where possible. In particular, reduced air conditioning space and operating hours are very effective ways to decrease energy consumption. Those are the lessons that can be learnt for developing countries to avoid making similar mistakes. Therefore, to reduce the cooling demand in the developing countries, simple building material measures, passive design and standards (e.g. buildings codes), or even avoiding the use of air conditioning equipment, must be emphasised.

Having looked at the different cooling applications and the number of people in need for cooling, we can now appreciate the increase of annual electricity demand for space cooling (i.e. air conditioning) in TWh from 2016 to 2050 worldwide from Fig. 4. The baseline scenario indicates a steep increase from 2020 leading to an annual electricity consumption of over 6000 TWh in 2050, which increased more

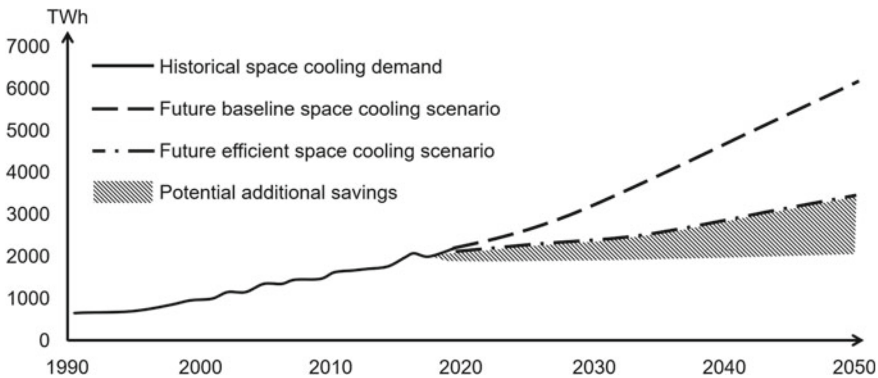

Fig. 4 Annual electricity demand for space cooling from 2016 to 2050 in a baseline scenario, an efficient scenario, and a scenario incorporating potential additional savings Adopted from "The future of cooling" report from the International Energy Agency (IEA) [7]

than threefold compared to that in 2016. As this business-as-usual case (baseline scenario) would require a massive additional power generation capacity, the International Energy Agency (IEA) has also developed an efficient cooling scenario in their "The Future of Cooling" report [7], in which there would still be an increase of 1500 TWh in cooling demand by 2050. It means that an increasing cooling demand cannot be avoided, which aligns well with the finding in [6] discussed earlier. It is important to be aware of the assumptions that have been incorporated in the efficient cooling scenario, which include, among others, doubling of the efficiency of the cooling equipment. The indicated potential additional savings span across building structure/façade material improvements and higher indoor temperature settings. In order to meet the efficient cooling scenario or even the potential additional energy savings in real life, significant technological advances and regulatory efforts (e.g. building codes) are paramount.

On the one hand, keeping the cooling demand as low as possible and using energy-efficient equipment are important. On the other hand, the energy supply also needs to be taken into account. If the increase in cooling demand is supplied by fossil fuels, the vicious cycle of global warming will be accelerated. Hence, fossil fuels are not an option and renewable energy supply has to be utilised to meet both the additional and existing cooling demand over the next decade or so. While renewable energy capacity increase is seldom a problem in well-designed grids in developed countries, additional challenges may arise in unstable and unreliable grids in developing countries. In fact, a higher increase in cooling demand will occur in the developing world, where access to energy is often limited or even non-existent.

In remote areas, different or adjusted solutions may be required to enable access to cooling for **The Rural Poor**. Even though **The Slum Dwellers** are located closer to the cities, unreliable electricity supply may also require tailored cooling solutions.

According to the "Renewables 2019 Global Status Report" from "REN21" [8], close to 1 billion people still do not have access to electricity. While the portion of the population with access to electricity is a risk for greenhouse gas emission increase due to purchase of cooling equipment, the 1 billion people without electricity access are the ones left behind, who really need electricity for basic energy services and refrigeration.

To sum up, the growth of the cooling demand is unstoppable given the growing population in the tropical belt and the rising temperatures due to the climate crisis. At the same time, the sharply rising cooling demand must not be supplied by energy from fossil fuels to escape the vicious cycle of global warming. Furthermore, the remote and unconnected areas where cooling is and will become even more of a necessity bring additional challenges due to unavailable or insufficient electricity grid infrastructure.

Sustainable Energy Solutions for Remote Areas in the Tropics are required for the following cooling-related needs:

- Uninterrupted cold chain for vaccines.
- Domestic and commercial food conservation.
- Food storage for harvest, fish, meat, etc.

- Ice for fish transport and storage.
- Thermal comfort in medical and other crucial facilities.
- Cooling of high indoor temperatures (caused by poor housing quality).

Those needs have to be fulfilled in a remote environment, which may imply limited, intermittent, or no access to electricity.

2 Technologies to Solve the Problem

There are two approaches to provide cooling: active and passive. While active cooling requires external energy input of some form, passive cooling does not require any energy input. The main technology groups for active and passive cooling are listed below:

Passive cooling	Active cooling
• Cool paint for roof and walls	• Forced ventilation
• Natural ventilation	• Evaporative cooling
• Passive design strategies	• Refrigeration

Passive cooling can be realised by using cool paints[1] with a high reflectivity to prevent heat from entering the building/house. Moreover, natural ventilation can enable a fresh air draft in the house. Various passive design strategies such as overhangs and self-shading bring additional benefits. The simplest active cooling technology is forced ventilation in the form of fans. In dry climates, spraying water on a stream of dry air (low relative humidity) can utilise the evaporative cooling effect to provide thermal comfort in building and reduce the energy demand for cooling. The most energy-intensive cooling technology is refrigeration. Refrigeration is enabled by thermodynamic cycles driven by mechanical energy (from electrical motors) or heat as input and cold thermal energy as usable output. Heat is a waste product from those cycles, e.g. absorption and vapour-compression cycle, which increases the surrounding temperature even more. The most common thermodynamic cycle is the vapour-compression cycle, which can be found in nearly all refrigerators and air conditioners.

In general, passive cooling should be preferred over active cooling to save energy, whenever possible. In Fig. 5, the technologies have been matched with the problems identified in Sect. 1, taking into account the variations under the different climates. For the tropics, the column hot-humid climate is most relevant. However, parts of the tropics are also less humid. Therefore, hot-dry (typically desert regions with cold

[1]Cool paints are coatings that reflect a major portion of the solar radiation and hence reduce the absorption of solar radiation. The result of applying cool paint to the roof (and walls) is lower indoor temperatures. Typically, the coating colour is white and/or contains special reflective pigments.

	Hot-humid	*Hot-dry*	*Temperate*
Uninterrupted cold chain for vaccines	Thermal energy storage for transport **Refrigeration**	Thermal energy storage for transport **Refrigeration**	Thermal energy storage for transport **Refrigeration**
Thermal comfort in medical and other crucial facilities	Natural ventilation Passive design Cool paint Forced ventilation **Refrigeration**	Natural ventilation Passive design Cool paint Forced ventilation Evaporative cooling **Refrigeration**	Natural ventilation Passive design Cool paint Forced ventilation **Refrigeration**
Food storage for harvest, fish etc.	**Refrigeration**	Natural/forced ventilation at cold nights Evaporative cooling **Refrigeration**	Natural/forced ventilation during winter and at night **Refrigeration**
Ice for fish transport and storage	**Refrigeration**	**Refrigeration**	**Refrigeration**
Domestic and commercial food conservation	**Refrigeration**	Natural/forced ventilation at cold nights Evaporative cooling **Refrigeration**	Natural/forced ventilation during winter and at night **Refrigeration**
Cooling of high indoor temperatures (caused by poor housing quality)	Natural ventilation Passive design Cool paint Forced ventilation **Refrigeration for extreme temperatures**	Natural ventilation Passive design Cool paint Forced ventilation Evaporative cooling **Refrigeration for extreme temperatures**	Natural ventilation Passive design Cool paint Forced ventilation
	Hot-humid	*Hot-dry*	*Temperate*
	Poor	→	**Rich**
	Developing	→	**Developed**
	Expensive solution	→	**Cheap solution**

Fig. 5 Suitable technologies for cooling applications in different climates; low/no energy technologies in non-bold and energy intensive technologies highlighted in **bold**

nights) and temperate (four seasons, mostly already developed countries, not at the equator) were added to the table for comparison.

Figure 5 lists the relevant cooling-related problems. They are sorted by their importance to the affected people, starting with cold chain for vaccines and ending with high indoor temperatures. The suitable technologies to address the problems are matched with the different climates. If more than one technology can be used, they are sorted by energy intensity in the specific cells, starting with the lowest (i.e. the recommended order of application).

The technologies, which have been categorised into active and passive previously, are now matched according to different problems and climates. However, here the two categories are "energy-intensive" (bold) and "no/low energy" (non-bold) are used. The "energy-intensive" category is solely for refrigeration technologies. All other technologies are either passive (no energy) or only require low energy consumption (e.g. fans and/or pumps).

It can be seen that for the hot-humid climate, fewer low-energy options are available. Due to the higher temperature and humidity, refrigeration is the only choice for cooling along the different stages of the food supply chain. However, for thermal comfort, fans, cool roofs/walls, and selection of housing materials can make huge impacts and help to avoid purchasing of refrigeration-based air conditioners. Even though passive measures should be preferred to provide thermal comfort, they may not always be sufficient, especially for medical facilities and under extreme weather conditions, which are expected to occur more frequently in the future.

The developed countries in temperate regions have more choices for cooling technologies that consume overall less energy. Desert regions have the advantage of cool nights and the possible use of the low-energy option called evaporative cooling which has a big potential. In tropical regions, the choices are few and refrigeration is crucial for development.

Moreover, remote regions in the tropics induce additional challenges. The active cooling technologies, i.e. fans and refrigeration devices, have to be operated on unstable and unreliable electricity grids or even without access to the electricity grid. While active cooling technologies can be powered uninterruptedly from the electricity gird in developed countries, in the remote tropics alternative power supply solutions have to be developed/utilised.

"Sustainable Energy for All" lists potential solutions for the rural poor in their "Chilling Prospects: Providing Sustainable Cooling for All" report [6]:

- Off-grid solar home systems to support fans, refrigerators.
- Cold storage and pre-cooling for transportation and sale of goods.
- Solar refrigeration and "last-mile" transport for vaccines.
- Public cooling centres and local heat action plans.

The use of refrigeration equipment should always be the last option, due to the high energy consumption. Nevertheless, as laid out before, refrigeration equipment cannot be avoided in many situations in the tropics, especially in the food supply chain, hospitals, etc. Therefore, "Sustainable Energy for All" lists solar-powered refrigeration equipment among the potential solutions. In fact, the majority of areas that need cooling the most are located in the tropical belt where solar energy is an abundant resource. Hence, solar-powered cooling is the logical and obvious solution to the problems. However, applications of stand-alone solar-powered cooling equipment imply various challenges that on-grid systems do not face.

Before discussing the challenges of off-grid solar-powered cooling in greater detail, a brief overview of the available technologies is given. In Fig. 6, the two approaches to solar-powered cooling are shown: solar thermally driven cooling, where heat is used to run a heat-activated chiller (e.g. sorption technologies), and solar-photovoltaic (PV)-powered cooling, where electricity from solar PV system is used to run a mechanically activated vapour-compression chiller.

Until the early 2000 s, research focussed nearly exclusively on solar thermally driven cooling, because the price for PV systems was still very high. However, thanks to the large-scale deployment of PV worldwide; the prices have dropped rapidly, which makes solar PV-powered cooling the more cost-effective technology today. Moreover, the vapour-compression chillers in the market have reached higher Coefficients of Performance (COP) recently (roughly in the range of 4–8 or higher,

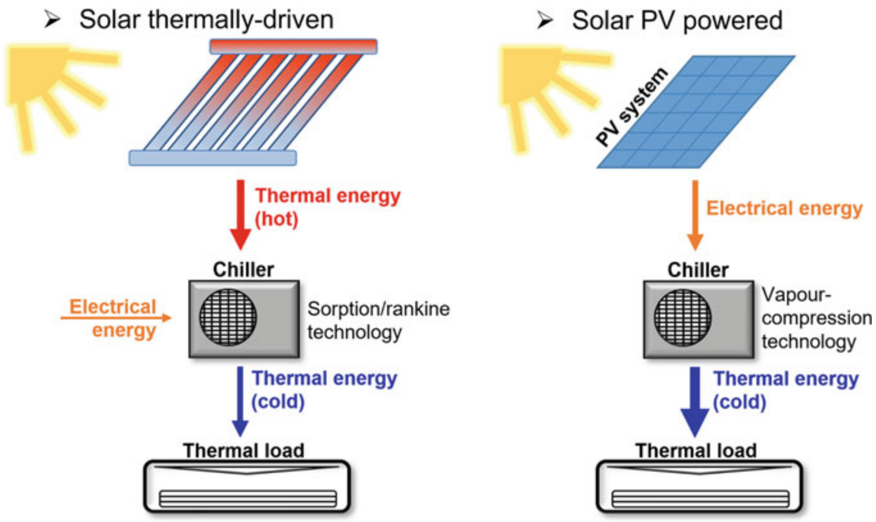

Fig. 6 Schematic of two solar-powered cooling principles: solar thermally-driven cooling (left) and solar PV-powered cooling (right)

depending on the scale and temperature difference), which brings further economic advantages for the PV-powered cooling solution. On the contrary, the price for solar thermal collectors has not decreased as quickly and the sorption chillers cannot reach comparable high COP, restricted by thermodynamic laws.

Moreover, vapour-compression chillers are more widespread in the market. Most refrigerators, air conditioners, and chiller plants use vapour-compression cycle equipment. Even in the developing countries, installation manpower that can handle vapour-compression chillers can be found. Furthermore, solar PV also requires less maintenance than solar thermal does. For sorption chiller technologies, specialised staff would need to be trained for installation as well as for maintenance and repair. This makes their implementation particularly difficult in remote areas, where the importing/training of specialised staff can be very costly and time-consuming. Although solar thermally driven cooling may still be an option for some large-scale applications for certain selected cases in developed areas, it is not the technology of choice for the remote tropics. In conclusion, PV-powered cooling is a promising solution to meet the cooling needs in the remote tropics without or with limited access to the electricity grid.

Because of its prominence and for convenience, the term “solar PV”, “PV” and “solar” will be used interchangeably in the remainder of this chapter.

PV-powered cooling systems can be realised in various system configurations. In remote areas with intermittent access to or without the electricity grid, energy storage plays an especially important role. Figure 7 shows an overview of possible systems configurations and illustrates their diversity. In an on-grid scenario, a PV system may supply energy for cooling (1a); however, when power outages occur,

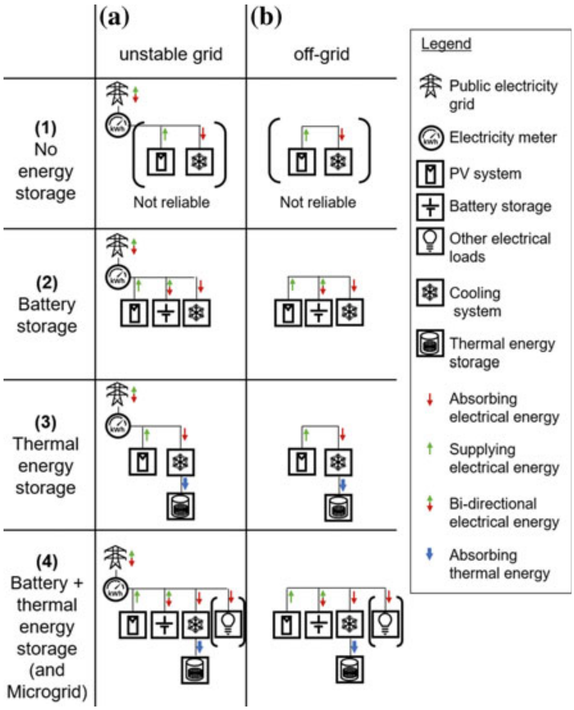

Fig. 7 System configurations for solar PV-powered cooling systems with unstable grid (**a**) and without grid access (**b**) and the integration of different energy storage systems Adopted from Luerssen et al. [9]

on-grid PV systems shut down as well, which does not allow for uninterrupted cooling. Furthermore, on-grid PV systems also shut down when the grid voltage, and frequency do not stay in certain tolerance bands. Therefore, reliable PV-powered cooling cannot be provided.

In an off-grid scenario, direct PV power supply for cooling without storing the energy for times where there is no sufficient sun (i.e. nights, rainy days, cloudy days) cannot guarantee reliable cooling either. Thus, energy storage must be incorporated in the system design for PV-powered cooling in remote areas without [off-grid (b)] or with limited/intermittent access [unstable grid (a)] to the electricity grid.

The necessity of an energy storage often leads to the use of a battery (2) to store surplus solar energy to use it to run the cooling system in times when the solar energy is not sufficient. This electricity storage was usually realised with lead acid batteries. However, the decreasing prices of Li-Ion batteries in recent years make them an increasingly viable alternative. In off-grid environments, batteries and PV, which are DC by nature, can be integrated with DC cooling equipment (2b). For integration of batteries with the grid, additional power electronics are required.

Cooling applications such as vaccine storage, which require a very high reliability, would lead to large and costly battery storages. Hence, thermal energy storage (3) may offer an alternative. In the case of thermal energy storage, the cooling system can be run only when solar energy is available, and the surplus energy is stored in the form of thermal energy instead of electrical energy. This can work in on-grid (3a) as well as in off-grid (3b) environments.

Thermal energy storage and battery storage can also be combined in one system (4) to potentially reduce costs and/or increase functionality. A cooling system could, for example, be added to an existing solar home system or microgrid without increasing the battery size too much when thermal energy storage would be incorporated. Classically, those solar home systems and microgrids are located in areas without grid access (4b), but unstable and unreliable grids also lead to a development towards on-grid solar home systems and on-grid microgrids (4a).[2]

The diversity of cooling-related problems (vaccine refrigeration, domestic and commercial refrigeration, cold storage for meat/fish and crops, as well as air conditioning) and the variety of system configurations discussed (Fig. 7) can lead to various applications of the technologies. Moreover, local context and other constraints might come into play in real applications of PV-powered cooling.

While passive cooling solutions should be preferred, refrigeration technologies are a crucial part of enabling access to cooling in the remote tropics. Due to the sunny nature of the tropics, solar-powered cooling is the natural choice of technology. Solar PV has now become more cost competitive and is simpler compared to solar thermally driven cooling. Nevertheless, the system configurations with special attention to energy storage can be very diverse. Compared to the developed areas with access to reliable electricity grids, the situations in the areas that need cooling the most (i.e. the remote tropics) are more complex and solutions are more expensive. Depending on the application, careful system design, or even product development, is necessary.

3 Applications of the Technologies

In order to solve the cooling-related problems in the remote tropics with PV-powered cooling systems, different applications are required (Table 1). Different types of PV-powered refrigerators can be used to store vaccines as well as for domestic and commercial food conservation (Sect. 3.1). Containerised cold storages can accommodate larger harvests as well as fish and meat (Sect. 3.2). Ice makers enable the transport and storage of fresh fish (Sect. 3.3). Air conditioners can provide thermal comfort in medical facilities and under extreme heat conditions (Sect. 3.4). Each application will be explained and discussed with regard to the situation in the market in the subsections below.

[2]More details on solar home systems and microgrids are covered in Chaps. "Swarm Electrification: From Solar Home Systems to the National Grid and Back Again?" and "The Sustainability Dilemma of Solar Photovoltaic Mini-grids for Rural Electrification", while the development towards on-grid solar home systems and on-grid microgrids is explored in Chaps. "Swarm Electrification: From Solar Home Systems to the National Grid and Back Again?" and "The Grid of the Future" of the book.

Table 1 Technologies to solve cooling-related problems in the remote tropics

Problem	Solution	Section
Uninterrupted cold chain for vaccines Domestic and commercial food conservation	Refrigerator	3.1
Food storage for harvest, fish, meat, etc.	Containerised cold storage	3.2
Ice for fish transport and storage	Ice maker	3.3
Thermal comfort in medical and other crucial facilities Cooling of high indoor temperatures (caused by poor housing quality)	Air conditioner	3.4

3.1 Refrigerator

PV-powered refrigerators can be used to store vaccines safely in remote areas. Moreover, domestic and commercial food conservation can be ensured through the use of PV-powered refrigerators. While vaccine storage and food conservation both require a high cooling reliability, vaccines always need to be kept in a narrow temperature window of 2–8 °C, and uninterrupted cooling is especially important [10]. Even though vaccines have stricter requirements in terms of cooling, the PV-powered cooling device is fairly similar: it is a PV-powered refrigerator.

Typically, a PV-powered refrigerator consists of a DC refrigerator, PV modules, a battery, and a charge controller as shown in Fig. 8. The refrigerator often has a thick polyurethane (PU) foam insulation to minimise the electricity consumption. With wider availability of vacuum panels, those can also be used for insulation as they provide better insulation properties while being thinner [11]. However, if the vacuum panel gets damaged and there is no vacuum anymore, it loses its insulation properties. Moreover, degradation may be an issue over time.

Companies such as Steca [12] and Phocos [13] from Germany have been selling this kind of PV-powered DC refrigerators for a long time. Those are in a higher price segment and are often also purchased for vaccines storage. Nowadays, there are also other manufacturers, including others many from China, who offer PV-powered DC refrigerators. For DC refrigerators, a battery (often lead acid) that can provide

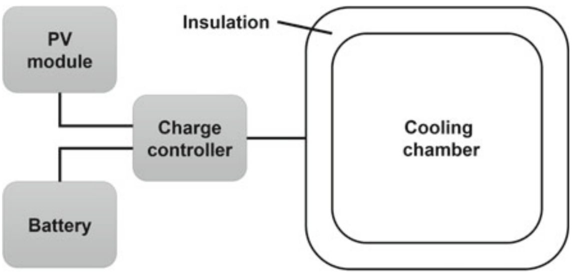

Fig. 8 Schematic of a PV-powered refrigerator with battery storage

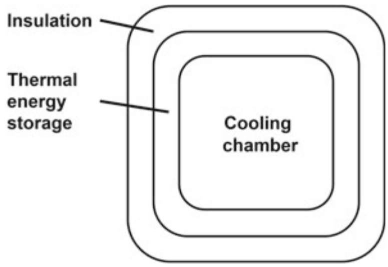

Fig. 9 Example for thermal energy storage integration into a refrigerator

energy for the required days of autonomy[3] has to be used. This results into a largely oversized battery. While this solution may provide sufficient reliability for domestic and commercial food conservation, the narrow temperature window for vaccines may not always be kept in "normal" refrigerators. Therefore, special vaccine refrigerators are used in on-grid medical facilities [14, 15].

In off-grid environments, refrigerators with thermal energy storage may offer an alternative solution. The storage medium would be located inside the cooling chamber and can be integrated in the case or around the evaporator as indicated in Fig. 9. Phase change materials (PCMs) with a suitable melting temperature, e.g. 4 °C, can be used to keep the storage temperature constant and provide the required days of autonomy. This solution can be combined with a smaller battery. It was also reported that there are "direct drive" solutions using super capacitors or other technologies to handle the high surge current when the compressor starts [16, 17].

The "surechill" technology [18, 19] utilises the abnormalities of water to ensure cooling at 4 °C. A large water tank is located around the cooling chamber. At the top, a vapour-compression cycle freezes water close to the evaporator. Since water is heaviest at 4 °C, it will sink, while a layer of ice will swim at the top. When the water around the chamber warms up, it will rise and gets cooled at the top of the tank. The technology ensures highly reliable cooling at 4 °C and provides a large number of days of autonomy through the big thermal storage, making it very suitable for preserving vaccines. A DC version that can be driven by PV modules is also available.

Domestic and commercial refrigerators may also be integrated into solar home systems and microgrids. Since solar home systems are mostly DC, DC refrigerators would be required as well. In microgrids, AC refrigerators can be considered, if the inverter is sufficiently sized for the surge starting current.

[3]Days of autonomy refer to the time that the load can be served without recharging the energy storage by solar energy.

3.2 Containerised Cold Storage

Not only is the quantity of the food demand increasing, but so is the demand for food quality. Moreover, the demand for packaged food for higher convenience is rising in developing countries where cities are growing due to urbanisation. In order to meet the demands in terms of quantity and quality, a functioning and reliable cold chain is paramount. Compared to certain developed economies with large agricultural companies and centralised cold storages (most extreme examples being Australia, Great Britain, the USA, Canada, and Belgium with above 100,000 m^3 average size of refrigerated warehouses [20]), food production in developing economies in the tropics is often highly decentralised. For example, in the largest archipelago in the world, Indonesia, agriculture and fishing happen all over the 7000 inhabited islands, and long shipping distances from production to consumption are a common issue. Food production capacities in rural areas often cannot be utilised, because the food cannot be transported to the bigger towns or cities due to lack of first-mile cold chain/storage.

In order to enable first-mile cold chain, instead of big cold storages owned by the agricultural company itself ("integrated", common for big food processing companies, e.g. Unilever, or big agricultural companies [21]), smaller cold storages closer to the production where space can be rented may be necessary ("non-integrated", not owned by the farmers/agricultural companies, independent operator that rents out space [21]).

The previously discussed challenge in the remote areas in the tropics, namely the unreliable or non-existent electrical infrastructure at the location for food production, complicates the implementation of a functioning cold chain starting from the first mile further. However, since the food storage capacity in each location is rather small, standardised containerised solutions powered by PV may be suitable. The solution comprises of a standardised shipping container or also custom-sized housing with a mounting structure that holds PV modules. The PV array also provides shading for the cold storage container on top of powering its energy consumption. A large battery bank (a), active thermal energy storage (b), and passive thermal energy storage (c), or their combination can be deployed as energy storage. Schematics of integration approaches are shown in Fig. 10.

Solution (a) requires a large battery bank that can run the energy-intensive compressor when sunlight is available and over a rainy day or two, which leads to a rather large investment. Instead, a variable refrigerant flow (VRF) compressor could be run directly by the PV array using a variable speed drive (VSD) with a maximum power point tracking (MPPT) software implemented to best utilise the energy from the PV array. In other words, the energy-intensive compressor is only operated when solar energy is available. This operation requires a thermal energy storage [(b) and (c)] to ensure cooling when no sunlight is available.

Thermal energy storage can be integrated as active (b) and passive (c) system. An active thermal energy storage (b) is basically a tank with a sensible or latent storage

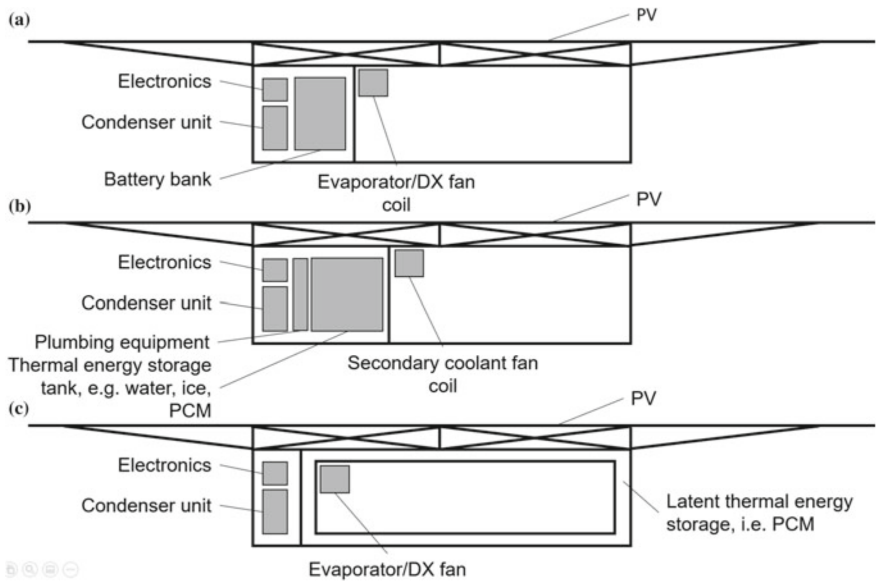

Fig. 10 Energy storage integration for containerised cold storages: (**a**) battery, (**b**) active thermal energy storage and (**c**) passive thermal energy storage. Combinations of (**a**), (**b**) and (**c**) are also possible

medium[4] (e.g. water, ice, other PCM). The evaporator coil may be located in the tank, and circulation of a secondary coolant is required to supply the fan coil unit (FCU). The tank temperature needs to be a few degrees below the desired cooling chamber temperature, which also implies lower evaporation temperature and hence lower efficiency of the vapour-compression cycle.[5] Moreover, a small battery may still be necessary because the secondary coolant still needs to be circulated through the FCU when no solar energy is available.

Passive thermal energy storage (c) would allow for direct expansion (DX) of the refrigerant in the FCU, and thus, it can have high-efficiency vapour-compression cycle similar to solution (a) with battery storage. Phase-change materials (PCM) are integrated into the cooling chamber as passive energy storage and are able to keep the temperature inside the cooling chamber constant for a long time without running the energy-intensive compressor and without circulation of any fluid (by pumps). This would enable an entirely battery-free system.

Typical temperature settings for cold storages are 13 °C (“banana”) for chilling-sensitive fruits, 2 °C (“chill”) for dairy, meat, and fish. Temperatures of −18 °C

[4]Sensible heat refers to an energy difference that is achieved by a temperature change of the storage medium, e.g. cooling down water. Latent heat refers to an energy difference that is achieved by a phase change, mostly from liquid to solid for cold thermal energy storages, e.g. from water to ice.

[5]The relation of COP and evaporation temperature follows the Carnot theory behind the vapour-compression cycle: $\text{COP} = \frac{T_L}{T_H - T_L}$, where T_L is the evaporation temperature and T_H is the condensation temperature in Kelvin.

("frozen") and −29 °C ("deep-frozen") are more common at the processing level than for first-mile cold storages [22]. Therefore, the thermal energy storage medium has to be chosen carefully. Ice is ideal for a high energy density: its latent heat is 334 kJ/kg, much higher than other PCMs in the market. Other PCMs in the relevant temperature ranges (−30 to 15 °C) are mostly paraffins, fatty acids, and salt hydrates. Those products are available with various melting temperatures and research on PCMs continues. The latent heat values for the available products range from 100 to 250 kJ/kg. While the cost of water is close to zero, other PCMs need to be purchased, although their costs are low compared to batteries. PCMs (except water) may also face degradation issues over time. Sensible thermal energy storages, i.e. chilled water tanks, require large space and hence may not be accommodated in the container. If large space outside of the container is available, chilled water storage can be considered as well.

Battery storage and thermal energy storage both have advantages and disadvantages; however, they can also work in synergy. A combination of a downsized battery and a larger thermal energy storage to sustain the night and rainy days may be a viable solution as well. Moreover, thermal energy storage may also be valuable for situations where cold storages are connected to unreliable electricity grids, making an uninterrupted cold chain possible, even if power outages occur.

Commercially available solutions include the "Cool Bot" [23] that turns a standard air conditioner into a suitable device for cold rooms. It is used for example by the Smallholder Foundation [24] in Nigeria. They use large battery storage and an inverter to operate the AC air conditioner. That being said, according to the "Photovoltaics for Productive Use Applications" document from the German Society for International Cooperation (GIZ) the cool down period is too long, and it is limited in functionality, i.e. no operation below 2 °C [24].

A system designed by the Institute of Air Handling and Refrigeration Dresden (ILK Dresden) [26] consists of a 20 ft container and 3.4 kWp PV array used as shade. While it still has a small battery, the main energy storage is an ice storage that ensures three days of autonomy. Since ILK Dresden is a research and development (R&D) enterprise and does not commercialise the solution within their entity, the solution is still to be adopted and commercialised.

There are also other manufacturers such as SunDazer [27] who offer commercially available solutions. Nevertheless, many of the cold storage projects are still pilots from international development organisations or non-governmental organisations (NGOs).

3.3 Ice Maker

Ice is of special interest in meat and especially in fish production. Fish that is stored in cold storages instead suffers from water loss, which results in a lower quality product. Ice provides the capability of rapidly cooling food down (pre-cooling) and can also be transported easily, which is crucial for remote areas where lorries with cooling chamber are often not available. Moreover, it can be used directly in fishing vessels.

According to Winrock International common ice makers generate 5 to 12 kg ice per kWh electrical energy [28]. However, efficient ice makers can yield 18.5 kg per kWh electrical energy. Pre-cooling of one tonne of food at 28–0 °C would need around 330 kg of ice. This equals 28–66 kWh for standard/common ice makers and only 18 kWh per tonne of food for the high-efficiency ice makers.

It is important to note that well-insulated containers are crucial for efficient use of ice, as the transfer of heat from the environment needs to be minimised. While the transportability of ice is one of the advantages, long distances to small and rural food production locations hinder the efficient use of ice for cooling, especially when poorly insulated containers are used.

Many coastal or island communities in countries such as Indonesia rely solely on fishing as income generation. Often, the fish can only be sold to the local market for local consumption, as the preservation is very limited without access to ice. In order to enable the fishermen to obtain higher prices for their fish, access to ice is paramount, as they need to travel to the cities to sell the fish while ensuring its freshness.

There are more than 800 fisher ports across all Indonesian islands, which run ice block maker on diesel generators or unreliable grids (often with large diesel generators as central power plants) [22]. Solar-powered ice makers may have the potential to offer a cost-effective and clean alternative to the high-operation-cost diesel-powered solution.

ILK Dresden, in cooperation with GIZ Indonesia, developed an ice maker that produces the same kind of ice blocks as the usual diesel-powered ice makers. The system is accommodated in a container and powered by 25 kWp PV. The output is one tonne of ice per day, and GIZ claims 30% cost reduction compared to diesel-powered systems [29]. The system runs the compressor according to the solar energy available and hence does not require a large battery bank. However, a small battery is used to power auxiliary equipment such as pumps and control uninterruptedly.

Conventional ice-block-making machines consist of a container with ice bins inside (Fig. 11). While the ice bins are filled with water (to make ice), the container itself is filled with brine that has a freezing temperature far below 0 °C (e.g. saltwater), which is used as coolant. The evaporator of the vapour-compression cycle is inside

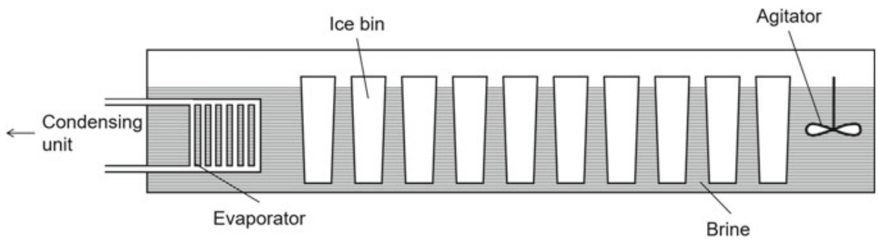

Fig. 11 Schematic of an ice maker for ice blocks; adopted from ILK Dresden [30]

the brine tank, and a stirrer moves the brine to create equal temperatures. During the ice making process, the container should be covered with an insulation material. The other surfaces of the container should also be insulated.

The prototype developed by ILK and GIZ adopts the general principle but adds a few variations to make it more suitable to be powered by intermittent solar PV [29, 30]. Therefore, the central brine compartment serves as thermal energy storage and has no ice bins. The ice bins are located in separate compartments, in which brine is circulated by pumps. The number of compartments in operation can be adjusted by the control system according to the available solar energy, i.e. to part load operation.

A supposedly more efficient way to make ice is by making ice flakes instead of blocks. ILK Dresden also developed a solar-powered ice flake machine with improved efficiency. However, this machine relies on a larger battery. The system fits into a 20 ft container and is integrated with a water tank as well as a UV water disinfection system. It can produce 250 kg ice per day and has storage space for two days of ice production. The PV system on the container has a capacity of 5.1 kWp [31].

Commercially available ice makers are in the market; however, solar PV-powered ice makers are not widely available yet. Hence, only development and prototype projects have been described in this section.

3.4 Air Conditioner

Usage of air conditioners should be avoided whenever possible: high indoor temperatures caused by poor housing quality should be tackled by design and material improvements, instead of installation of an air conditioner. However, in crucial facilities such as medical institutions, it may not always be possible to avoid air conditioning. Moreover, extreme heat events may increase the demand for air conditioning to protect the vulnerable part of the population from negative health impact or even death. Another application for air conditioners in the remote tropics is the cooling of telecommunication equipment in remote telecommunication stations.

Solar PV-powered air conditioners that can be found in the market are often the following two types (Fig. 12): (1) On-grid without batteries or (2) off-grid with batteries. The on-grid version (1) is sometimes advertised as “hybrid”. The PV modules are directly connected to the condensing unit. However, this air conditioner is also connected to the usual household socket (i.e. connected to the grid) and stops operation once a power outage occurs, because there is no grid-forming inverter integrated in the condensing unit. Thus, it is not suitable for remote areas that experience power outages or have no access to the electricity grid at all.

Off-grid air conditioners (2) are usually DC powered. A classic set-up of PV modules, batteries, and charge controller can power this DC unit. The battery needs to be rather large, as the energy consumption of the air conditioner is high, which makes the setup expensive. There are various companies offering the “hybrid” (1) or off-grid (2) systems/packages including many Chinese suppliers/wholesale. Nevertheless, systems with thermal energy storage are rarely seen in the market.

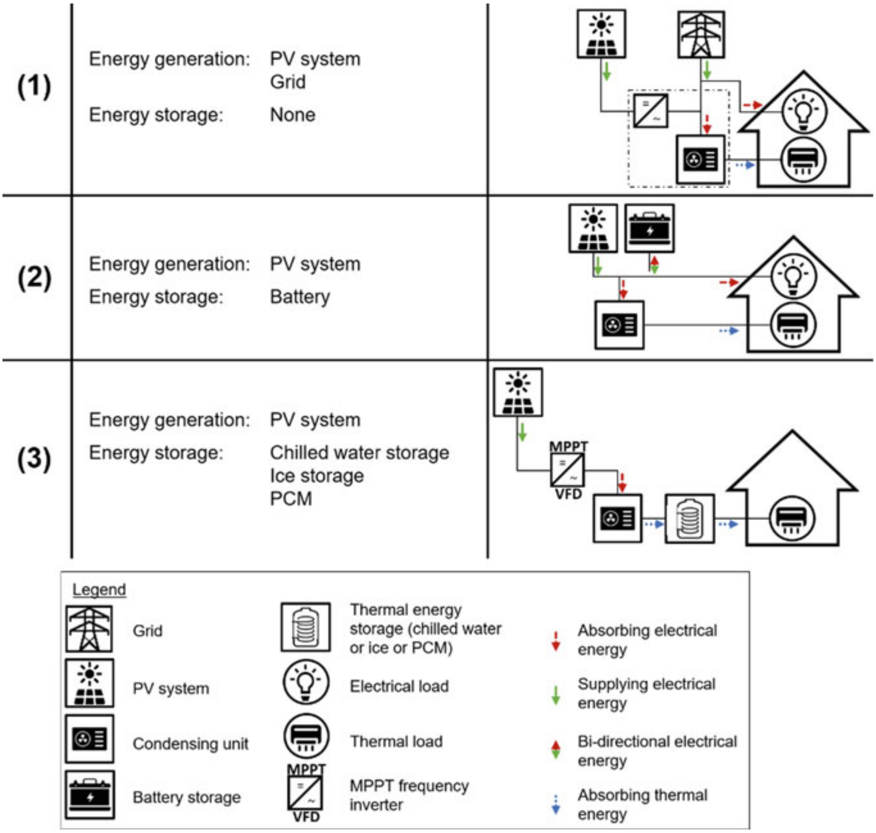

Fig. 12 System configurations for solar-powered air conditioning: on-grid (1), off-grid with battery storage (2) and direct-driven with thermal energy storage; adopted from Luerssen et al. [36]

A system set-up that has the potential to reduce the battery size to a minimum (only for control and auxiliary equipment), or even remove the need for a battery entirely, and yet still usable in places with limited access to electricity can be realised by utilising thermal energy storage (3). PV modules can be connected to variable frequency drive (VFD) with MPPT function (similar to the refrigerator, cold storage, and ice maker with thermal energy storage). Thus, the vapour-compression cycle is run according to the solar energy availability. The evaporation may take place in the heat exchanger of a thermal energy storage. The thermal energy may be stored as sensible heat, i.e. chilled water, or latent heat. The storage medium may be chilled water when sufficient space is available, or a PCM when space is limited. and hence, higher energy density (i.e. latent heat of the phase change) is required. While ice can be used as PCM, other PCMs with a higher melting temperature of 5 to 8 °C may be interesting for the air conditioning application as well. The vapour-compression cycle could be run at a higher evaporation temperature and hence more efficiently [32].

A secondary coolant (water or glycol, if ice storage is used) needs to be circulated through the thermal energy storage to the FCU. Standard chilled water FCUs (7 °C supply and 12 °C return temperature) may be used for this application.

Even though the desired room temperature may be between 23 and 27 °C, a low chilled water supply temperature of 7–8 °C needs to be maintained in order to ensure sufficient dehumidification of the humid air in the tropics, i.e. to achieve relative humidity below 70% to ensure thermal comfort. In less humid areas, the system can be operated at higher evaporation and energy storage temperatures, which reduces the energy consumption.

Systems with thermal energy storage (3) are not readily available in the market yet. However, there are pilot and prototype efforts. For example, Atisys Concept [33] from France has set up a test bed system with batteries and VFD for compressors and a 180-litre chilled water tank in the scope of a research project [34]. A pilot project has been implemented at LooLa Resort in Indonesia to enable air conditioning for the resort guests at night using the solar energy harvested during daytime. While the bulk of the energy is stored in two 1000-litre ice storages (ca. 92 kWh each), the system still relies on 46 kWh lead acid battery. The chillers are not equipped with VFDs, which makes it not feasible to run them according to the available solar energy [35]. Moreover, there are other system inefficiencies such as unnecessary heat exchangers stages and too high chilled water supply temperature, which do not allow for dehumidification of the air.

There is still research and development work to be conducted and system configurations to be optimised in order to bring an efficient and cost-effective solar-powered air conditioner of the remote tropics into the market.

4 Business Models

The commercial business with solar-powered cooling devices, i.e. refrigerators, cold storages, ice makers, and air conditioners, in the remote (and underdeveloped) tropics is still limited to date:

- Solar-powered **refrigerators** are purchased by NGOs, international development organisations, and multilateral organisation to be deployed in remote areas for safe vaccine storage. Sales to households and small businesses (e.g. shops) are still very limited.
- Solar-powered **cold storages** are explored in demonstration and pilot projects, which are financed by grants from various sources. Commercial operation of small-scale solar-powered cold storages is probably still extremely limited.
- Solar-powered **ice makers** have been developed in R&D projects but are yet to be adopted for commercial manufacturing and commercial operation in the remote tropics.

- Solar-powered **air conditioners** are in the market, but there is still room for product improvement. Usage in the remote tropics may be still limited to some NGO-supported medical facilities, if any.

Project descriptions of initiatives supported by international development organisations are described including information on the intended business model in the annex of the GIZ report "Promoting Food Security and Safety via Cold Chains" [37]:

- Solar-powered cold rooms for fruits and vegetables in Nigeria.
- Ice production for fish cooling in Senegal.
- Solar-powered cold storage for fish in Kenya.
- Solar-powered milk cooling in Tunisia.
- Off-grid bulk storage for vegetables in India.

The GIZ DC appliances report [25] highlighted business opportunities for small shops/kiosks that sell cold drinks, frozen meat, and fish, as well as ice. The breakeven points for the respective solar-powered refrigerator or freezer were estimated to be within 7–10 months. The payback for the diesel-powered refrigeration/freezer is 50% shorter, but as the operational costs for diesel are high, it eventually incurs higher lifetime cost [25]. Overall, the solar-powered solution makes economic sense, even though the initial investment is considerably higher with the current solar-powered refrigerators and freezers in the market.

Even though solar-powered cooling devices are the most promising solution for the remote tropics, the business activities are still very limited, because the remote tropics imply challenges that are unknown to areas with higher population density and with reliable and affordable electricity grid access. The challenges were compiled partly based on the different sections of the GIZ report "Promoting Food Security and Safety via Cold Chains" [37] in Fig. 13. It can be deduced from the compiled points that the challenges do not only lie in the technology. The challenges are grouped into the following: distribution efficiency to remote places, financing schemes, affordability of solutions, education, and conventional local food supply chain mechanisms (established practices).

All these challenges call for locally adapted and integrated business models. Despite all the challenges, there are also many opportunities in terms of business models for solar-powered cooling devices in the remote tropics, which include, but by far are not limited to the following:

- Integrating educational aspects in the business model.
- Utilising pay-as-you-go (PAYG) technology to sell refrigerators/freezers to kiosks/shops, which sell their cooled products at a premium and to residential households [25].
- Enabling local entrepreneurship for distribution/sales of refrigerators/freezers and operation of cold storages (renting out storage space) and ice makers (sales of ice).
- Mobile cold storages can be moved to different areas according to harvest seasons of different food products to overcome seasonal challenges and enable better utilisation of the cold storages.

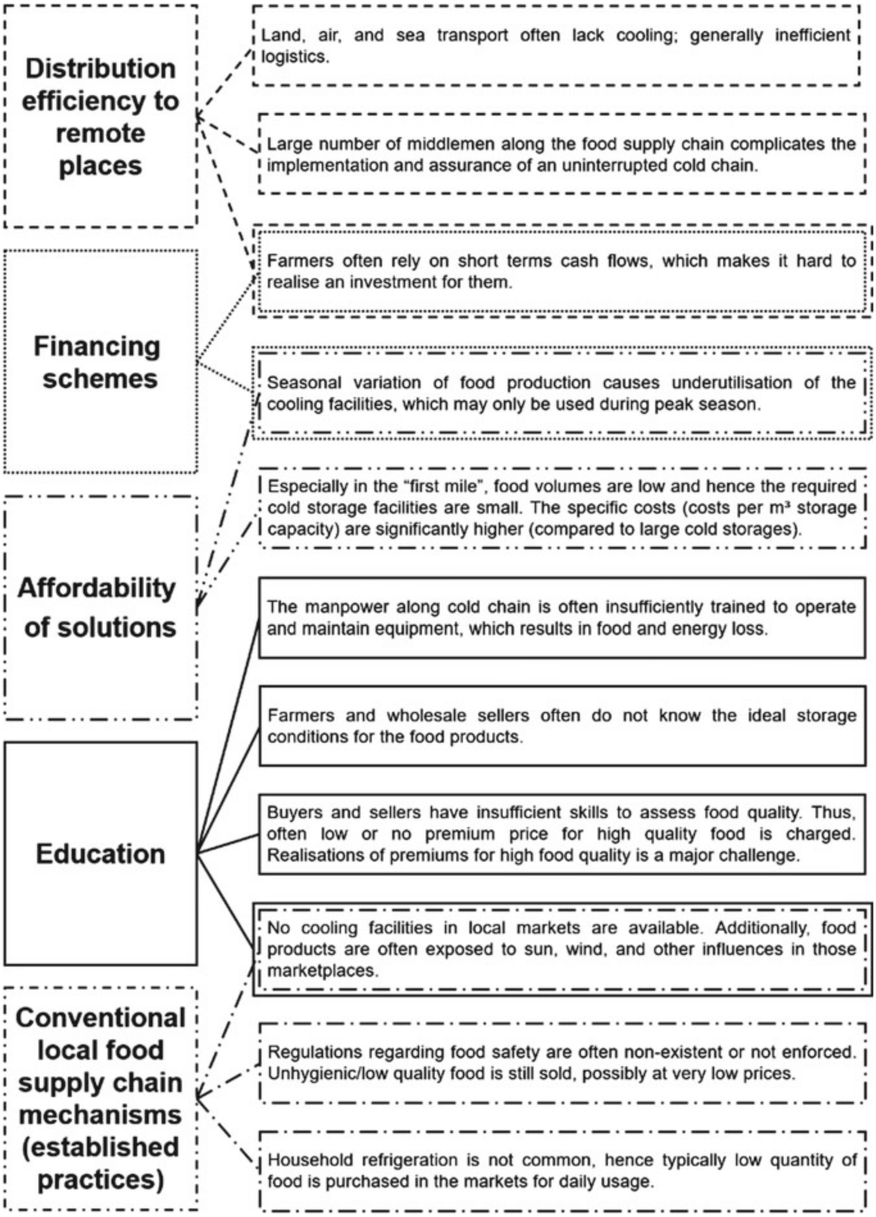

Fig. 13 Challenges for a functioning cold chain in the rural tropics. *Source* partly adopted from the GIZ report "Promoting Food Security and Safety via Cold Chains" [37]

- Tailored system design and product development for remote conditions.
- Utilisation of communication and digital technology to cut middlemen.
- And many many more …

Even though the prices for solar-powered cooling devices will decrease through component price declines and development of cost-effective products, the products will remain as a considerably high investment for the people of the target market. Therefore, it is important to identify the actors who are experiencing the pain and who also have the purchasing power, who may differ across regions.

In order to craft locally adapted business models for solar-powered cooling devices, it is recommended to include the following aspects:

- Thorough understanding of local value chain.
- Robust quality management, service, and after-sales support system.
- Understanding of financing requirements of the local target market.
- Education programmes on food quality and how the device can help.

As laid out in Sect. 1, the overall target market is massive. Sections 2 and 3 pointed out that the solar-powered cooling technology is ready. The remaining challenges are to be overcome by business model innovation to enable large-scale adoption of solar-powered cooling devices in the remote tropics.

5 Impact

The existing impact of solar-powered cooling in the remote tropics is probably mostly limited to projects that have been implemented by NGOs and multilateral organisations. The main existing impact is access to safe refrigerated vaccines through solar-powered refrigerators in remote areas, which is indispensable to avoid outbreak of certain diseases [10]. However, the current deployment cannot be seen yet as a large-scale implementation that allows millions of people to have access to solar-powered cooling.

Nevertheless, the potential impact is very high, due to the readiness of the technology and the large target population. The types of possible impacts have been mentioned throughout this chapter. In this section, the possible impacts are summarised and arranged into three categories: (1) economic, (2) social, and (3) environmental impacts.

1. Economic impacts: Support for economic development

- Shop owners can sell refrigerated or frozen products at a higher price, increase the products' shelf life and hence increase their income.
- Fishers can use ice to cool down the fish, keep it cool during transport, and sell it at a higher price, because of increased quality.
- Farmers can store their harvest longer, because of the increased shelf life when cooled and fetch a higher price when they sell it at a more strategic point in time.

- Long-term savings when solar-powered cooling devices replace cooling equipment powered by diesel generators due to fuel savings.
- Locally manufactured and/or assembled products create jobs.
- Distribution, maintenance, sales, installation, and operation enable local entrepreneurship, i.e. create more jobs and even businesses.

2. Social impacts: Health, employment, productivity, and education

- Increased food security, i.e. food availability, access, and quality, by extending shelf life through an uninterrupted cold chain.
- Lower risk for foodborne diseases when cooling is ensured (especially for fish and meat), i.e. increased food safety.
- More flexible food consumption (through longer shelf life) enables a higher variety in nutrition.
- Access to safe vaccines that are kept within the correct temperature range at all times.
- Improved thermal comfort through air conditioning in crucial medical facilities for the vulnerable population.
- Less unemployment due to new jobs in the value chain of solar-powered cooling.
- Farmers and fishers can increase their production through access to cold storages and ice.
- Decreased food losses due to longer storage time post-harvesting and post-slathering.
- Better knowledge on benefits of an uninterrupted cold chain for food products by getting introduced to and using solar-powered cooling devices. Thus, there would be higher appreciation of food quality, which hopefully leads to fewer occurrences of foodborne illnesses.
- New jobs and businesses in the value chain of solar-powered cooling enables a wider skill set of the target population that is no longer only limited to e.g. farming certain crops.

3. Environmental impacts: Potential greenhouse gas emission reduction

- Reduction of greenhouse gas emission when a diesel-powered cooling device is substituted by a solar-powered cooling device → positive environmental impact.
- Increase of greenhouse gas emission when a solar-powered cooling device is used where no cooling took place before → negative environmental impact.
- Solar-powered cooling devices have the potential to be an environmentally friendly product when the value chain is kept as local as possible (reduced emissions during transportation) and refrigerants with low or no global warming potential (GWP) are used (explanation in Sect. 6).

Overall, solar-powered cooling devices are environmentally friendly, sustainable product that have the potential to have enormous positive social and economic impacts on many lives in the remote tropics.

6 Future and More Sustainable Solutions

It can be concluded that solar-powered cooling devices are a sustainable solution that can contribute a tiny bit to solving the two main challenges of humankind, the ecological transition towards a carbon positive or at least carbon neutral society until 2050 in order to limit global warming to 1.5 °C [38], and the development of the poor countries towards global equality; no fossil fuels are burned for the operation of solar-powered cooling equipment, and it especially helps the remote regions in the poor countries with unreliable or no electricity access to develop. However, several points need to be considered to move towards truly sustainable cooling. Those are not only relevant for the solar-powered cooling devices, but also to sustainable cooling in general.

1. Avoiding of cooling, if possible

As stated several times in various sections of this chapter, cooling is mainly necessary for the food supply chain to enhance food quality and reduce food loss. Usage of air conditioner to cool buildings should be minimised. Passive design strategies, energy-efficient architecture, and urban planning strategies have to be the first choice to provide thermal comfort for the occupants. As a result, less (solar-powered) cooling equipment has to be manufactured, transported, and operated, which reduces emissions. The best energy-efficiency measure is avoiding the usage in the first place. In cities, this will also help to reduce the Urban Heat Island (UHI) effect that is partly caused by the heat dissipated from the condensers of cooling equipment.

2. Natural refrigerants

After the biggest CO_2 emissions from fossil fuels and industrial processes (65%), CO_2 emissions from forestry and other land usages (11%), methane (11%), and NO_x (6%), fluorinated gases—i.e. hydrofluorocarbons (HFCs) or refrigerants—are contributing 2% of the global greenhouse gas emissions [39]. These are the gases currently used in vapour-compression cycles of refrigerators, air conditioners, and chillers. Depending on the exact type, their global warming potential (GWP)[6] can be 12–14,800. HFCs replaced chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) in the 1980 s, because of their high ozone depletion potential (ODP)[7] which caused an increasing destruction of the ozone layer. Under the Montreal Protocol, the world community has agreed to phase CFCs and HCFCs out [40]. The political decision was made despite strong complaints from the refrigeration industry. However, it turned out that the industry was able to adapt to the new rules quickly. Nevertheless, although HFCs do have zero ODP, they still have high GWP.

Another switch to the so-called natural refrigerants with low GWP is necessary to reduce the GHG emissions caused by refrigerants. While there are products in

[6] GWP is the contribution of a gas to global warming compared to CO_2 as a reference. The GWP of CO_2 is defined as 1.

[7] ODP is the contribution of a gas to degradation of the ozone layer compared to the refrigerant R-11. R-11 is a CFC that is used as refrigerant. The ODP of R-11 is defined as 1.

the market that use natural refrigerants, their efficiency is often lower and their price higher. Hence, the refrigeration industry has to put more effort into increasing their efficiency and bringing the prices down. Similar to the situation in the 1980 s, the refrigeration industry does not seem to make the change on their own and may require another political decision to force the change. The Kigali Amendment to the Montreal Protocol aims to do so by gradually phasing down HFCs by more than 80% within the coming 30 years [41]. The Kigali Amendment was ratified by 65 countries and a certain group of countries started the phase down in 2019 [42].

3. Long product lifetime

White goods (i.e. kitchen appliances), such as washing machines, dish washers and also refrigerators, often have a short lifetime of 5–10 years these days. This might be driven by the manufacturers who want to sell more products to maximise their profits. At the same time, efficiency improvements may justify a replacement or upgrade of white goods after some time.

However, long product lifetime is achievable as can be seen from products that have been purchased 20 or even 30 years ago, are still in operation and working fine. Since PV modules have a lifetime of at least 25 years, it would be suitable, if the refrigeration equipment for the solar-powered cooling devices can also reach the same lifetime.

4. Principle of circular economy

Another reason why old products are often still in operation is that they are "repair-friendly", meaning that their components are accessible and can be repaired or replaced easily. Moreover, the spare parts are available at an affordable price and can be used for various models. For more recent models, however, technicians often suggest buying a new product, because replacing single components does not make sense economically. High spare part prices and a lot of effort are required for component replacement, while the prices for new products have decreased. Although the profits for the manufacturers are maximised this way, it also accelerates the depletion of natural resources.

The sustainable way is to return to "repair-friendly" products and additionally design product lines in a way that they can be upgraded with new technological advances once available without the need to replace the entire product keeping the principle of a circular economy in mind. Once a (solar-powered) cooling device cannot be used anymore for its original purpose, as many components as possible are to be reused for other purposes as many times as possible, e.g. the PV modules for solar home systems. Additionally, once the components are not usable anymore, they are to be recycled as far as possible and fed back into the production loop.

5. Sustainable material choice

In order to be able to apply the principles of the circular economy, it is crucial to make sustainable material choices in the product or system design phase. For example, the widespread insulation material for refrigerators is PU foam (and also partly

Styrofoam). PU foam is a crude-oil-based product and hence requires extraction of crude oil from the earth shell. A more sustainable choice would be the usage of recycled PU foam, which is getting more popular in the mattress industry. An even more sustainable choice would be glass wool, which is made of recycled glass, or stone wool, which is made of natural stone that is a by-product of lava cools and steel production.

It is not easy to avoid the use of plastic entirely, because the material properties are practical for many components. However, recycled plastic can be utilised. Furthermore, it is important to avoid creating plastic compositions, which are not recyclable, but use plastic types that are commonly recycled. In the future, organic plastics might be a sustainable and affordable choice too.

Other materials with many benefits are steel and other metals. Here, recycled metals should also be preferred over freshly mined metals.

It may also be beneficial to reduce the battery size to a minimum or find a way to replace it (partly or entirely) with, for example, thermal energy storage, because batteries are resource-intensive products. Lithium for the increasingly popular Li-Ion batteries is mined in South America which necessitates high water and land usage as well as long sea transport. At the moment, many Li-Ion batteries also still use Cobalt from questionable mining practices in the Democratic Republic of Congo, not to mention that the manufacturing process is also energy intensive.

6. <u>Sustainable supply chain</u>

Not all components are manufactured by the solar-powered cooling device manufacturer itself. For true sustainability, it is important to audit the supply chain closely in order to not only ensure that it is environmentally friendly/neutral, but also that it complies with human rights, good working conditions, and gives fair salaries to workers, among others.

From an environmental point of view, the requirements for suppliers could for example be a production facility that runs on 100% renewable energy and low/no emission transport. However, is it difficult and expensive to audit supply chains. Thus, suppliers that have been certified for a sustainable supply chain by a trustable certification entity can be chosen.

7. <u>Development of rigorous regulations</u>

It is unlikely that points 1–6 will be adopted by companies in the current capitalist society, in which companies aim to maximise their profits globally. Therefore, these points have to be regulated strictly and heavy fines need to be enforced, if companies do not follow the rules. The regulations may include, but are not limited to:

- Gradually increasing minimum energy performance requirements for the manufactures of refrigeration equipment; the steeper the requirements increase, the better. Financial punishments and bans should be implemented if targets are not reached.
- Accelerated phasing out of HFC refrigerants in a similar manner as it was done for CFC and HCFC refrigerants.

- At the moment manufacturers of refrigeration equipment profit from selling big equipment for big cooling loads. The cooling load should be minimised and then the refrigeration equipment downsized, respectively. In order to achieve that, ambitious limits for cooling loads are to be implemented and checked by a certification body. For different building types, limits in terms of kWh/m^2a and refrigerators in kWh/l a. These values vary for different regions, because of the differences in ambient temperature and humidity. This should lead, for example, to improvements of passive design on buildings and better insulated refrigerators. The limits should become stricter over time.
- Space cooling could be taxed to slow down the purchase of air conditioners. It may be easier to implement high tax on the equipment than taxing the usage.
- The money collected from taxes and fines from mostly developed countries and urban areas could be allocated to support sustainable cooling in the food supply chain in remote and poor regions in the developing world.
- Mandatory reporting of Life Cycle Assessment (LCA) for cooling equipment: Implementation of limits for embodied CO_2 that is emitted along the supply chain and for manufacturing of the products.
- And many more …

For sure, there are many more ways to regulate the industry and usage on the way towards truly sustainable cooling. However, it will be a long and tedious process to convince the authorities of each country to implement such regulations.

8. Legal anchoring of sustainable cooling targets in multilateral agreements

Since the effect of one country implementing restricting regulations, as listed under the previous point, is rather small, it is indispensable to bring nations together and formulate targets in binding multilateral agreements to increase the chance of the rules to be adopted globally. The countries who sign up then need to develop national regulations to reach those targets to avoid fines. This can easily affect more than a billion people or so, which is a huge part of the customers of multinational companies that serve the increasingly globalised world. Those companies are then forced to change the direction towards sustainable cooling to ensure the company's future existence.

Recent examples for such multilateral agreements are the Paris agreement [43] and the UN Sustainable Development Goals (SDGs) [44]. These are huge and all-encompassing agreements that are very high level. However, it may be worth it to include the aspect of cooling, which is certainly just one part of the big picture in those agreements, as it may be an effective opportunity/way to limit the increase of energy consumption and improve food security at the same time.[8] The role of cooling should not be underestimated on the journey to reduce global greenhouse gas emissions.

[8]The refrigeration sector accounts for 17% of the global electricity consumption in 2015 [45].

The eight points explained can be implemented right now, without the need of any future technological advancements or disruptions. This would lead to more sustainable cooling and would also even make solar-powered cooling even more sustainable.

In terms of technologies, there will definitely be advances in the future. The vapour-compression cycle refrigeration equipment will become more efficient and may be replaced by another technology once its efficiency limits are reached and another more efficient technology is market-ready. Similarly, PV modules will become more efficient and may use different semiconductor materials once efficiency limits are reached and other materials are ready for the market. Battery technologies will evolve and advance, and their ecological footprint will reduce. The properties of PCMs will become more favourable, e.g. higher energy density. Insulation materials will improve. Electronics and better control algorithms will allow for energy consumption reduction. All these are mostly incremental improvements, as it is common for most technologies. However, there could also be disruptive technological improvements that cannot be predicted.

Nevertheless, in order to enable large-scale adoption of sustainable solar-powered cooling devices, innovation and disruption are needed in adapting the technology to local needs and bringing it to the people. Depending on the local circumstances, innovations in financing, distribution, and other aspects of the business model may be the key to large-scale adoption. The core technology is ready, and the opportunities and the positive impact are evident.

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Swarm Electrification: From Solar Home Systems to the National Grid and Back Again?

Raluca Dumitrescu, Sebastian Groh, Daniel Philipp and Christian von Hirschhausen

Abstract Electricity produced through solar home systems (SHS) represents attractive energy supply solutions for the unelectrified population in the Global South, particularly in its remote areas. Together with the respective range of appliances, SHSs represent an unattended and untapped infrastructure. We re-define the different categories of unelectrified and electrified population in the Global South, while describing the applications and usage characteristics of SHSs and the national grid. We introduce the notion of servicing the national grid through swarm electrification, defining the future of utilities through a combination of bottom-up interconnected individual solutions and top-down concentrated energy supply.

Keywords Solar home system · Microgrid · Renewable energy · PAYG · Remote · Prosumer · Peer-to-peer · Swarm electrification · Grid extension · Service to the grid · Weak-on-grid · Close-to-the-grid · DRE

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1 Introduction

Nazir is "mining the sun". He, a farmer, his wife and four children live in unelectrified Bangladesh. His household is one of the more than four million [1] households in Bangladesh that did not wait for the national grid to come, but rather decided to acquire, through a microcredit, a solar home system (SHS). Or in other words, Nazir is one of the 73 million [2] decentralized renewable energy system (DRE) users in the Global South who took the future of his electrification into his own hands, opting for a stand-alone solution that can satisfy his immediate needs for low power uses: lighting, mobile phone charging, watching television (TV) and listening to the radio.

According to the International Energy Agency (IEA), there are approximately one billion people who do not have access to electricity [4], limiting their chances to improve their quality of life. The majority of these people are located in 20 developing countries in Asia and Africa, or also known as the Global South, and about 80 per cent live in rural areas in those countries, representing the last mile of electrification. Figure 1 shows how access to electricity (% of population) varies by country. The colour shade of the country corresponds to the magnitude of the indicator; the darker the shade, the higher the value. The country with the highest value in the world is Bahrain, with a value of 100.00. The country with the lowest value in the world is Burundi, with a value of 7.00.

Access to electricity is a key factor to human and economic development, and access to clean and modern energy services (i.e., available, reliable, resilient and affordable) is a precondition for human health and well-being. Access to electricity can increase productivity and at the same time allow people to break free from poverty patterns [5]. Despite considerable efforts with international donor support, expansion

Fig. 1 Access to electricity worldwide [3]

of the national electricity grids in the Global South has been slow and limited. In the last years, DREs, such as SHS, have represented an alternative for the off-grid and weak-on-grid population, terms that will be elaborated later in the chapter.

The rest of the chapter offers an overview on SHS, explaining current conditions that lead to the deployment of the SHS, its technology, its business model, its future for electrification in the Global South and innovations that can change the way we perceive utilities nowadays.

2 The Technical System

Due to the limited storage of the SHS's battery and the limited generation capacity of the SHS's solar panels, Nazir is still constrained in his usage of electricity—during the day, he does not utilize his system, as the entire family is either in school or working in the field; during the evening, when most of the demand occurs, he can only watch the news for a couple of hours, turn on three lights and charge only one mobile phone per day. To eliminate the constraints of his SHS, Nazir, as a consumer, decides to interconnect to the SHS of his neighbour (peer-to-peer/P2P), Hussain, a prosumer (producing consumer), so that each time he needs to consume additional electricity, he could simply buy Hussain's unused electricity.

Such P2P transactions have been made possible through an electricity trading platform that runs on an ultra-low-voltage direct current (DC), smart microgrid hardware layer as well as through a real-time data monitoring and data analytics backbone. The hardware layer is formed by an integrated power management and smart meter unit (see Fig. 2), which connects to the Internet of Things (IoT) architecture, using a local GSM to Wi-fi router. The smart meter automatically controls the power flows and the corresponding bi-directional net-metering between users of the scalable microgrid, which can organically grow through the addition of existing SHS. Additionally, the smart meter is equipped with key smart grid features including interfaces with grid management, remote monitoring, data analytics, payment management (through mobile money) and customer support infrastructure.[1] Trading volumes can vary from only a few Wh to several kWh per month. In 30 grids throughout the remote areas of Bangladesh, early research on impact assessment, conducted by the Singaporean organization Impact Investment Exchange (IIX),[2] has shown that for every US dollar invested into one of the P2P microgrids, such as the one where Nazir is trading, generates a social return on investment (SROI) of USD 4.85.[3]

With increasing technology development and spread of DREs, innovative solutions such as P2P connections propose alternative pathways to electrification—pathways which start from the last mile and grow organically from the bottom-up, catching

[1]For further information please refer to www.me-solshare.com, a Bangladeshi start-up that in 2015 installed the world's first solar P2P grid.

[2]For more information please refer to https://iixglobal.com/.

[3]SOLshare—impact assessment conducted by IIX Global.

Fig. 2 Integrated power management and smart meter SOLbox. *Source* www.me-solshare.com

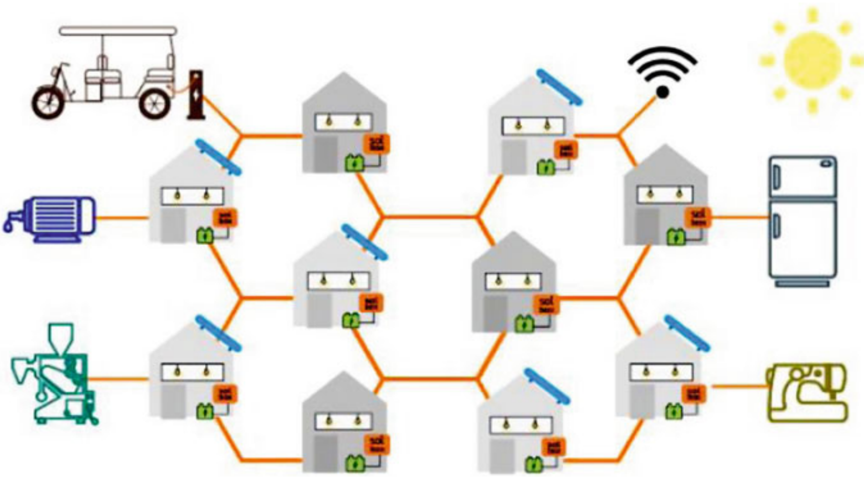

Fig. 3 Schematics of the P2P grid. *Source* www.me-solshare.com

up with the expansion of the national grid and eventually even interconnecting with the national grid itself. The possible P2P connections in rural areas are illustrated in Fig. 3.

Nazir and Hussain are two of the millions of potential prosumers for which the national grid can represent a backup solution rather than the main source of electricity. And the other way around, for the national grid, Nazir and Hussain can represent battery-enabled service providers available at any hour.

3 Overview of the Problem

The potential of the DRE market does not end where connection to the grid starts. Even a population which is officially considered on-grid can still have no or limited access to good quality electricity services (e.g., due to voltage fluctuations, insufficient duration and/or low capacity), thereby representing a potential market for DREs. This phenomenon has already been acknowledged by DRE companies, with an increasing number of customers connected to the grid and with unreliable supply also acquiring diesel generators, portable photovoltaic (PV) lamps (pico PVs) and SHS as backup generation. At the same time, the fact that the national grid's outreach slowly increases does not automatically imply that existing DRE infrastructure already installed there gets abandoned, ultimately rendering a DRE company's business model and the investments in it obsolete.

A closer look at the electrification rates in the Global South reveals differences among diverse databases. The World Bank and IEA maintain a separate country-by-country database of global electricity access rates but use different data collection methodologies [6]:

- The World Bank derives estimates from a suite of standardized household surveys conducted every two to three years with a multi-level non-parametric model used for extrapolation. This methodology favours the user-centric perspective on electrification and is typically conducted by the national statistical agency of each country.
- The IEA sources data where possible from government-reported annual values for household electrification supplemented with a new measurement of off-grid access. The data are typically reported by the ministry of energy in each country and favour the supply-side perspective on utility connections and electrification.

Together, the two databases provide different and important quantifications of electricity access. This illustrates the complexity of measuring electrification and the value of having multiple sources of information, which have led the IEA and World Bank to engage on a comparison and reconciliation exercise to develop a joint database over time. Although the question on how to rightfully measure energy poverty and electricity access remains, advances in newer multi-dimensional frameworks such as the multi-tier framework (MTF) for measuring energy access from Energy Sector Management Assistant Programme (ESMAP) have made great strides

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

Fig. 4 Simplified multi-tier matrix of energy access (household electricity supply). *Source* World Bank/ESMAP

from the largely constrained binary metrics [7]. However, the level of detail proposed through the MTF (see Fig. 4) can be too complex to operationalize at the global tracking level and too prescriptive to gain acceptance in national energy programmes. It is therefore important to understand these limitations when interpreting electrification rates and other parameters quantifying energy access.

The following section presents a more nuanced end-user market segmentation than the traditional rigid dichotomy of on-grid/off-grid.

4 Proposal of New Categories

4.1 Off-Grid

The off-grid population worldwide has been increasing since 1990. Despite the millions of people who have been connected, the population growth is outpacing the extension and densification of the grid. This trend is expected to continue with several millions of people left behind each year [2]. For example, with the current rates of investments for electrification, the number of people without access will increase in Sub-Saharan Africa (SSA) by 2030 from 590 million to 655 million [8].

Since higher population densities translate, on average, to lower connection costs, urban and peri-urban areas will be connected faster to the national grid. However, for the more remote areas, extending the access to the off-grid population through different technological means is a matter of cost comparison. For example, the average levelized cost of electricity (LCOE) per megawatt hour (MWh) of grid-supplied electricity in East Africa rises from just over USD 97/MWh (when the grid is already built) to more than USD 435/MWh [9] even in cases where power lines must be extended only by 2–3 km to reach the population. This means that the LCOE for the locations further than 2–3 km from the existing grid will be at least 350% higher.

4.2 Close-to-the-Grid

The close-to-the-grid population is represented by those consumers located in the immediate vicinity of the national grid (in many cases, their households are even below transmission lines or next to electricity poles), but for which a physical connection to their houses/businesses is missing. Although already having access to some stand-alone solar solution (pico PV, SHS and mini-grids), this segment of the market still represents an untapped potential and a diversification market for DRE companies. On the one hand, over time, households and commercial and industrial (C&I) consumers could require additional energy services and capacity to satisfy their needs, such that additional appliances, bigger storage units and more diversified financing mechanisms for their acquisition are necessary. On the other hand, although the extension of the traditional grids can be either cost prohibitive for the utility or not cost efficient at present, as this market segment grows, it will also make itself ready for the grid.

The level of grid readiness depends on the infrastructure factor (e.g., in-house wiring, appliances), the financial factor (e.g., customer financial education, creation of a payment history), the social factor (e.g., energy usage patterns, incorporation of productive-use activities) and the economic factor (e.g., creation of an elastic demand market for higher-quality outputs/products).

The number of households relying on stand-alone solar PV systems as their primary or secondary energy source is predicted to rise from 25 million in 2015 to 99 million worldwide in 2020 [5], while the retail value of the off-grid market would grow to around USD 2.5 billion by 2020. All market segments would continue to grow, but larger SHS (larger than 10 W) are likely to increase their share of served households from about 10 to 25% by 2020 [10] as they would continue to become even more affordable and as consumers trade-up from portable lanterns, using that first rung to improve their access to energy [2].

4.3 Weak-on-Grid

The weak-on-grid population is represented by those consumers connected or officially considered on-grid, but facing the challenge of an unreliable national grid. Extending and densifying the national grid is not enough to ensure universal access to electricity. Countries need to increase their generation capacities to meet the growing demand, as well as to upgrade ageing or low-quality transmission and distribution networks. Where the national grid is expanding without an increase in its generation capacity, the electricity services cannot be offered continuously. The quality of electricity highly depends on the quality of equipment across the transmission and distribution networks, as well as on the geographical proximity of generation sites. Apart from unplanned outages (e.g., due to extreme weather events, animal contact with lines of transformers or electricity theft), when faced with a shortfall in supply, utilities, in most cases, resort to load-shedding. Estimates[4] show that in countries with significant off-grid population, an average of 60% of rural on-grid customers and 20% of urban on-grid customers live in unreliable-grid areas (or 47% nationally) [2]. When the missing generation capacity is mixed with poor distribution and transmission infrastructure and mismanagement, which is often the case, irregular power outages lead to unreliable electricity supply. Although the quality (in terms of reliability and availability) of urban-based grid infrastructures is assumed to be higher than rural ones, the general lack of data and statistics does not provide full details on the disparity between all countries in the Global South, regarding power outages.

5 Technologies to Solve the Problem

DREs can be a fast and cost-effective way to advance energy access in the remote areas. Local renewable energy generation reduces transmission losses, can help stabilize prices and lowers carbon emissions. DREs are in constant growth because of technological progress, cost reduction, improvement of the political situation and/or reduction of administrative barriers. Solar DREs have gained predominance due to their easy implementation, efficient hardware and continually falling prices. Until 2017, the global off-grid solar sector has provided electricity access to an estimated 73 million households (or around 360 million people), making them less dependent on fossil fuels for their lighting needs [2].

An SHS is a small-scale and autonomous electricity generation and supply for end-users. It is normally composed of several independent components: solar PV modules, charge controllers, battery and the loads, as illustrated in Fig. 5. It produces DC power for a wide range of electrical appliances from lighting, mobile charging

[4] Based on a weighted average for the countries: India, Indonesia, Philippines, Ghana, Senegal, Pakistan, Bangladesh, Ethiopia, Papua New Guinea, Tanzania, Myanmar, Kenya, Uganda, Nigeria and Democratic Republic of the Congo.

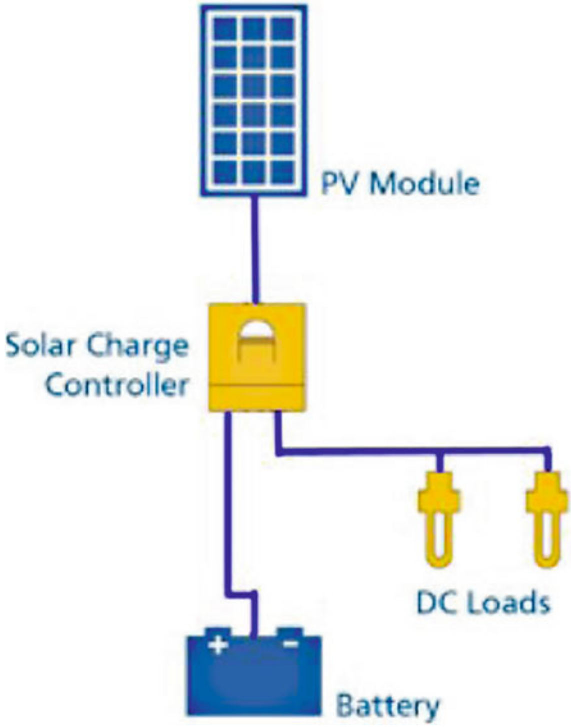

Fig. 5 Solar home system schematic [11]

and up to productive appliances such as water pumps. For AC loads, the system can integrate an inverter. The typical user segments are households, businesses and C&I customers and community facilities (schools, health centres) up to Tier 5 capacity.[5]

The smallest of the SHS (10 W) is considerably basic and provides enough power only for a couple of lights for several hours. The larger systems can provide lighting for an extended period and charging for a mobile phone, although some trade-offs are required. It is worth noting that the system specifications of individual SHS can vary widely and so can their price. Below 100 W, the systems are relatively homogeneous, and the focus is on low upfront costs. These inexpensive entry-level systems offer smaller battery storage capacity to reduce costs and increase affordability. However, at around 100 W or greater, product differentiation begins, with a range of systems with greater or lesser capability based on battery size and service provided (e.g., mobile phone charging docks, small radios, etc.). Accordingly, the small sub-1 kW

[5]MTF redefines energy access from the traditional binary count to a multi-dimensional definition as "the ability to avail energy that is adequate, available when needed, reliable, of good quality, convenient, affordable, legal, healthy and safe for all required energy services". That is, having an electricity connection does not necessarily mean having access to electricity under the new definition, which also takes into account other aspects, such as reliability and affordability. Energy access is measured in the tiered spectrum, from Tier 0 (no access) to Tier 5 (the highest level of access), as shown in Fig. 4.

size group of SHS has an extensive range of total installed costs: from as low as of USD 4.45/W to as high as of USD 17.82/W, with the majority of systems lying in the range between USD 5.9 and USD 14.5/W [12].

In general, SHS is highly expandable and can satisfy a wide range of household energy needs. Many SHS are sold without the need of subsidies as they remain within the affordable range of rural end-users. Larger systems with higher upfront costs require mature business models to help cover the investment. The stand-alone solar market segment has expanded with an average annual growth rate of 140% between the years 2013–2016 favoured by pay-as-you-go (PAYG) strategies [2]. This trend is expected to continue and overcome the pico PV solar market revenues between 2023 and 2025 [2]. There is an indirect link between the stand-alone solar market segment and PAYG penetration. As mobile money ecosystems mature and spread, one of the biggest barriers hindering stand-alone solar market growth will be removed.

6 Applications of the Technology

In 2017, the most demanded appliances by DRE users were consistently LED lighting, mobile phones and mobile phone charging banks. These are also the three most widely available products nowadays and can be considered basic. The DRE appliances market is not limited to the household segment. The appliances, such as grain millers, rice hullers, egg incubators and milking machines, are also utilized in the C&I sector. Also, although little data are available, the healthcare and clinical sector benefit from off-grid appliances for refrigeration (e.g., vaccines),[6] information and communication technologies (ICT) (e.g., computers, radios and vital signs monitors) as well as neonatal infant warmers. This is an indication of the commercial opportunity for DRE companies to extend their product portfolio beyond electricity-providing products.

In fact, in 2018, a drastic change observed in the product ranking could suggest that the off-grid sector may be shifting its focus collectively towards larger business/productive appliances such as refrigerator and solar water pumps [13]. One reason for this shift could be the increasingly saturated market for phone charging and lighting. As solar lamps now routinely come with a phone charger port, this could mean that the phone charging business is no longer viable in many markets. The global off-grid appliance market itself is critical for increasing access to electricity and services. For those end-users lacking access to reliable electricity, a highly efficient use of the amount of power that they can afford (or access) is crucial, as it enables off-grid customers to run more appliances on a certain (even if limited) amount of electricity.

[6] As outlined in Chapter "Solar-Powered Cooling for the Remote Tropics" of this book.

The off-grid appliance market and the renewable energy market are therefore inextricably linked: with efficiency improvements and an increasing number of customers moving up the energy ladder, the global market is poised for significant growth with the potential to become a USD 4.7 billion market by 2020 [14]. Innovations in business models reflect the connection between these two markets: an increasing number of SHS companies are extending their product portfolio by bundling access to energy and DC appliances all-in-one. It is important to mention that generally speaking, household appliances, whether in the Global South or North, are running on DC but are AC-connectable (mobile phones, TVs, radios and laptops). Off-grid appliances running on DC and DC-connectable are favoured because they eliminate the need for and losses of DC/AC conversion. The drawback is that, in general, DC appliances are relatively more expensive. The higher cost of DC appliances is caused by the current small production volume and the current level of market and technological maturity. Nonetheless, prices are already starting to decline. Recent technological advances have also provided the market with highly efficient DC appliances at a cost that is affordable by under-electrified populations. The DC appliances available in the market can be categorized into two: consumptive appliances, such as fans, TV and refrigerators, as well as productive appliances such as water pumps, sewing machines and power drills.

The market is not only constrained by the end-customers' purchasing power, but also by their limited access to electricity. The projected growth of the SHS market and the greater access to electricity is expected to go hand-in-hand with the rise in sales of highly efficient DC appliances, both trends reinforcing each other, especially in the off-grid areas, where people acquire appliances for the first time. A few analyses and projections suggest that the addressable market for TVs, fans and refrigerators will require new market entrants to supply this anticipated demand [14]. For example, the market for off-grid TVs is expected to experience a significant year-to-year growth (about 25%) [13]. The off-grid TV market is particularly important as it can have one of the biggest socio-economic impacts [14] by providing access to information and entertainment. A smart TV can represent more than just a one-way communication towards a passive viewer; it becomes a two-way channel through which the consumer can actively interact and communicate. Smart TVs, much like smartphones and smart home devices, offer internet connectivity, can run sophisticated apps, manage other devices (e.g., lights, thermostats) and even include voice command. When it comes to refrigerators, there are high expenses as they are exposed to high transportation costs due to their large size.

7 Business Models

Understanding the weak-on-grid and close-to-the-grid segmentation reveals that the line between off-grid and on-grid markets segments is disappearing.[7] Current DRE companies come from diverse paths of business: from established on-grid Western and local energy market players looking for new market opportunities in off-grid, to completely new off-grid energy ventures with no track record in traditional energy, or even financial institutions which are diversifying their portfolio. At the same time, pico PVs, SHS, mini-grids and the national grid are increasingly recognized as complementary rather than competing solutions, not only in current completely off-grid scenarios, but also in weak-on-grid and close-to-the-grid environments. Indeed, the increasing number of those devices connected to the national grid is an opportunity for DRE companies, whose value proposition does not represent a double infrastructure, but a complementary offer to the grid. Accordingly, understanding the potential of DRE companies implies also a look at the growth and development of on-grid markets from the perspective of off-grid markets. The adaptability of products and/or services to the grid and the embedment of the DRE business strategy in the national electrification plans in the Global South are key for understanding the future of utilities worldwide.

7.1 Microfinance …

Originally, microfinance was focused on the provision of small loans to low-income families to help them undertake productive activities or grow their small business. From the beginning of the 2000s, the possibility to deliver energy services, such as improved cooking ovens or solar lighting systems, through end-user financing schemes offered by microfinance institutions (MFIs) started to become a largely discussed topic. Microfinance can, in fact, support the dissemination of SHS by making energy systems more affordable. The prominent role that MFIs can play in this field derives from their ability to offer flexible loans and adapt their services to the needs and income patterns of the poor.

Nazir and Hussain are two of the four million Bangladeshi SHS users who have acquired their system through microloans. Already back in 2003, Bangladeshi authorities initiated a publicly co-funded SHS microloan programme, managed by the public Infrastructure Development Company Limited (IDCOL) and implemented through local MFIs (so-called partner organizations). The IDCOL SHS programme

[7] In 2017, M-KOPA Labs published a note on lessons learnt from their experience with rural electrification in Kenya. According to the note, the population can be segmented relative to the national grid: (i) bad grid segment (access to an unstable power supply); (ii) idle grid segment (population unable to use their grid connections beyond lighting; in need of highly efficient appliances); (iii) under grid segment (households within connection distance of a low voltage transformer but not connected to the grid).

is characterized by local stakeholders implementing the programme in a decentralized manner and by a highly standardized SHS, which is packaged with a simple microloan for the end-users. The distribution system to bring the SHSs to rural Bangladeshis is one of the key elements of the programme. The four million SHSs installed are even more remarkable, considering that the solar market did not exist in the 1990s and none of today´s more than 50 IDCOL partner organizations—which are in charge of organizing the distribution of the SHSs—were active before the IDCOL SHS programme started. However, there are two exceptions, the distributors Grameen Shakti and BRAC. Both started operations before the IDCOL programme was initiated. Grameen Shakti (GS or "village energy" in English), one of the most successful and innovative MFIs in the world, is a spin-off of the popular and well-established Grameen Bank. Its founder, Muhammad Yunus, and the Grameen Bank itself, were awarded the Nobel Peace Prize in 2006, "for their efforts to create economic and social development from below".[8]

GS started off with the idea to migrate the successful MFI model of Grameen Bank into the energy sector, by utilizing a one-hand business model. Operations started in 1996, and its business model was based on three principles:

1. The customer/user of the SHS is responsible for the financing. He/she pays a down payment and commits himself to monthly instalments.
2. GS field staff provides full service, including installation, collection of instalments and maintenance.
3. The provided SHS is fully owned by the user.

The provision of energy services can offer a profitable diversification strategy for the portfolio of MFIs [15]. In this regard, the most commonly practiced model by MFIs engaged in energy lending is the two-hand model in which the MFI partners with a specific technology supplier provide their clients with quality systems and offer proper installation and after-sales services. In this model, the MFI takes care of the financial services, while the supplier copes with all the processes related to the provision, installation and maintenance of the technology. While this may solve the issue of low-quality systems or installation, a major drawback is the proper allocation of responsibilities between the MFI and the supplier, more specifically due to the need to combine their respective infrastructures. A strong partnership and a common vision shared by the energy provider and the MFI at the management and operational levels are crucial for ensuring the long-term success of the partnership. International experience shows that over time, MFIs tend to vertically integrate the energy business and to take over the technical responsibilities, especially if the energy provider is not delivering proper services or product guarantees, which are crucial to loan repayment [11]. Division of responsibilities and allocation of risk is a major challenge that the one-hand model manages to overcome. In this model, the MFI or technology supplier

[8]According the Nobel Peace Prize 2006 press release, The Norwegian Nobel Committee (https://www.nobelpeaceprize.org/); the statement goes on "Lasting peace cannot be achieved unless large population groups find ways in which to break out of poverty. Microcredit/microloans are one such means. Development from below also serves to advance democracy and human rights."

becomes the sole entity providing credits to the end-user as well as taking care of the provision of the technology, installation and after-sales services.

Yet, with the exception of Bangladesh, scaled-up and financially sustainable energy-lending programmes based on traditional microfinance are scarce [16]. Despite the availability of models that allow different levels of involvement of the MFI into the field of energy service supply and a significant market opportunity, implementing such programmes has proven to be particularly challenging when it comes to financing larger technologies such as SHS, where the required financing can exceed the typical cash loan amount that MFIs are accustomed to [17]. In some regions, such as East Africa, this has led the sector away from traditional end-user microfinance to PAYG mechanisms to bridge affordability barriers to accessing renewable energy technologies.

7.2 … and PAYG

By relying on mobile phones as a platform for making payments, PAYG offers its customers increased flexibility in their payment plans both in terms of upfront payment, as well as amount and frequency of instalments. For example, ICT-enabled PAYG has been one of the main drivers for the scale-up of SHS in the African continent. In financial terms, PAYG refers to leasing-based finance set-ups which allow end-customers to either purchase a clean energy generation asset (i.e., lease-to-own) or perpetually use the energy service delivered by it (i.e., lease-to-use). While the former allows end-customers to gain ownership through incremental payments, the latter is comparable to a typical utility service, whereas the asset ownership remains with the energy service provider. The current lease-to-own set-ups in the market span from as little as 1 year up to 10 years. In technological terms, PAYG has been enabled by a combination of ICT technologies, including embedded remote controls for switch-off and usage monitoring. The lockout technology turns borrowers' lighting (or lack thereof) into an immediate and tangible reminder to repay their debt, making clean energy a flexible, as-you-go experience, akin to a prepaid mobile phone plan [18].

The first PAYG-enabled renewable energy technology market has been the solar one. With a beginning in the early 2010s and annual growth rate of ~140% in the last 5 years [19], PAYG sales of differently-sized SHS (4–200 W+) have totalled 800,000 units in 2016 and are forecasted to reach up to 7 million units worldwide in 2020. Four East African markets (Kenya, Tanzania, Uganda and Rwanda) are making up most of the PAYG sales (>95%) [19]. Fig. 6 shows the geographical distribution of the main PAYG players. While East Africa leads in terms of variety and number of PAYG solutions due to the strong mobile money ecosystem, India has a very low PAYG penetration corresponding largely to its minimal mobile money market and relatively low uptake of plug-and-play SHS.

SHS companies can be assessed and classified according to which energy access tier(s) their product/service offering cater to using the MTF framework as shown

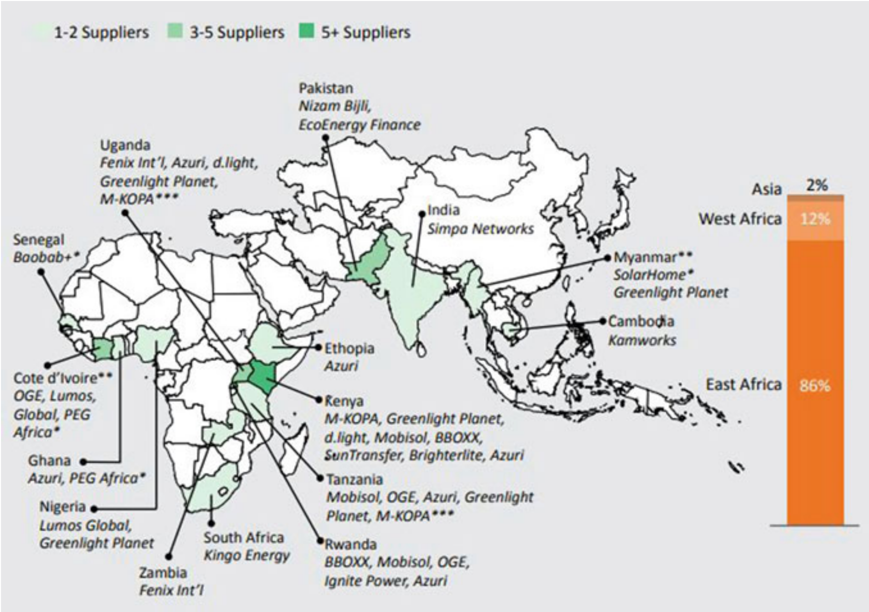

Fig. 6 Presence of PAYG players by country and geographical share of the PAYG market (2013–2017) [2]

in Fig. 4. By observing SHS companies' offerings through the MTF lens, differences in their general focus on standardization versus customization in their products, processes and offerings can be observed. SHS companies with business models requiring fast moving of smaller units (fast-moving consumer goods style) for lighting and communication (Tier 1) depend on plug-and-play characteristics of their offerings with rather low complexity for its functioning and enabling the last mile/end-customer to install the SHS easily. Current solar companies practicing ICT-enabled PAYG offer products in Tier 1 to Tier 2 range of capacity. The business model practiced requires standardization for fast distribution, ease of use and low level of technical skills required at the last mile (i.e., the use of plug-and-play solutions). Accordingly, the hardware is limited in weight and size and provides a limited capacity of electricity, corresponding to the lower tiers of the energy access ladder.

8 Swarm Electrification as the Future

A SHS is an attractive individual solution for the unelectrified population, allowing users to "mine the sun"—it is the most extreme form of distributed energy, as it is a closed system that allows one to produce electricity directly where it is consumed. However, it is not a community solution; it creates limited individual impact, while enhancing individual ownership. To reach the value added at the level of the community, as well as enabling the individual itself to climb the energy ladder seamlessly, numerous individual systems need to be installed and used, while the economic benefits aggregated as a whole. This is also one of the reasons why governments prefer top-down centralized electrification approaches, irrespective of their cost, for reaching the last mile and the end-user's high barrier for getting connected (in many cases due to the prohibitive costs of connection and wiring of the house, as well as access to and financing of appliances).

Top-down centralized electrification solutions, however, need to tackle a redundancy problem: integration of the existing user infrastructure with the newly created infrastructure. A user living in an unelectrified area does not necessarily mean that he or she has no electricity usage; the user might have access to a car battery, a diesel/gasoline generator and/or a DRE. As DRE expands rapidly in the Global South, so do the appliances, which in their majority are DC based. Thus, the newly emerged bottom-up infrastructure can lead to a usage lock-in for DC power. As the centralized national grid slowly reaches the last mile, it also forces an AC-based infrastructure, either restricting the end-user due to her range of DC appliances, or pressing her into acquiring additional devices that allow for the conversion AC to DC.

However, there are technical solutions that tap into the existing user infrastructure and facilitate the modular growth of energy access in the remote areas of the Global South. Swarm electrification drives a transformation from stand-alone solar systems and households without energy access to P2P microgrids [20]. In such P2P swarm microgrids, SHSs are no longer individual solutions, but rather contribute to the whole by pooling the surplus electricity generated (consumers become prosumers) and activating the unattended users. Compared to a centralized microgrid, the swarm P2P ones can grow, in a bottom-up manner, through the incorporation of new and/or existing usages, storages and generations, enabling a network economy based on prosumerism and local value creation.

As Fig. 7 shows that the P2P swarm microgrid grows incrementally, bottom-up, it can reach the national grid, transforming the last mile of electrification into the first mile. Thus, on the one hand, stand-alone decentralized solutions become, when interconnected, the infrastructure itself that should have been built through the expansion of the national grid. On the other hand, they also become a service provider to the centralized national grid, by providing shared storage to the grid in order to stabilize frequencies or to compensate demand in other parts of the grid.

Nazir and Hussain are part of a P2P swarm microgrid in Bangladesh. At *an individual level*, each of them has managed to unlock the potential of their respective SHS—Nazir is no longer bounded in his daily activities by the limitations of its storage or generation capacity; if he needs additional electricity to watch a live cricket game on his DC TV: he simply buys it from Hussain or from any other member of the P2P swarm grid who now generates income by selling the locally, individually produced and stored renewable electricity—"mining the sun". At *a collective level*, Nazir is part of the swarm electrification infrastructure, becoming a battery-enabled energy service provider for the national grid, available at any hour. ME SOLshare, the Bangladeshi start-up, which runs a platform on which the swarm electrification

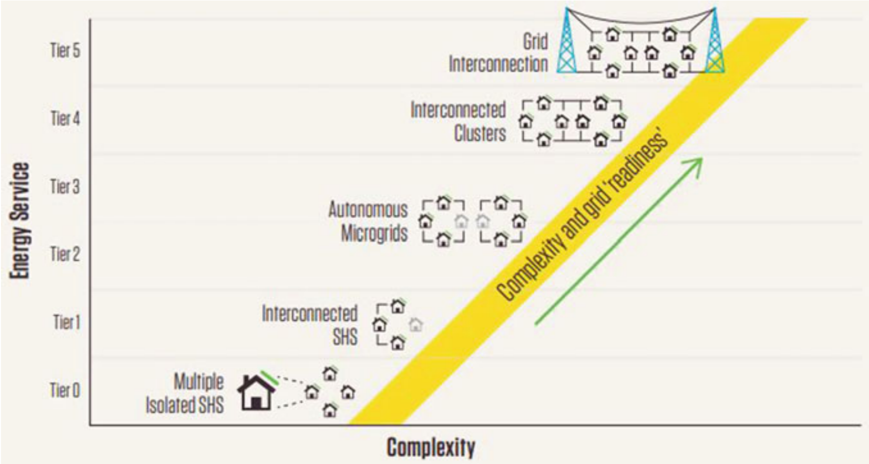

Fig. 7 Electrification path through swarm electrification [21]

approach is currently being rolled out, has set its goal to be better than the grid. This, in turn, opens up an entirely new question: Is it possible that once Nazir swarms towards the grid, his own infrastructure would become more reliable and affordable than the national grid itself? And in such circumstances, would Nazir opt out from the national grid? Presently, this trend is observed in the Global North, where consumers voluntarily go off-grid [22]. Are we seeing the first signs of a reverse innovation in electricity? These innovative approaches towards electrification in the Global South, in which the vulnerabilities of top-down centralized structures are offset through bottom-up decentralized infrastructures, can become the future in the Global North, as solutions to a weakening and obsolete centralized infrastructure [23]. We just need to turn the world a little bit.

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The Sustainability Dilemma of Solar Photovoltaic Mini-grids for Rural Electrification

Amalia Suryani and Patrick Dolle

Abstract Solar photovoltaic (PV) mini-grids are generally seen as a way to provide an affordable and sustainable energy supply to rural communities. Especially in regions with high economic growth, high energy demand, and remote areas without a grid connection like Southeast Asia, many different actors plan, build, and run PV mini-grids. Nevertheless, there are many barriers to be tackled when using PV mini-grids for rural electrification. In this chapter, we explore the opportunities in implementing PV mini-grid programmes as well as the challenges along the economic, social, and environmental dimensions of sustainability. We also present ideas on possible solutions, based on the experiences of the authors in Indonesia, as well as a literature review from PV mini-grid programmes in other countries. We conclude that the sustainability dilemma of PV mini-grids can be resolved by fulfilling the following factors: PV mini-grids projects (1) are implemented in the remote villages with clustered settlements where a main grid connection is not feasible, (2) involve the rural communities from the planning phase to the end of the project cycle and provide necessary knowledge on a continuous basis, (3) apply life cycle thinking in developing the system, (4) ensure the autonomous functioning of the system—including quality assurance of the installations and warranty for all components as well as using locally available materials wherever possible—and (5) incorporate a scenario when the national grid is available for the PV mini-grid community. This chapter is written by and addressed to practitioners by providing a comprehensive overview of the potentials and risks of using PV mini-grids.

Keywords Energy access · Mini-grid · Photovoltaics · PV mini-grid · Rural electrification · Sustainability

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1 Introduction

In 2017, the global electrification rate is about 89% [1, 2]. That means more than 800 million people worldwide still have no access to electricity, especially in rural and remote areas. Even if considerable progress has been made (according to Organisation for Economic Development (OECD)/International Energy Agency (IEA)), over 1.4 billion people were without modern electricity services in 2010 [3] and over 1 billion in 2016 [4]), the global electrification rate is only slowly increasing, as those who remain unconnected are often located in areas where extending the existing grid is very difficult and expensive. Considering the recent development, in 2030, approximately 650 million people would still be left without electricity [1]. This is despite the Sustainable Development Goal 7 aiming to "ensure access to affordable, reliable, sustainable, and modern energy for all" by then [5]. These numbers also neglect that access to energy is often defined in very different ways; for example, in some countries, one hour of electricity supply per day is already viewed as "electrified". Therefore, the number of people with limited access to electricity may be much higher than the official numbers published by the World Bank or other organisations.

In Southeast Asia, the energy demand is among the fastest growing in the world. But due to the existence of thousands of remote islands and other rural areas, there are still around 45 million people in Southeast Asia who have no access to electricity [6]. These communities are mainly dependent on agriculture. On top of lacking energy, there is often no or only limited access to information and education, no or simple sanitary facilities, and no or a difficult connection to the closest urban areas.

Very often, photovoltaic (PV) system is seen as a solution to bring energy to these rural communities and in many cases replacing the high-maintenance and polluting diesel generators. For small communities consisting of several households, often the so-called PV mini- or micro-grids are installed, meaning that the energy supply is independent of the national grid. These systems are equipped with a solar power generator (i.e. PV modules), energy storage (i.e. battery bank), power electronics, and auxiliary components such as cables and protection devices.[1] In this way, the rural communities are empowered to produce their own energy and are autonomous from the grid. Due to this big potential of electrifying rural areas using PV mini-grids, many governments, non-governmental agencies, and implementing agencies of international development cooperation have been promoting the installation of such mini-grids in the last decades worldwide, especially in emerging economies with high energy demand and low electrification rates.

Unfortunately, the big potential comes with many challenges, among others: difficult planning phases due to the involvement of many different stakeholders, land rights issues, long and challenging transportation routes to deliver the PV system

[1]All components of PV system other than the PV modules are commonly known as balance of system.

components, and the lack of skilful personnel in those areas to ensure a good installation, operation, and maintenance. Moreover, small returns on investment are a significant problem as they cause a lack of interest from private investors to successfully implement PV mini-grid systems.

In this chapter, we investigate the potential and challenges of PV mini-grid systems for the electrification of remote areas in Southeast Asia by looking particularly at Indonesia as a case study. With its more than 250 million inhabitants, its approximately 17,500 islands (of which around 2300 are inhabited [7]) and more than 700 installed PV mini-grids[2] [8], Indonesia is a good example to illustrate both the potentials as well as the problems in implementing rural electrification using renewable energy technology, in particular the PV mini-grids. An example of a PV mini-grid installation is shown in Fig. 1. Additionally, we also discuss examples from other countries in Asia and Africa to enrich the insights on certain issues in PV mini-grid implementation. Furthermore, the different PV technology applications and mini-grid operation models are briefly described to provide a common understanding of the subject. Subsequently, the different challenges are discussed, including economic, social, and environmental perspectives to finally answer the question whether PV mini-grids can be a sustainable solution for electrifying rural areas and achieving the global goal of ensuring universal access to affordable, reliable, and modern energy services by 2030.

Fig. 1 Indonesian government has been massively deploying over 700 PV mini-grids from 2012 to 2018 with installed capacity ranging from 10 to 150 kWp. Some of these sites can be viewed here: http://remap-indonesia.org/. *Photo* GIZ

[2]This only accounts for the PV mini-grids developed by government agencies.

2 Technologies and Applications

This section describes the existing technology applications for electricity services in typical rural areas in tropical countries, particularly the Southeast Asian region, with emphasis on the PV technology solutions.

Before entering the era of electricity, people in rural villages commonly use kerosene lamps for lighting purposes. With the growing demand of services, small diesel generators become an advanced option preferred by individual households for more energy-intensive activities. As part of the electrification strategy, diesel-powered mini-grids were commonly implemented in isolated regions such as small islands. These were prevalent practices in many regions in Southeast Asian countries.

Interestingly, depending on the locally available sources of energy, some renewable energy technologies were also introduced quite early, for instance the run-of-river micro-hydro power (MHP) plants.[3] With a capacity of 10–100 kilowatts (kW), an MHP can be a reliable basic power source for a village with around 20–200 households. Rural communities in countries like Indonesia, Malaysia, Myanmar, and the Philippines[4] have been applying this technology for decades. The turbine technology itself has been evolving, particularly in its efficiency, and is currently widely manufactured locally in these countries. Nevertheless, not all remote villages have hydro potential and MHP cannot be applied in these places.

The more modern development in PV technologies has brought innovative solutions for villages with abundant solar radiation. Different PV technologies serve different applications and scales of electricity solutions in rural areas located remotely from the grid. The smallest-capacity device is the pico solar lantern, which is mainly used for lighting. A pico solar lantern set usually consists of a lamp with a built-in battery, a PV module of 1–10 Watt-peak (Wp), charging cables, and other optional accessories (sometimes with a radio). In addition to lighting, the battery can also be used to charge small devices like mobile phones. Such lamps can be purchased as a stand-alone system or as a shared system where the end-users own (or rent) the pico solar lanterns without possessing their own PV module and charging cable. Instead, they will charge their lamps in a charging station owned by a nearby kiosk or operator. Sundaya,[5] an Indonesian company established in 1993, is one of the pioneers of PV solutions for rural households who do not have access to electricity grids. In the neighbouring country, Laos, Sunlabob[6] has been selling solar pico lanterns with shared charging business model since 2001.

[3] MHP and its applications in the rural Philippines are elaborated in Chapter "Micro-hydro Power System" of this book.

[4] These countries are active in the network of community-based small-scale hydropower practitioners in the global south. www.hpnet.org/.

[5] www.sundaya.com/.

[6] www.sunlabob.com/.

In a settlement with scattered houses, the individual house solution, commonly known as the solar home system (SHS), is often the preferred option.[7] It is usually a small PV system ranging from 50 to 200 Wp capacity which operates at a rated voltage of 12 V direct current (DC). Such a system is generally used for basic power purposes like lighting and other low power DC appliances like DC televisions (TV). An SHS typically consists of a PV module, a battery to store the energy for use at night, and a charge controller to regulate the battery charging and discharging. The PV module can be installed on the roof or a stand-alone pole in the vicinity of the house.

A slightly bigger system, widely known as PV charging station, is usually installed in the community centre where the community can have services such as charging of mobile phones and pico solar lanterns. The PV modules, solar charge controller, power inverter, 12 V battery bank, and charging docks are centrally located in one common facility, which requires people to travel (a short distance) to obtain the services. Rental of pico solar lanterns is also a common practice in many villages. With a rental scheme, the community does not need to own or maintain its own individual system (i.e. SHS) at home.

These aforementioned solutions are examples of off-grid PV technologies. Other specific applications of stand-alone systems for non-lighting purposes, such as solar water heater, solar cooling,[8] solar irrigation, water pump or water purification, are not discussed in this chapter. An overview of the applications of PV technologies is given in Fig. 2.

In a settlement where the houses are clustered closely and therefore dense enough to create electricity demand, and where sufficient land is available, PV mini-grids become a favourable solution. PV mini-grids, also known as micro-grids or isolated grids, are widely applied in many remote areas and are the main focus of this chapter. The scheme has a battery storage and its own grid system to distribute the electricity to the users.

There are different definitions of mini-grids adopted by different countries. The International Renewable Energy Agency (IRENA) defined mini-grids/micro-grids as “distributed energy sources (including generators and energy storage appliances) and interconnected loads integrating an energy infrastructure, which can operate in parallel with the main grid, off-grid or in islanding mode” [9]. In this chapter, we use the term PV mini-grid to define a small, localised, stand-alone solar power generation system with a capacity of 10 kWp to 10 Megawatt-peak (MWp) and a limited distribution to a number of customers via a distribution grid that can operate in isolation from the main transmission networks [10]. The main advantages of PV mini-grids are their ability to provide electricity services for appliances with higher requirements and that they mostly operate in alternating current (AC) voltages which

[7]More detailed discussion on SHS and its impact on rural communities as well as its future development are explored in Chapter “Swarm Electrification: From Solar Home Systems to the National Grid and Back Again?” of this book.

[8]Various solar-powered cooling technologies are discussed in detail in Chapter “Solar-Powered Cooling for the Remote Tropics” of this book.

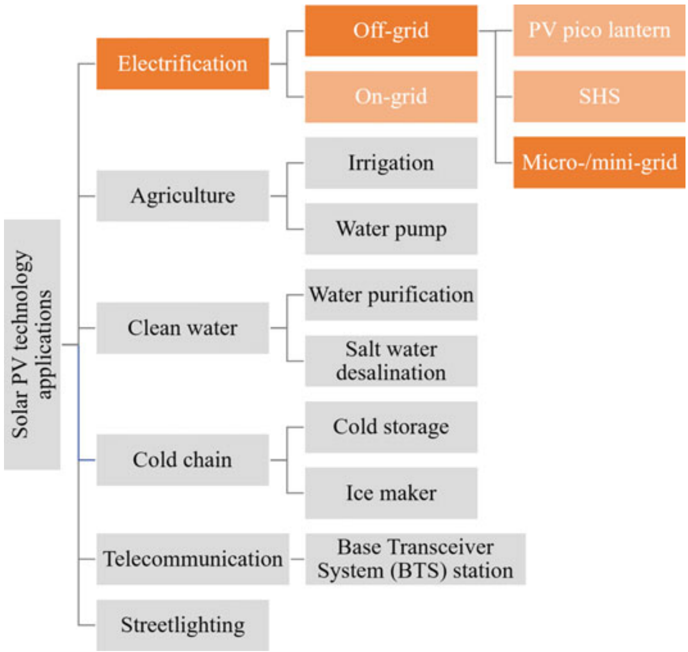

Fig. 2 Examples of solar PV technology applications. Only micro-/mini-grid is elaborated in detail in this chapter

can easily be transformed to higher or lower voltage levels. A PV mini-grid mainly consists of an array of PV modules, a battery inverter, solar charge controller(s) (a grid inverter for AC-coupled system), and a battery bank, as can be seen in Fig. 3. The lead–acid battery type is the most widely used in PV mini-grids, but there is a shift to use lithium-ion (Li-ion) batteries which are more energy dense and more durable.

The main purpose of a PV mini-grid is for electrification in rural areas. Having a PV mini-grid does not always result in the replacement of a fossil fuel-based power generation. In fact, some believe that a PV-diesel hybrid mini-grid is the optimum solution to improve the reliability of the mini-grid [12] as the diesel generator reduces the dependence on battery storage, one of the most costly components in the mini-grid [13, 14]. In Indonesia, however, generally the PV mini-grids are not complemented with a diesel generator as a backup. This is because despite the high subsidy and the one-price policy for fuels, fuel price in the remote villages can be extremely high. That is why the government aims at electrification using purely renewable energy sources available locally.

In Table 1, we summarise the typical applications of PV technologies in the off-grid rural electrification context including a cross-comparison with the ESMAP[9]

[9]The Energy Sector Management Assistance Program (ESMAP) is a global knowledge and technical assistance programme administered by the World Bank.

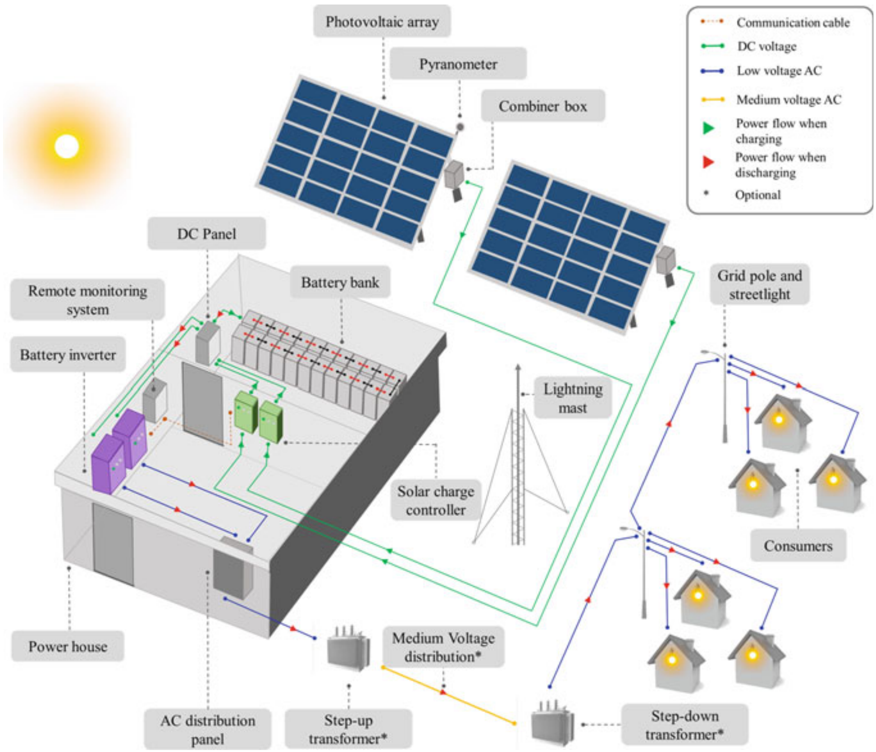

Fig. 3 Typical solar PV mini-grid scheme with its components. *Source* [11]

Table 1 PV technology applications in rural areas

Typical PV technology	Typical applications and services				
	System capacity	Power per connection	Service level	Daily energy supply capacity per connection	Type of services
Pico solar lantern	<50 W	Min 3 W	Tier 1	Min 12 Wh	Lighting, phone charging
SHS	50–200 Wp	Min 50 W	Tier 2	Min 200 Wh	General lighting, television, fan
Micro-/mini-grid	>10 kWp	Min 200 W	Tier 3	Min 1 kWh	Tier 2 and medium power appliances
Grid-connected	>1 MWp	Min 800 W	Tier 4	Min 3.4 kWh	Tier 3 and high-power appliances

classification on the level of electricity services as presented in its energy access multi-tier framework [15].

3 Operation Models

There are at least four business models commonly applied in rural mini-grids, namely the community-based model, the utility operator model, the private operator model, and the hybrid operator model. Each model contains a combination of arrangement about who invests in the development, who owns the asset, and who operates the system. In rural PV mini-grids schemes, asset ownership does not determine the operation and maintenance of the systems [12]. Usually, the ownership is transferred to the system operator which could be the rural community.

3.1 Community-Based Model

In this model, the local community operates and manages the system. In the case of PV mini-grids, most of the time the systems are largely, if not entirely, funded through grants from the government or donors. The asset ownership either remains with the funder or is transferred to a local community-based organisation. This scheme is applied in areas where the utility has not reached or where the private sector has no interest to invest. This can either be due to unfavourable regulation or economic viability reasons. In Indonesia, the community-based model is the most applicable model with asset ownership officially being transferred to local authorities, e.g. the Governor, meanwhile the operation and maintenance are carried out by the community.

Under this model, it is strongly advised that the community establishes a legal entity to empower the organisation in managing the system. It can be in the form of a cooperative, a village-owned enterprise, or an enterprise co-owned by the community and the local government. Through a cooperative model, the electricity customers will be members who have a voice to determine the operations and the management of the mini-grid. While through an enterprise model, the organisation may have access to funding from the government or other entities.

3.2 Utility Operator Model

In this model, the national or regional electricity utility is responsible for the installation, operation, and maintenance of the mini-grid. They generally also own the asset. In the case of renewable energy or hybrid systems, the financing can be partially supported by the government to relieve the capital investment burden. Usually, the electricity tariff is the same as the tariff for regular utility's customers connected to the main grid [10]. In case there is a gap of generation cost between the mini-grid and the regular electricity generation cost, a cross-subsidy scheme may be applied.

The Indonesian state-owned utility, Perusahaan Listrik Negara (PLN), initiated the 1000 Island Programme to electrify remote islands using PV mini-grids. The programme was included in the PLN's Electricity Supply Business Plan (RUPTL) 2013–2022 [16] and is still part of the latest RUPTL 2019–2028 [17]. Different from the Indonesian government's PV mini-grid programme, PLN implements PV-diesel hybrid mini-grids in its programme. Until December 2018, PLN has built and owns 78 PV power plants amounting to 12 MW [from the total installed generation capacity of more than 57.8 Gigawatts (GW) in Indonesia, including the rented power plants and independent power producer (IPP)] [18]. However, the statistics do not clearly state how many of them are grid-connected systems and how many are mini-grids.

As a comparison, in Kenya, the utility operator model is being implemented for PV-diesel and wind-diesel hybrid mini-grid systems. The Kenyan utility (Kenya Power, KPLC) operates and maintains at least seven hybrid mini-grids from the total of 19 publicly-owned and KPLC-operated mini-grids [19, 20]. The assets belong to the Kenyan government, while KPLC is responsible for providing electricity services to the customers. KPLC itself is partially state-owned, with 50.1% public and 49.9% private shareholding [20].

3.3 Private Operator Model

The private operator model is rarely applied for PV mini-grids for a few reasons, such as the high initial investment, low electricity demand which leads to low revenues, and high in-between component replacement costs. In this model, the mini-grid system is owned, installed, operated, and maintained by a private entity. Such scheme can be lucrative for MHP plants where the investment and maintenance costs are relatively low compared to PV mini-grids. Given the geographical challenges in most rural areas in developing countries, the private sector often needs some form of public financial support [10, 12].

In Indonesia, the government created an opportunity for private companies to build and operate renewable-energy-based mini-grids in remote places which are not covered by PLN under the Ministry of Energy and Mineral Resources (MEMR) Regulation No. 38/2016 [21].[10] An example of this model is applied by an Indonesian private company, Electric Vine Industries,[11] that introduced a modular PV system in Papua. Different from the usual PV mini-grid, this scheme allows several distributed modular 5 kWp PV systems to be connected to a local grid. The company conducts a

[10]Under the 1945 Constitution of the Republic of Indonesia, only the state-owned national utility PLN is allowed to sell electricity to Indonesian residents.

[11]https://www.electric-vine.com/.

full implementation of the system from planning, construction, operation and maintenance, and providing energy services to the community. It acts as a small utility in the village.

3.4 Hybrid Operator Model

This model combines two or more features from the three models above where the investment, ownership, and operation are carried out by different entities. A public–private partnership approach can be seen as a hybrid operator model. As an example, a public utility invests in the construction of a PV mini-grid and later transfers the operation and management of the mini-grid to a private company, including organising the tariff payment from the customers. The Renewable Energy Service Company (RESCO) approach is another example using a hybrid business model where a RESCO has a contract with the owner of the mini-grid. Under this model, a clear regulation allowing such a business model is a prerequisite.

The Millennium Challenge Account—Indonesia[12] introduced a business model which combines a private company and the local community as the operator of the PV mini-grid [22]. One of the projects is the development of four PV mini-grids with a total installed capacity of 600 kWp in Karampuang, a village in West Sulawesi province. They are expected to provide electricity to around 780 households. For the operation and management of the PV mini-grid, a village-owned enterprise was established, with 51% share ownership of the community through a cooperative and 49% owned by a private company. The ownership shares come from a compact grant from the U.S. Millennium Challenge Corporation (MCC). The operation model ensures 20 years of support from the private company to the community cooperative.

Box 1 Example of a regulation allowing private sector to develop and operate renewable energy-based mini-grids in Indonesia

The Regulation of the Indonesian Ministry of Energy and Mineral Resources (MEMR) No. 38/2016 [21] aims at accelerating the electrification initiative in approximately 2500 villages across the country by utilising renewable energy sources. The Regulation opens up the opportunity for private companies and cooperatives to develop and implement a small-scale power plant (up to 50 MW capacity) in areas that are not covered by the public utility, particularly the underdeveloped villages located in the small remote islands and border regions. The permit to act as a small utility providing electricity to the community shall be granted by the Governor, after the Minister gives approval on the business areas and an assignment for electricity provision is released. Despite

[12]Millennium Challenge Account—Indonesia (MCA-Indonesia) is a trustee institution formed by the Government of Indonesia as the implementer of the U.S. Millennium Challenge Compact Grant.

the supposed aim to allow private entities to sell electricity to the unelectrified population, only few companies have been able to obtain permission under this regulation.

4 Sustainability Challenges and Possible Solutions

All the technologies and operational models described in the previous sections suggest the possibility to bring sustainable energy solutions to rural areas and to foster the achievement of the global target of providing clean energy for all. In any case, the often-dispersed population and remoteness of islands make the expansion of the grid unviable, and mini-grid or stand-alone systems are the only available option for expanding electrification [23]. One of the claimed benefits of PV mini-grid is the reduced cost of electricity provision for remote regions, while the social and environmental benefits are often claimed despite limited evidence [24]. However, successful implementation of PV mini-grids is not as easy as many campaigns claim. There are several challenges and obstacles that have to be overcome by PV practitioners. Major risks facing the development of PV mini-grids are community integration, equipment compatibility issues, inappropriate business models and geographical isolation, among others [24]. In this section, the most common dilemmatic challenges are presented, categorised according to the three sustainability dimensions: the economic, social, and environmental dimensions. At the end of each subsection, possible solutions are discussed.

In a comparative study on MHP in Indonesia conducted by the German development agency Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH in 2013, there are six main areas to look at for the sources of sustainability risks to an MHP scheme as presented in Fig. 4. These six perspectives are the enabling environment (relevant to institutional setting), community preparation, technical

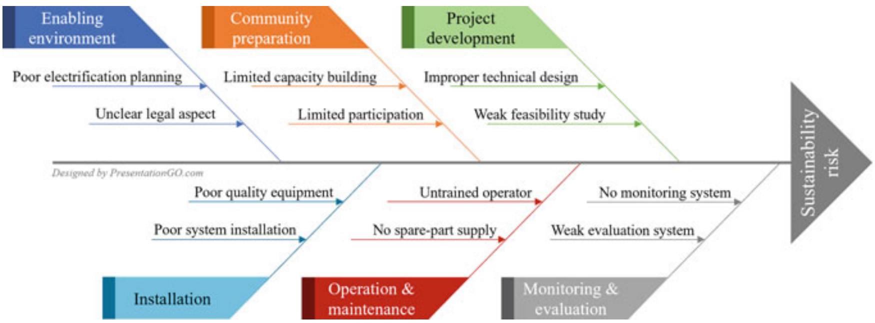

Fig. 4 Possible causes risking the sustainability of mini-grids. Adapted and modified from [25]

project development, system installation, management, operation and maintenance, and monitoring and evaluation [25]. Even though the study focused on MHP schemes, the results are also applicable to other off-grid rural power generation systems including PV mini-grids. The fishbone diagram illustrates the various types of challenges but does not necessarily imply the magnitude nor the urgency of the causes. Issues on poor electrification planning and unclear legal aspects including land rights, for instance, are among the institutional predicaments. These concerns are not less or more important than the issues of untrained operators or the absence of a (remote) monitoring system.

Embarking from the sustainability risks set forth above, we introduce three overarching questions by looking at the three dimensions of sustainability in order to assess the opportunities and challenges of using PV mini-grids for rural electrification.

4.1 Is It Economically Viable?

The costs of a PV mini-grid system can be divided into the capital expenditures (CAPEX), which include the costs of investment to plan and design the system as well as to purchase the components, and operational expenditures (OPEX). As most of the PV mini-grids in Southeast Asia are funded by the government or international donors (and then operated using a community-based model), the CAPEX is usually not an issue for the rural communities. The OPEX is more important as the PV systems are normally handed over to them after the completion of the system, including the responsibilities for operation and maintenance.

On the one hand, the mini-grid operation requires management skills and constant savings for repair and replacement of certain components. Considering the remoteness of the communities, the procurement of spare parts can be very costly and time consuming as the route of transport can be long and logistically challenging. On the other hand, there is a reduction of operation costs for the community when they can replace diesel fuel with the energy from PV. Hence, for the community-based model, the economic viability of the mini-grid depends on the success of the management to generate revenue from the electricity services.

The provision of electricity may also create more energy demand. For this reason, in areas where villages get energy supply from a PV mini-grid and the users are collecting tariff, the motivation for the electric utility to extend the grid to these regions will increase. This leads to a possibility of grid extension to the mini-grid communities which might make the PV mini-grid obsolete. Therefore, close coordination between the government's rural electrification programme and the utility's expansion plan is crucial for the effectiveness of the mini-grid projects. When the PV mini-grid is meant to eventually feed power into the larger distribution network, it has to be compatible with the existing transmission and distribution network. At the national level, the key elements to achieve the mini-grids' full potential are a clear grid extension plan and a regulatory framework on how to integrate mini-grids when the main grid arrives, as well as clear rules for setting the tariffs [4]. Such long-term perspective is essential for a successful mini-grid implementation. In very isolated places like remote islands, the mini-grids will most probably remain as stand-alone systems.

To answer the question if a PV mini-grid is economically viable, we will discuss two important aspects in more detail below: the cost breakdown and the tariff setting.

4.1.1 Costs Breakdown

CAPEX can be categorised into two: hard costs and soft costs. Hard costs are the costs related to the procurement of equipment and supplies, whereas soft costs are those related to the project development and logistics. We want to illustrate the different investment costs in different countries by referring to a benchmarking study published by the World Bank in 2017 [14] (in this study, the installation costs are analysed as a separate category). It is important to mention beforehand that prices can vary in different years of the mini-grid development and that a small sample size of the benchmarking study might not be statistically significant to conclude an average investment costs of PV mini-grids. However, these numbers can serve as a guide for the readers about the proportion of the different cost categories. The chart in Fig. 5 shows the categorisation of investment costs of ten PV mini-grids in Africa and six in Asia with installed capacity ranging from 10 to 228 kWp and the number of customers

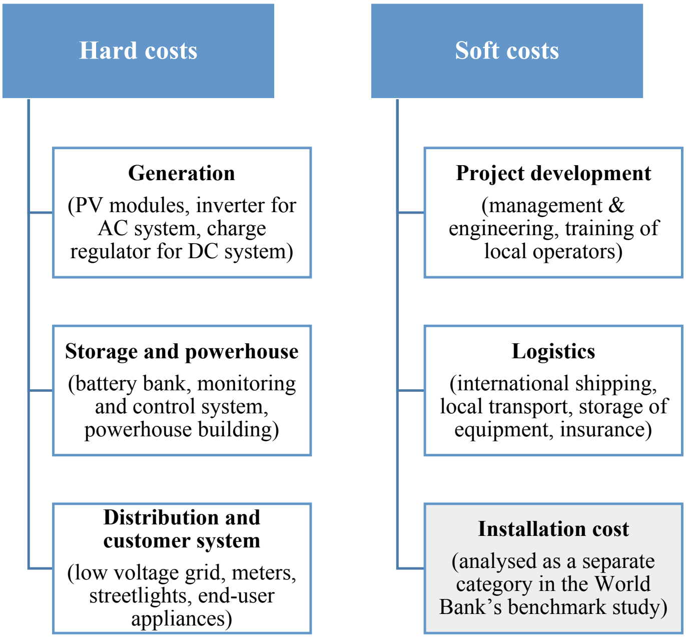

Fig. 5 Types of investment costs of solar PV mini-grids. Adapted from [14]

Table 2 Profile of five PV mini-grids for comparison

No.	Country	Year of start operation	Installed capacity (kWp)	Battery capacity (kWh)	Number of customers (connection)	CAPEX/kW without installation ($/kW)	CAPEX/kW with installation ($/kW)
1	Sierra Leone	2016	128	488	204	2868	3130
2	India	2017	30	86	95	2953	3207
3	Bangladesh	2017	228	887	1099	4607	4782
4	Myanmar	2016	10	87	130	8505	8859
5	Guinea Bissau	2015	200	1987	1421	11,875	16,314

Data from [14]

ranging from 39 to 1421 connections. These PV mini-grids started their operation between 2014 and 2017, of which half of them apply a "private utility" model, while the remaining apply a "public utility" and a "community-based" models.

The benchmarking study shows a quite wide range of CAPEX of the PV mini-grids: 3130 $/kW (for a 128 kWp system in Sierra Leone) to 16,314 $/kW (for a 200 kWp in Guinea Bissau). It also concludes that generation and storage and powerhouse components account for most of the overall CAPEX. Table 2 outlines the details of five mini-grid projects, such as the CAPEX, the installed capacity, and the number of customers. We highlight these five mini-grids to illustrate how the capacity and geographical factors may influence the investment costs, especially related to the installation works. It is apparent that PV mini-grid development may highly be dependent on the regional location, regardless of the PV installed capacity and the battery storage.

As an illustration for PV mini-grid projects in Indonesia, Table 3 presents the estimates of the direct and indirect costs based on the Clean Energy Handbook for Bank and Financial Institutions published by USAID Indonesia Clean Energy Development (ICED) in 2015 and other online sources [26]. Using these price estimates and excluding the mobilisation/demobilisation costs, a 15 kWp PV mini-grid may cost between $83,000 and $108,000 or between 5566 $/kW and 7186 $/kW, comparable with the systems in Bangladesh and Myanmar.

There is a downside in the top-down approach observed in the Indonesian PV mini-grid programmes in regard to the system sizing. Deploying nearly one hundred PV mini-grids per year since 2012[13] had been resource-intensive. The government therefore opted to standardise the size of the system in correlation with the number of households residing in the village. The mini-grid sizes range from 10 to 150 kWp, with a 5 kWp step difference in between. Problems arise when household data are not accurate which lead to either over-sizing or under-sizing the mini-grid capacity. Different from the publicly funded system, the mini-grids initiated by a

[13]The massive PV mini-grids programme by the Indonesian national government had ceased since 2018. PLN now has the mandate to continue the development of rural PV mini-grids.

Table 3 Price estimates for PV mini-grids component and installation in Indonesia

Components	Price range
Direct costs	
PV module	\$0.5–0.85/Wp
Inverter	\$0.25–0.30/W
Battery (VRLA)	\$0.13–0.15/Wh
Solar charge controller	\$0.25–0.30/W
Civil work	\$0.1–0.3/W
Commissioning	\$0.05/W
Cable and poles	Depends on the number of connection and distance of houses
Indirect costs	
Engineering design	IDR 40–60 million/50 kWp
Mobilisation and demobilisation	Depends on site location
Contingency	20–30% of total costs

Source [26, p. 79]

private entity pay more attention to the system sizing as they are not bound to a uniform tender specification applied in the government projects. A private company has the urgency to conduct a more careful calculation on their investment metrics such as their potential customers and revenue model.

4.1.2 Tariff Setting

In the community-based operator model, once a PV mini-grid system is commissioned, the communities have to organise funds to cover the OPEX. OPEX comprises some fixed costs, particularly the remuneration for the operators and management staff, and variable costs which include regular replacement for components like inverters, batteries, and public streetlights. The challenge is to balance these operational costs and revenues collected by the management. The stream of revenues to cover the mini-grid operation and maintenance expenditures can be obtained through connection fees, subsidies, and electricity tariffs [10], or their combinations. Connection fee, a one-time payment to connect a house to the distribution grid, varies in different countries, even in different regions. Based on cases from various countries in Africa and Asia, such connection fee ranges from \$65 to \$275 per connection and usually covers the connection and in-house installation [10]. Subsidies can be applied not only to support the project planning and development but also for the mini-grid operation and component replacement.

The last revenue stream is closely related to the communities. Generally, the customers pay a flat-rate tariff, which means that the actual energy consumption is not considered. This tariff can be distinguished into two types: power-based and energy-based. Both tariff types can either be prepaid or post-paid. Power-based tariffs are set based on the expected maximum power available to consume at one time. They require the use of a load limiter at the house connection point and are calculated on a Watt basis. The energy-based tariffs, meanwhile, are set based on the energy consumed by the customers. In the Indonesian PV mini-grid case, the customers are mostly connected to 200–300 W of power [27]. Most of the PV mini-grids apply the energy-based tariff with fixed daily allocation using an energy limiter device. Depending on the size of the mini-grid and the number of customers, 150–1000 Wh of energy might be allocated per connection per day. In the Annual Report of Energising Development (EnDev) Indonesia released in 2015, the reported average energy allocation is 320 Wh per household per day [28], much lower than the Indonesian average consumption of 4057 Wh per household per day.[14]

PV mini-grid tariff can be determined through consensus among the users or through a regulation set by the (local) government responsible in supervising the mini-grid operation. Both approaches should always consider the actual operational and maintenance costs. In some cases, the electricity tariff for PV mini-grid can be set according to the electricity tariff for the regular grid customers. Nevertheless, a subsidy scheme might be required to cover the discrepancy between actual operational costs and mini-grid revenues. In the Indonesian PV mini-grid case, there is a gap in the tariff setting as it does not take into account the costs of electricity, operation, and component replacement [29]. Moreover, although the tariff agreement will be formalised by the local authority—in this case the Governor—the consensus is solely dependent on the community's ability and willingness to pay.

Considering the nature of CAPEX and OPEX arrangement described above, an alternative operator model through a performance-based service contract can be pursued. This may involve two main actors: the government who provides funding for the initial installation and a private operator (i.e. RESCO) who will manage the operation and management. Such RESCO will be responsible for daily operation, maintenance, tariff collection, monitoring and reporting to the PV mini-grid owner.

4.2 Is It Socially Acceptable?

The underlying purpose of implementing a mini-grid programme in remote areas is to achieve universal energy access. Energy access is believed to be a key enabler of socio-economic development [15] as it provides services which allow the users to conduct various productive activities in their households and beyond. It is therefore important to not only binarily measure the access with electrified/non-electrified distinction but to also consider the quality of the energy access. ESMAP developed the multi-tier framework to measure the energy access based on seven attributes; Table 4 presents the classification based on two of the seven attributes: peak capacity

[14] Calculated based on data reference in PLN Statistik 2018 [18].

Table 4 Multi-tier matrix for measuring access to household electricity supply

Attributes		Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Peak capacity	Minimum power capacity rating (W)	3 W	50 W	200 W	800 W	2 kW
	Minimum daily energy capacity (Wh)	12 Wh	200 Wh	1 kWh	3.4 kWh	8.2 kWh
Availability (duration)	Minimum hours per day	4 h	4 h	8 h	16 h	23 h
	Minimum hours per evening	1 h	2 h	3 h	4 h	4 h

Source [15]

and availability. Ideally, PV mini-grids should be able to deliver services in Tier 3 [15]. However, in reality, PV mini-grids in Indonesia mostly only deliver services in Tier 2. When they are measured against the minimum daily energy capacity, they barely fulfil the minimum criteria of 1 kWh per day [29]. This is not only because of the incapability of the PV mini-grid to provide more energy to the users but could also be due to the use of an energy limiter device in each household connection. This can mean a loss of opportunity for the community to utilise the available energy. To address this issue, the energy limiter should be adjustable, and the operator should be given the authority to regulate the energy allocation according to the mini-grid's technical capability. As a prerequisite, the operator and the management shall be knowledgeable and skilled to conduct such modifications.

A PV mini-grid in a village, providing modern electricity services such as entertainment and productive appliances, brings notable changes in people's daily life. From the author's personal experiences in the field, a number of positive life-changing experiences were reported by the communities such as the feeling of safety to travel at night due to the installation of streetlights, the feeling of comfort that the PV mini-grid is quiet compared to the loud diesel generator, the cleaner air in the room with the absence of smoke from kerosene lamps, the comfort in taking care of infants at night, as well as the access to communication and entertainment services through TV and audio systems. These anecdotes imply an improvement in quality of life in the remote villages.

Moreover, various support programmes promoting PV mini-grid development have a positive side-effect in empowering women in the community. Social shifts are taking place, from improving participation of women in decision making related to the mini-grid operation, to having women in leading positions in the mini-grid management [30–32]. The PV mini-grid programme, which is intended to address the energy access problem, indeed leads to a positive spill-over in gender equality issues. This is due to the decentralised nature of the programme where women participation in the mini-grid management can be fostered since the planning phase. Meanwhile, the conventional grid expansion implemented by PLN is generally implemented using a top-down approach with not much room for gender-specific intervention on the ground.

Nevertheless, despite its claimed social benefits, PV mini-grid also has human-related aspects which can trigger social conflicts. The first example is the issue of inequality in electricity provision. Rural electrification in small islands and mountainous areas often deals with very dispersed settlements where one community lives relatively far from the neighbouring community. In some cases, a village may have a few residents who live separately from the cluster, which causes cost-inefficiency to connect the mini-grid network to their houses. If the electrification does not reach the residents' houses, jealousy might emerge. A short-term solution to tackle this issue can be to provide an off-grid solution like SHS to the houses separated from the cluster.

Second, the human capacity issue: due to the remoteness of the areas, generally, the level of education of the communities is low. This leads to a lack of both technical and management skills of the locals to maintain the system. Rural communities, who mostly obtain only basic education, are confronted with big challenges of operating a power plant, setting the tariff, conducting troubleshooting, as well as organising the maintenance cycle, for example, when the batteries need replacement. Therefore, the focus of many actors who finance and/or implement PV mini-grids should be to transfer the required knowledge to the communities and enable a peer learning platform for them. Unfortunately, most of these projects and programmes have a limited budget and a short project duration, and hence, such learning measures are usually insufficient or lacking consistency. Often, the villagers are left frustrated with the miscellaneous issues in the operation and management of the mini-grid. This problem can be lessened if the above-mentioned peer learning network is established, where the members can seek support and help from their peers who had been trained. Moreover, awareness raising and knowledge sharing on good practices in PV mini-grid implementation are also important among the key players in local institutions to improve the decision-making processes.

Third, the tariff payment issue: there are social conflicts arising from the obligation for the users to pay an electricity tariff from a mini-grid that is given (for free) by the government. Often the communities feel entitled to get the electricity at no cost, especially when knowing the energy source is free (unlike diesel generators). The multi-tier framework sets a benchmark on the affordability attribute where the electricity cost of 365 kWh/year is ideally less than 5% of total household income. This benchmark applies only for Tier 3 and above. The majority of PV mini-grid customers in Indonesia pay more than 5% of their total income for the electricity [29].

4.3 Is It Environmentally Sustainable?

PV mini-grids might be ideal for remote areas and small islands unreachable by the grid. The ability to replace diesel either completely or partly (through the PV-diesel hybrid system) is an obvious advantage compared to the usage of diesel generators in terms of costs, air pollution as well as climate change mitigation. However, there is a big concern when looking at the entire life cycle of all the PV technology components in regard to the potentially toxic and hazardous materials [33]. We will look at the two most significant components: the PV modules and the batteries. PV modules are generally long-lasting; they degrade about 0.5% per year [34]. That means, after 30 years of its lifetime, the module may still be producing about 85% of the electricity that it produced in the first year. Although PV modules might not be a significant issue in the short term, wear-out failures such as glass breakage, transport damage, and delamination, might occur before a module reaches its end-of-life. Due to thinner cells used in newer modules manufactured after 2008, it was reported from several studies that 40% of PV modules inspected have at least one cell with microcracks [35]. The long transport, as well as improper installation and maintenance—common in rural electrification—can cause microcracks that result in hotspots and reduce the durability of PV modules significantly. These either lead to a reduced performance of the plants, or in the worst case, even make them not produce any electricity at all.

Early failures may lead to an early problem of abandoned modules, and in at least 20 years from now, many of the modules will reach their end-of-life. In the countries where PV mini-grids suffer from dysfunctional modules, there is a prominent risk that these modules will harm the environment as a proper waste management does not exist yet. The majority of PV modules installed in these rural areas are the crystalline silicon (c-Si) type. Around 76% of a typical c-Si PV module's materials are glass, with 10% polymer (encapsulant and back-sheet foil), 8% aluminium (frame), 5% silicon (solar cells), 1% copper (interconnectors), silver, and other metals (mostly tin and lead) [35].

Once PV modules reach their end-of-life, "recycling" is perceived as a sustainable solution to reduce the environmental hazard as well as to conserve resources as an alternative from using virgin materials to produce a new module. In recycling, it only makes sense to recover the valuable component such as the glass, aluminium, and copper. As the majority of a PV module component is glass, generally PV modules are treated in glass recycling facility. Therefore, there is still risk that the hazardous material like tin and lead might contaminate the soil [35, 36]. At the moment, EU is leading in regulating the PV-specific waste management through its Waste Electrical and Electronic Equipment (WEEE) Directive of 2012. In this Directive, PV modules are categorised as e-waste, and the extended-producer-responsibility (EPR) principle is applied. This means, the producers have the responsibility to collect, treat, and monitor their PV modules until the end of the lifetime.

The batteries are in general more robust, but their performance decreases gradually with every charge and discharge cycle. Field observation in Indonesia showed that many lead–acid batteries are no longer functional after about two years—especially when they are not sized properly leading to high depth of discharge—and they need to be replaced frequently. The situation is even worse when the batteries are installed in locations with high temperature like the remote tropics. However, the existing business models generally do not include future investments in new batteries, or the communities simply do not have access to the battery providers. When the batteries are not working properly anymore, they normally remain connected to the system and may cause short supply of electricity. There is also a risk of leaking, where the chemicals and heavy metals can infiltrate the environment.

Lead–acid batteries are widely used in PV mini-grids due to its availability, its relatively lower prices, and its robustness. The two main components of lead–acid batteries are lead and lead oxide (65% of the total weight) and sulphuric acid (10–15% of the total weight), and both can contaminate the soil and groundwater. There are existing markets for waste lead–acid batteries and lead scrap as the world market price for lead is attractive, around $725/ton and $1785/ton, respectively [36]. These lead-recycling businesses mostly deal with the automotive batteries, and not as widely with PV batteries yet. The reasons vary from unawareness of the value of the PV battery waste to the uncertainty regarding the ownership of the batteries.

Li-ion batteries do not contain heavy metals. However, they can react with water or explode in the case of fire, on top of containing scarce resources. Unlike the lead–acid batteries, Li-ion batteries have little recycling value and are therefore not very attractive for the recycling markets [36]. Storing and transporting Li-ion batteries are quite complex and costly, therefore dealing with the waste Li-ion batteries requires regulations.

Due to the risks of endangering the health of the environment and the people, the actors of PV mini-grid programmes should consider creating a framework to tackle the components' end-of-life. Compared with the other PV technology applications like pico solar lanterns and SHS, mini-grid systems actually have more logistical advantage (see Fig. 6) [36]. The challenge lies on the availability and accessibility of recycling scheme that allow mini-grid providers to have a feasible business model. Activating the reverse logistics for batteries can be an approach to alleviate the logistical problems. This means that at the end of their life cycle, the batteries are returned to or picked up by the producer and are processed to extract certain parts to be recycled.

Another approach to mitigate environmental damages is quality assurance to increase the lifetime of PV modules and batteries (see Box 2).

Other than the component-specific environmental impact, there is also a concern in the land use and threats to the ecosystems. A PV power generation requires a relatively large area, and there is a risk of reduction of cultivable land [33]. In Indonesia, a typical 20 kWp PV mini-grid requires approximately 500 m^2 area, while a 50 kWp around 1500 m^2 [26]. Securing such area may be a challenging task in the remote villages. Adopting the modular PV mini-grid system as introduced by Electric Vine Industries may be a solution to reduce the amount of space required. Land clearing is also needed in most cases, and this has to take into account the characteristics (topography, geology, hydrography, and seismic) as well as the status of the land

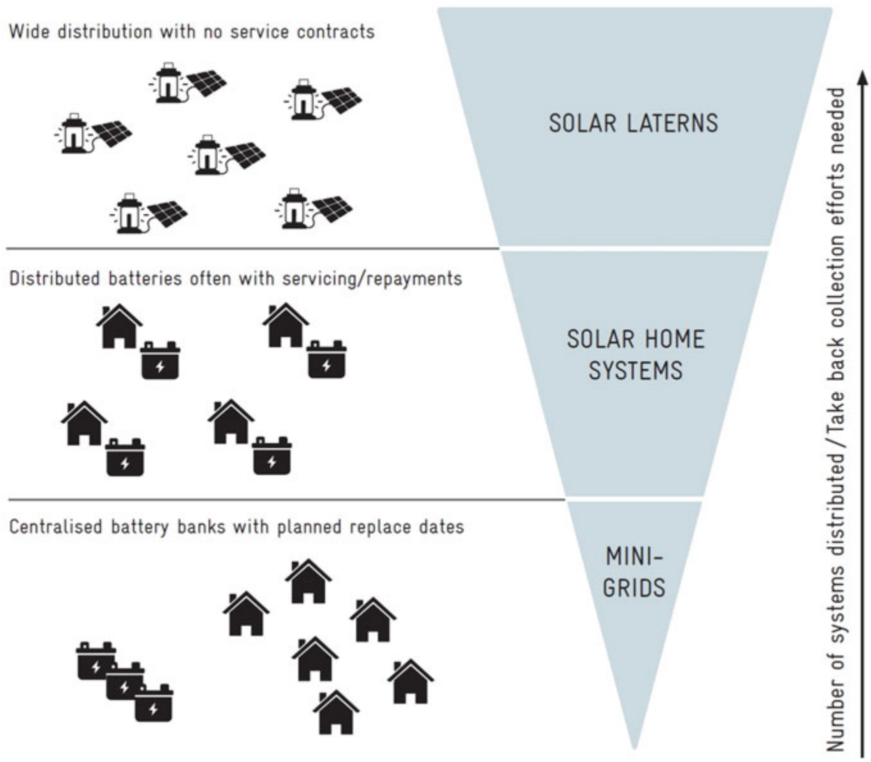

Fig. 6 Logistics of waste collection for different PV technology applications. *Source* [36, p. 25]

(conservation or agricultural) and transportation access to the location. The involvement of authorities, including the authority responsible for conservation areas, in handling the land use issues is therefore crucial.

The different issues and their potential solutions are summarised in Table 5.

Table 5 Summary of issues with PV mini-grids and the potential solutions

Sustainability dimension	Issues	Possible solutions
Economic	Arrival of the main grid	– Close coordination among key actors – PV mini-grid design that is compatible with future grid connection – Installing PV mini-grid only in isolated area with zero or very small chance of grid connection
	High initial investment costs	– Public–private partnership allowing co-financing
	Insufficient tariff for replacement or repair of components	– Partial subsidy for operational costs – Performance-based service contract (through RESCO)
	Unreliable electricity supply	– Hybridising the PV mini-grid with diesel generator – Technical quality assurance for both components and installation – Assigning a trained operator
	Under- or over-sizing of system	– Ensuring accurate data from the field during the planning phase (e.g. household and location data) – Site-specific system design
Social	Non-optimal utilisation of available energy due to energy limiter use	– Adjustable energy limiter by the authorised operator according to the mini-grid's technical capability
	Jealousy between electrified and non-electrified communities and households/individuals	– Mediation of the conflict – Provision of alternative solutions, e.g. solar home systems, if possible
	Lack of local technical skills	– Applying the private or utility model where a skilful operator is assigned for the operation – Improving capacity building measures for the operators and managers

(continued)

Table 5 (continued)

Sustainability dimension	Issues	Possible solutions
	Local communities are reluctant to pay for electricity service from the PV mini-grid	– Community inclusion since the planning phase – Electricity costs are set at <5% of total household income
Environmental	Waste management of potentially hazardous waste such as from batteries and PV modules	– Clear regulations on PV-specific waste which cover collection, recovery, and recycling arrangement – Developing a recycling framework and facilities to be available regionally – Ensuring the quality and a long lifetime through a national quality assurance
	Land use change with possible threats to ecosystems or reducing arable land	– Coordination and involvement of land authorities – Avoiding the construction in conservation areas or on arable land
	Land availability	– Applying the modular PV mini-grid scheme which requires less space

Box 2 Quality infrastructure as a cross-cutting approach

Quality infrastructure (QI) describes a system of public and private institutions as well as legal and regulatory frameworks and practices that establish and implement standardisation, accreditation, metrology, and conformity assessment (testing, inspection, and certification). This system shall ensure the quality of products and services in a country. A functioning QI system supports the effective operation of the domestic market, and the international recognition of QI services can enhance the access to foreign markets [37]. The idea is that products and services are offered following certain international standards, which set a certain quality and security level as a minimum requirement. Standards are voluntary and developed by different stakeholders such as representatives from industry, research and civil society. They can be referred to in technical regulations by the respective regulatory body (e.g. ministries)—making the requirements legally binding—as well as in tender documents, contracts, government programmes, or other technical documents.

QI is a complex system which requires the necessary bodies to be in place nationally and also being connected to the international system. Therefore, a national framework that clarifies the responsibilities and the cooperation between these bodies and has sufficient funding and strong organisational structures is needed. Furthermore, the stakeholders, private industry, as well as regulators, have to be aware of that system and demand it. In many emerging economies and developing countries, not all of these requirements are fulfilled. Especially, a lack of a national production or provision of a service may lead to a small interest from the stakeholders to develop the required quality assurance through the quality infrastructure institutions. For a PV mini-grid project developer, it is important to check the existing national standards and how far they are being implemented. For example, PV modules should be certified in accordance with the international standard IEC 61,215 to assure a minimum quality and safety.

5 Conclusions

PV mini-grid development, on the one hand, is a promising electrification solution in areas where the main grid has not reached. On the other hand, its sustainable implementation is challenging. Hence, the key question is when PV mini-grids are a good and reasonable solution for villagers and investors/donors for rural electrification. The benefits of avoiding or replacing the noisy and polluting diesel generators and smoky kerosene lamps in remote islands with a small population are evident as the grid connection is usually not an option there. PV mini-grids can also be a reasonable solution in villages with dispersed but clustered settlements in isolated areas. This requires coordination with the (local) electricity provider to make sure that the grid will not reach the area at least in the next decade or the PV mini-grid is designed to be connected to the grid. Hybrid systems where PV is combined with other renewable energy technologies such as hydro- or wind power can improve the reliability for the villagers. Also, a combination with diesel generator is highly recommended if diesel is accessible and affordable.

Looking at the economic dimension, it is important to understand that PV mini-grid projects are often publicly funded. Such projects have an underlying purpose to provide electricity access for the first time to communities in geographically challenging locations. This often leads to low-quality components and installation as a result of logistical impediments and lack of local technical expertise. Additionally, different from the capital expenditures which are mostly covered through grant schemes, PV mini-grids' operational expenditures are in the hands of the operators. Therefore, implementing the suitable operator model becomes crucial to ensure the economic sustainability of the mini-grids.

On one side of the social dimension, electricity delivered by the PV mini-grid evidently will improve the quality of life for the users. On the other side, a PV mini-grid is an advanced technology that is foreign to common people with very limited or no technical background. There have been complaints and frustration when the community lacks the technical and management skills to operate and manage the PV mini-grid, despite receiving some training. We strongly recommend an intensive involvement of the local communities as well as authorities throughout the PV mini-grid development processes to assure the commitment of the people. This must include a series of awareness raising and capacity building measures for the local key actors. For certain technical problems, a technical assistance from experts will still be required. In this case, the necessary technical capacity should at least be made available and affordable locally, along with good documentation to be accessible at the facility, such as the contracts and technical specifications. Ideally, the warranties are specified in detail so that the villagers know whom to contact.

When assessing the environmental dimension, we found that despite its potential to mitigate carbon dioxide emissions in its electricity generation, a PV mini-grid can also threaten the environment, especially in regard to the land use and end-of-life of its components. The two most apparent threats are from the PV modules and batteries which potentially cause hazardous waste that may contaminate the environment if not properly discharged. This issue is country-specific, depending on the availability of recycling schemes for such components as well as a clear regulation that govern the management of PV-specific wastes. We suggest further assessments on the recycling market potential of both PV modules and batteries and the possible business models for the rural PV mini-grids. As a prevention measure, a functioning national quality assurance system based on international standards and trustworthy product certification can support the quality of the components and ensure that the PV mini-grids will be long-lasting and safe for the users.

In conclusion, many conditions have to be fulfilled to make PV mini-grids a sustainable and reasonable solution for rural electrification. Despite some bad practices of PV mini-grid projects, as the interest and pressure in meeting political goals on the local, national, and global scale are high, most of these projects are not evaluated critically. This chapter shall not be used as an argument against using PV mini-grids but instead to reflect on its potential and what could be improved for future implementations. As a closing remark, IEA is quite optimistic that decentralised solutions such as mini-grids are still the most cost-effective option to deliver electricity in the remaining unelectrified areas [4].

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Micro-hydro Power System

Alvin B. Culaba and Isidro Antonio V. Marfori III

Abstract This chapter talks about micro-hydro power (MHP) system and its application to rural communities. At the beginning of the chapter, the problems associated with rural communities' inaccessibility are discussed, followed by fundamental concepts of MHP system. Although it is important to understand the fundamental concepts of MHP, this chapter only provides basic technical concepts and focuses more on its application in the rural communities. Given that MHP is a good alternative source of energy for off-grid rural communities, discussion on the social, environmental, and economic impacts is also included. Aside from the discussions on the application of MHP to rural communities, this chapter also includes a detailed case study of building a real MHP system in a rural community in the Philippines. Through the case study, the problems and challenges in the implementation of MHP systems are elaborated.

Keywords Micro-hydro · Community electrification · Rural electrification · Sustainability

1 Introduction

When talking about MHP installations, one of the common characteristics is that they are often situated in remote areas [1]. For instance, a successful community-based MHP plant called Mataragan micro-hydro requires a 12-h bus ride, followed by a 6-hour rough-road jeepney[1] ride, and finally, a 4-h trekking to reach this community. Another successful MHP installation is situated in north of the Philippines, the Parina

[1] Jeepneys are common public transportation vehicles seen in the Philippines.

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micro-hydro where a 20-h bus ride followed by a 4-h jeepney ride is required to reach the community. In most developing countries, this is a typical scenario for MHP as this technology is often implemented in rural areas which the utility grid is not able to reach.

The Philippines has a tropical climate—the country only experiences rainy season and dry season—and as a developing country, the disparity in development is vast. In large cities such as the capital of the Philippines, Manila, development is evident in tall skyscrapers, complex road network, congested traffic, air and noise pollution, and of course smart phones. It is the opposite in the almost inaccessible remote communities in the provinces. Skyscrapers are replaced by hardwood houses with nipa roofs. Road access is sometimes non-existent, and for some areas, road access is seasonal due to flooding and landslides during the rainy season. Instead of the smart phones, the go-to communication is the old bar phones as these phones are cheaper and have greater battery capacity. However, even the bar phones may not be very useful as many remote communities have no access to phone signal and electricity.

On the positive side, remote communities have many to offer. For one, there is no traffic congestion and the air is still fresh. Foods are in their most delicious state as they are served fresh from harvest and are not heavily processed. And finally, the people's hospitality, culture and values are more than enough to replenish one's spirit. These are the driving force for the success of an MHP system in remote communities. MHP system in remote communities has many benefits to income, health, environment and education. However, the MHP system must be designed to be community-centred from the very beginning for it to be successful.

2 The Role of Micro-hydro

The purpose of MHP should first be identified. Initially, the concept of MHP is to electrify a community, and this is mostly the case. However, there are also other applications of MHP. The easiest implementation of MHP is for private use, meaning that the energy generated is meant to be used for one's own consumption [2]. This is true in some MHP installations seen in resorts and the like, where the main purpose of the energy generated is to minimize the resorts' dependency on the utility grid. Commercial MHP is also common in some countries [3] and works in the same principle as a large hydro-electric power plant. The only difference is the scale in terms of power capacity and business model. Many commercial MHP achieve financial sustainability through feed-in-tariff mechanisms established through government policies.

Private-use MHP systems are the easiest to implement as they mostly only involve technical and financial aspects. Commercial MHP, on the contrary, may be more difficult to implement, as it is often regulated by government bodies and certain standards must be followed. Yet, in terms of achieving sustainability, commercial MHP can be argued to be easier as its sustainability is mainly financial, and as long as a sound planning and feasibility study are conducted, sustainability can be easily achieved [4].

Table 1 Comparison of LED bulb and kerosene lamps

Social categories	LED bulb	Kerosene lamp
Health	LED bulbs provide illumination without the problems associated with fumes from fuel-based lighting source	Fuel-based lamps often emit fumes that may be harmful to one's health and pose fire risk to households using them
Education	LED bulbs provide superior illumination allowing for children to have longer study time	Fuel-based lamps provide adequate illumination for tasks such as cleaning and cooking, but not for reading or studying
Income	Modern LED bulbs are now cheaper and can last up to 5 years. They typically provide savings to the homeowners. Modern LED bulbs also consume less electricity, lowering the operational cost	Fuel-based lamps require periodic replenishment of its fuel. In most cases, the cost of the fuel is higher than the cost of electricity and the LED bulb
Environment	LED bulbs have no environmental hazardous emissions	Fuel-based lamps emit fumes, which may have adverse effects on the environment

Different from a private and commercial MHP, a community MHP heavily relies on the participation of the people in the community. Depending on the financial mechanism, the sustainability of the MHP will depend on the capability of the community in technology management [5].

A community MHP is meant to improve the living condition of the people in the community. This can be evaluated based on four social categories, namely health, education, income and environment [6]. The objective of the community MHP must therefore be in-line with the four categories. For instance, the most basic use of the electricity generated by MHP is for lighting. Depending on the quality of the electricity from the MHP, lighting source can either be compact fluorescent lamp (CFL) or light-emitting diode (LED) bulbs where the latter is preferred due to its efficiency. The effects of LED lighting compared to kerosene lighting are shown in Table 1 based on the four social categories.

Although MHP systems have many applications as described previously, this chapter will focus on community MHP, in particular how MHP can be a sustainable energy solution for the rural communities. The succeeding sections of this chapter will therefore be in the context of the community.

3 Implementation of a Micro-hydro Power System

The implementation of MHP system usually comes in phases: planning and feasibility study, development, and use phase. The challenges for each phase in the implementation of MHP systems are discussed in this section.

3.1 Planning and Feasibility Study

In the planning and feasibility study phase, challenges are usually in terms of financial and technical capacity, where the latter is more common. Financial challenges may be in the form of lack of financial resources. However, this is more related to the access to financial resources, rather than the financial resources not being available. MHP systems for community electrification are often low-cost solutions, and many financial resources are available. For instance, the Department of Energy, Philippines, had identified and allotted financial resources to many potential community MHP [7]. Private entities such as universities and corporations have also channelled financial resources through community service programmes or corporate social responsibility (CSR) programmes that can be used for MHP. The challenge, however, is the access to these financial resources [5]. In the context of a community situated in the remote areas, accessing these financial resources becomes a great challenge due to the lack of information about the available financial resources. Furthermore, accessing such financial resources requires extensive documentary requirements such as legality, proof of technical capacity, government issued documents and so on, which the residents of these remote areas are not familiar with.

The other challenge in the planning and feasibility phase is the lack of technical capacity. The technology of micro-hydro is already well established; however, this does not necessarily translate to ease in technology adoption [8]. For professionals in the field of engineering, micro hydro technology is straightforward. The theories, principles, equations, and best practices are well documented and are abundantly available, especially for those with access to the Internet. However, it is different for the communities who do not have access to basic information. In this phase, additional activities such as information dissemination, trainings, workshop and the like must then be incorporated, which add another layer of challenge. Another concern in the planning and feasibility study phase is the site-specific characteristic of micro-hydro technology [9]. Although there are many elements of the MHP that can be standardized, such as the electro-mechanical components, the major component of an MHP, which is the civil works, is difficult to standardize because their characteristics are different from site to site. Each micro hydro civil work needs to be customized according to different terrains, vegetation, net head slope, soil quality and relative distances, just to name a few. These particular characteristics make it challenging to design the MHP system.

3.2 Development of an MHP System

The development phase of an MHP system is typically similar to that of a construction project. Depending on the business model, community MHP is often based on sweat equity where the people from the community provide contribution in the form of labour. This not only lowers the cost of the MHP project, but it also gives a good sense of ownership to the people. The sense of ownership will be realized later in the use phase in terms of technology management. Most people in remote communities have excellent background in construction projects, and therefore, labour skills are normally available. Given that the community MHP works through sweat equity, the challenge lies in the deployment of the available manpower. In the context of micro-hydro, sweat equity means that the people need to provide labour without pay. Consequently, the work schedule must then revolve around the schedule of the people who will provide the manpower. This usually results in a maximum of two-day work per week, which leads to a slow progress of the project. This particular scenario then makes it more difficult to motivate the workers, as they do not see or experience the results of their efforts immediately.

Some of the other challenges are related to the inaccessibility of the micro-hydro site, such as hauling, road access, as well as lack of equipment and electricity. Although this can often be solved through engineering solutions, some challenges may require more innovative solutions.

3.3 The Use of MHP

The use phase is when the MHP is being utilized by the community. In this phase, it will take some time for the community to establish the operation of the MHP system. Some may opt to have the system operational only a few hours per day at night-time, while other communities may opt to operate it 24 h a day. Establishment of an MHP operational cooperative or group must be completed prior to the use phase for smooth and sustainable operation. More details on this will be discussed in the succeeding sections of this chapter.

The common challenges in the use phase can mainly be associated with technology management. Although the lack of technology or poor technology implementation may be the cause of challenges in the technology management, there are even more complexities when it comes to issues regarding administration, finance, culture and community dynamics. For instance, a common problem most MHP plants experience is the maintenance of the electric generator. This problem involves technical problem because the installed generator is a brushed synchronous type, which requires frequent brush change. The same problem involves administrative issues: the periodic brush change frequency is not followed. Issues in finance and culture also play a role as there is not enough fund to repair the broken generator because the tariff collection is not 100%. The lack in tariff collection is then attributed to the culture of the community as the people are not used to monthly payments. Typically, these kinds of problems are solved through additional financial subsidy in the next year or two. However, for most MHP plants, this is often the cause of unsustainable operation and often results in the downfall of the MHP plant.

4 The Micro-hydro Power Plant System

Depending on the country standard, micro hydro is usually categorized as a hydro power system with capacity between 2 and 100 kW [10]. Figure 1 shows a typical MHP schematic diagram with the essential components for off-grid electric generation. MHP system does not require large dams. Most often, the design is run-of-the-river system which avoids water impounding. For MHP, dam is replaced by an intake weir wherein some amount of water is taken from a river or stream. The water is then channelled through a canal made out of concrete or other suitable material to minimize water leakage. The water goes to a holding structure called the forebay, where sand and other particles are removed. The water is then dropped through a steel or plastic penstock to the water turbine inside the powerhouse. The water turbine converts potential energy from the falling water into useful mechanical energy. The water turbine is commonly coupled to an electric generator converting the mechanical energy to electrical energy. From the water turbine, the water is brought back to the river.

The power generated by an MHP system is calculated based on the available head and flow rate given the following equation:

$$P = \delta Q H \eta \tag{1}$$

where:

δ specific gravity of water, 9.8 kN/m^3
Q flow rate of water in m^3/s
H elevation in metres is the overall efficiency of the MHP.

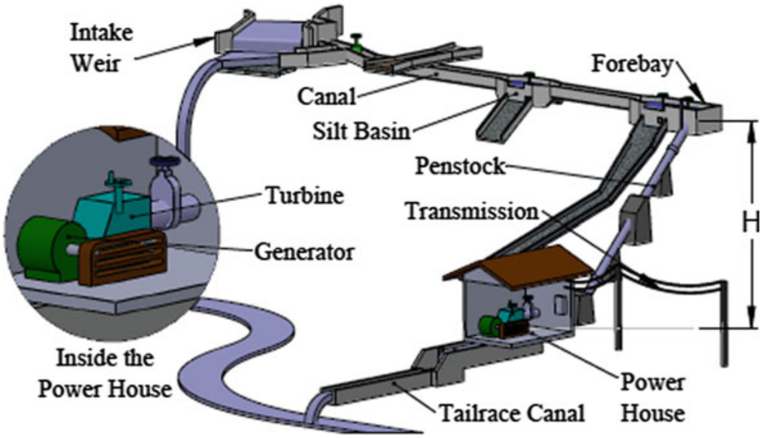

Fig. 1 Micro-hydro power plant components

The available head is taken as the vertical distance between the forebay and the turbine less the friction loss, while the flow rate is typically the annual average flow rate. The overall efficiency of an MHP is affected by many factors which include electrical transmission, generator performance, mechanical losses, and turbine hydraulic efficiency. Furthermore, the type of turbine also greatly affects the overall efficiency, making proper turbine selection an essential aspect of MHP system design. Even for similar turbine types, the efficiency will also vary because of different blade profile design, or because of varying construction techniques.

Most MHP systems are designed with the simplest construction methods and materials with simple design. This enables the system to become feasible for community-based electrification. However, important parameters of each component must be designed to meet at least the minimum requirements. Each of the components will have a specific function and will be further discussed in the succeeding sections. Depending on the site condition, some components of the micro hydro power plant may be omitted such as the secondary silt basin discussed in Sect. 4.3 for MHP system with short canal length. Canal crossing discussed in Sect. 4.6 can also be omitted in some MHP schemes where gully is not present in the selected site.

4.1 Intake Weir

The intake and weir are structures which serve as a medium to divert water from a river stream to the MHP system in a controllable manner. The intake and weir structures must be able to control the flow of water during low-flow and high-flow conditions. Low-flow condition refers to the flow rate of water during normal operation, most often during the dry season. High-flow condition usually occurs during rainy season and can also be related to flood condition. Figure 2 shows the detailed design of the intake and weir.

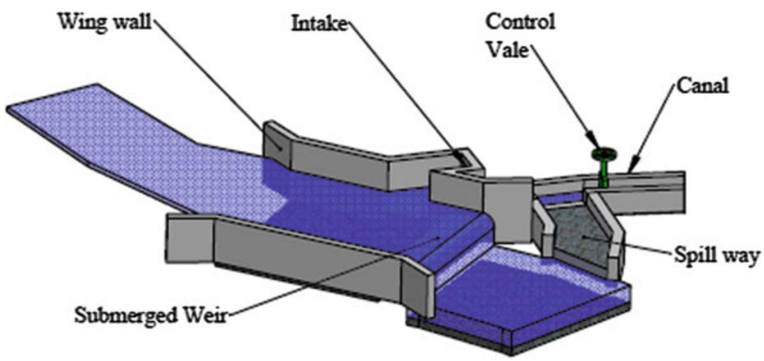

Fig. 2 Intake and weir components

For most MHP, direct intake scheme design is followed. The direct intake as shown in Fig. 2 has the advantage of having less sediment build up at the mouth of the intake, making it more advantageous in terms of maintenance. The intake weir is designed to withstand the highest flood condition of the site, and therefore must be designed to have high structural integrity. The intake must allow flood water to pass through over the submerged weir while allowing only the designed flow rate to pass through the direct submerged intake. The submerged intake as also seen in Fig. 2 is connected to the spill way followed by a control mechanism. The control mechanism must be situated far enough from the submerged weir and intake to allow safe operation during flood condition. Typically, a distance of at least 10 m away from the weir and intake should be adequate. However, this distance must be verified through local knowledge of the people in the site. Control mechanism seen in Fig. 2 utilizes gate valve; however, this is not a must as other control mechanism can also be implemented. A popular choice is the use of simple wood planks wedged against a concrete collar. The materials used for the intake weir are mostly materials for concrete making, namely cement, sand, aggregates and large stones.

4.2 Headrace and Tailrace Canal

The headrace canal is the component of an MHP system that conveys the diverted water from the intake weir to the silt basin, and then to the forebay. A similar structure is also used to return the water to the downstream river and is called tailrace canal. Both the headrace and tailrace canal must be designed to allow optimal velocity of water. This velocity is called the canal design velocity, and each canal section should be designed using this value to allow suspended particles to flow with the water. Velocity higher than the design velocity will cause rapid wear on the canal walls, while velocity lower than the design velocity will cause the suspended particle to settle on the canal floor. Although settling of suspended particles on the canal floor cannot be avoided in all sections, especially at bends, it can be minimized.

The canal is usually built just below the ground surface, and therefore, earth excavation is required. Figure 3 shows the canal of the Parina micro-hydro. The particular canal shown in Fig. 3 is made using concrete hollow blocks for the side walls, while the canal flooring is made of stone masonry. To minimize wall and floor friction, a layer of concrete plastering is applied to the canal walls and floor. Figure 3 shows an ideal construction of an MHP canal. However, some sites may not have access or capacity for hollow block making. In this case, other canal types can be utilized such as stone masonry, wood planks and even earth lined canal. Each canal type will have its unique characteristics, and there are many published literature to identify this, such as the micro-hydro design manual [11].

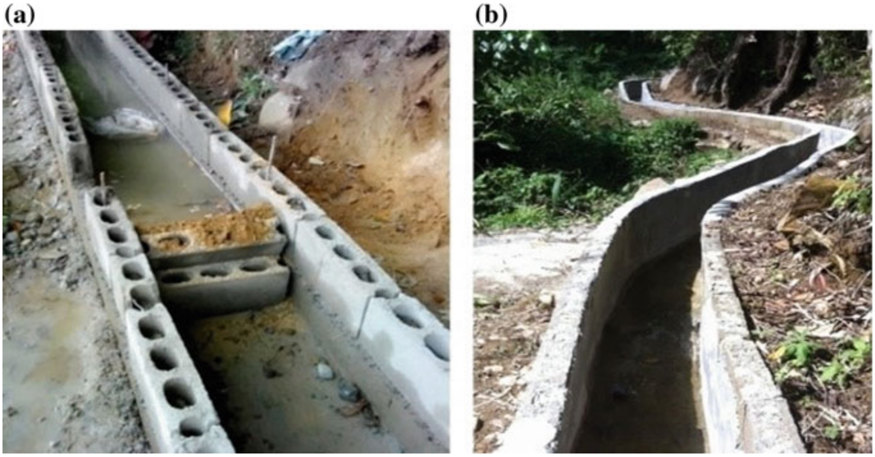

Fig. 3 **a** Canal made with concrete hollow blocks and **b** canal with concrete plastering

4.3 Silt Basin

The water from the river fed to the turbine will carry suspended particles. This is referred to as silt load, which is composed of hard abrasive materials such as sand, and will cause damage and rapid wear to the turbine runners. Water flow must be slowed down in a silt basin where the sand particles are allowed to settle at the bottom of the basin through gravity. The collected silt will then be periodically flushed out. Figure 4 shows a typical silt basin design, while Fig. 5 shows a silt basin incorporated in the forebay. The specific functions of the silt basin are to: (1) have length and width large enough to cause settling of the silt, (2) allow sufficient capacity for the collection of silt sediments, (3) allow for easy flushing of silt deposits in a frequent interval,

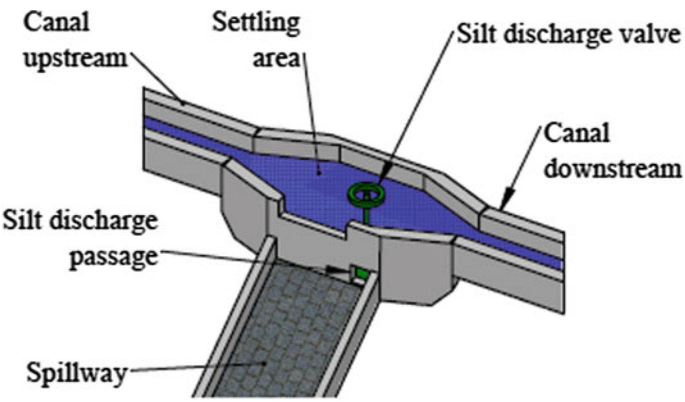

Fig. 4 Typical silt basin design

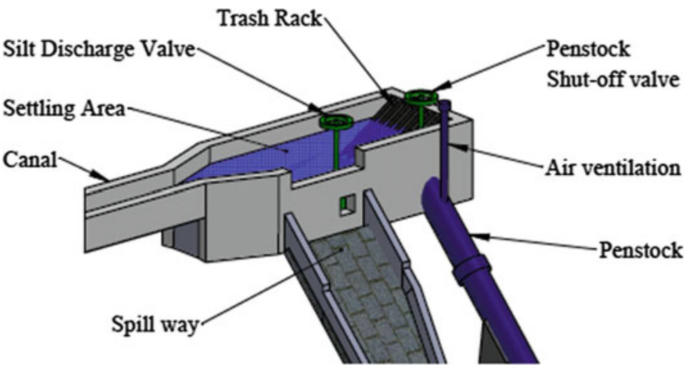

Fig. 5 Details of forebay

(4) prevent the water from flushing away from the civil works and other components of the MHP, and (5) avoid flow turbulence caused by sharp area changes.

Similar to the intake weir and canal, the silt basin is also made up of mostly concrete materials. However, the use of stone masonry is more tolerable for the silt basin as the uneven surface of the stones causes the water to slow down. For flushing of silt, a silt discharge valve is a common component included in the silt basin, as shown in Fig. 4. Other silt flushing mechanism can be employed; one of the most common mechanisms is the use of wood planks with concrete side support, held up by the pressure of water. A concrete-lined spill way is also essential for silt basins. This ensures that excess water is allowed to flow away from the civil works in a controlled manner. The lined spill way also prevents soil erosion.

4.4 Forebay

The forebay tank is the transition between the penstock and headrace canal. The forebay is used to make sure that the inlet of the penstock is fully submerged with a rule-of-thumb depth of at least four times the penstock diameter. In some MHP systems, the silt basin may be incorporated with the forebay. In the said design, the exit portion of the silt basin will be replaced by a trash rack and penstock entrance. A trash rack is a device placed before the penstock entrance to block large objects suspended in the water such as leaves and tree branches. Figure 5 shows the details of a forebay.

Regardless whether or not silt basin and forebay are combined, a spill way should always be included. The spill way in a forebay will often have water flowing due to the water flow setting of the turbine in the powerhouse, as discussed in Sect. 4.7. Because of this, the forebay spill way should be made of concrete or stone masonry construction to avoid soil erosion. The forebay should also include a penstock shut-off valve with air ventilation. The air ventilation will allow remaining water inside the penstock to discharge through the turbine without creating excessive vacuum pressure inside the penstock.

4.5 Penstock

The penstock is a large pipe, usually made of steel, that delivers the water from the forebay to the turbine. Penstock has the biggest cost contribution among civil works' components, especially for high-head MHP. Consequently, it is essential to optimize its design. The major elements of the penstock are shown in Fig. 6.

The sizing of penstock is mostly based on the summation of the head loss and other losses due to bends and contractions. Head loss is determined by the friction of flowing water against the wall of the penstock, which in turn is affected by the penstock material and the inside diameter of the penstock. The objective is to maximize the penstock inside diameter to yield an acceptable head loss and acceptable material cost. Acceptable head loss should not be more than 10% of the gross head, *H,* illustrated in Fig. 1.

The penstock supports, such as anchor block and side block, will be necessary, and their design is based on the slope, soil bearing, penstock weight, water weight and penstock expansion. Common practices for anchor blocks are to use 1 m^3 of concrete for every 1000 kg of combined penstock and to distribute water weight evenly across the penstock length.

Penstock may also incorporate an expansion joint. The expansion joint is used to account for thermal expansion of the penstock in MHP situated in places where there is large temperature difference between winter and summer. For tropical climate, thermal expansion is negligible, and therefore, expansion joints are not necessary.

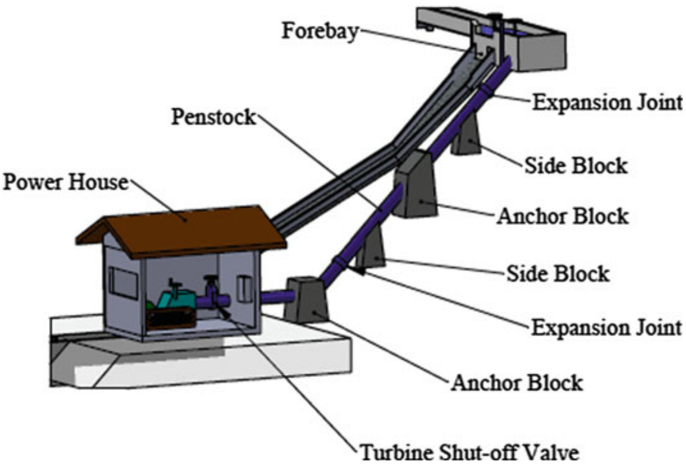

Fig. 6 Details of penstock

At the end of the penstock, just before the turbine, a shut-off valve must be installed. This is necessary for turbine maintenance and repair. Common penstock materials are polyvinyl chloride pipes, high-density polyethylene pipes and steel pipes. Although steel pipes are more expensive, they are a common choice for MHP as they are more robust against misalignment and the jointing process is simple through welding application.

4.6 Canal Crossing, Retaining Walls and Other Safety Features

Canal crossings and retaining walls are a few components of an MHP system that have no direct effect on its function. But for safety and sustainability reasons, these components are necessary. Canal crossings are installed in canal areas where gullies are present. Gullies are land formation caused by heavy rainfall often situated on mountainous slopes. Gullies are similar to ditches or rivulets and are several metres deep [1]. During heavy rainfall, flood water will most likely flow through gullies. In an MHP system, the canal will often cross at least a gully in its path. This area in the canal must be reinforced, and a canal crossing must be installed.

Typical canal crossing design is shown in Fig. 7. Retaining walls are rigid structures to support soil from erosion. Landslide-prone areas close to the components of the MHP should be equipped with retaining walls. High importance should be given to canal crossings and retaining walls to assure the survival of the components of an MHP during heavy rainfall. The functions of a canal crossing and retaining walls are only essential during heavy rainfall, which is rare and seasonal, and therefore, these components are often neglected. Moreover, their construction adds cost to the MHP system. However, these are necessary safety elements of the system; they ensure

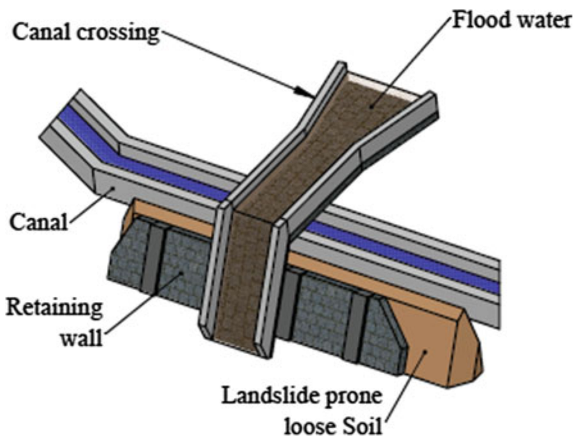

Fig. 7 Example of a canal crossing

continuous operation, safeguard the MHP main components, and protect the operators. While the cost of repairing an MHP depends on the severity of the damage, experience tells us that more often than not, it is higher than the cost of having the canal crossing and retaining walls.

4.7 Turbines

A turbine converts the energy of falling water into rotating shaft power. The turbine for a particular MHP plant depends on the site characteristics, such as head and power. There are many micro-hydro turbines that are being used; among them is the cross-flow turbine. Cross-flow turbine (Fig. 8) is a good choice for high-to-medium head application as it is robust and easy to manufacture. However, there are some micro-hydro sites that require a low-head application turbine, and the cross-flow turbine becomes inefficient for this condition. Turbine for low-head application are Francis turbine and propeller turbines with the latter more common for MHP.

For any turbine type, flow regulation mechanism is always essential. This allows for proper control of the power generated by the turbine based on demand. Flow regulation mechanisms are often incorporated in the turbine device itself and are actuated either manually or automatically. The flow regulation mechanisms will either provide maximum water flow rate or partial water flow rate. In cases where partial flow is set, the excess water will flow out from the MHP system through the forebay spill way. The water flowing from intake to forebay is often set at maximum since the control valve is often designed to be either fully open or fully closed. However, the flow through the turbine varies depending on the customer demand.

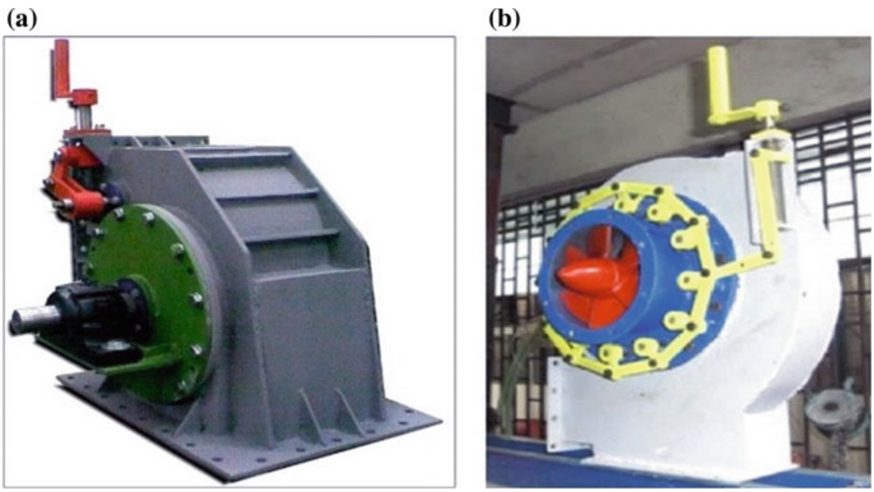

Fig. 8 Examples of **a** cross-flow turbine and **b** axial flow turbine

For instance, in the late afternoon where there is still sunlight, demand for electricity would still be low and thus, lower flow rate would be sufficient. During night-time, use of electricity is at maximum and would thus require higher water flow rate. In the former, excess water will be directed to the spillway.

To select a suitable turbine for a specific site, the specific speed SP of the site needs to be calculated. For specific speed between 10 and 35, Pelton turbines should be selected, for specific speed between 35 and 400, cross-flow turbines should be selected, and for specific speed greater than 400, axial turbines should be selected.

$$\mathrm{SP} = \frac{\mathrm{RPM}\sqrt{\delta Q H \eta}}{H^{1.5}} \tag{2}$$

where

SP	specific speed
RPM	turbine rotational speed in revolutions per minute
δ	specific gravity of water, 9.8 kN/m^3
Q	flow rate of water in m^3/s
H	elevation in metres
η	overall efficiency of the MHP.

The overall efficiency can be estimated between 60% for low-cost MHP system and 70% for more complex MHP using sophisticated turbine design. The turbine rotational speed, in most situations, has a certain degree of design freedom where it can be chosen to result in a certain turbine type. However, it should not go too far based on the generator rotational speed, which is typically 1800 rpm. Turbine rotational speed between 800 and 1800 rpm should work without problems.

4.8 Governing

Governors are used to control the speed of the turbines. The governor is an essential component of an MHP to insure proper operation of both the mechanical and electrical equipment of the MHP. Without proper governing, both turbine and generator speed can become either too high or too low. Although the turbines may be able to tolerate high speeds, for the case of generators, speeds beyond their nominal speed will result in the generator rotor components veering off from its position due to high centrifugal force, causing it to strike the stator, thus damaging the equipment. Too low a generator speed will result in a high current, which is often higher than the rated current for such generator. The high current can cause overheating of the coils, which may subsequently lead to eventual burning.

Governing for MHP is either flow governing or load governing. On the one hand, flow governing works by varying the amount of water flowing through the turbine with the use of special valves called guide vanes located inside the turbine. These vanes are actuated through a hand lever by an operator during manual operation. It can be actuated via a motor for automatic operation. Vanes are also used to adjust the water flow rate. On the other hand, load governing works by maintaining a constant electrical load to the generator and turbine assembly. Water flow rate in this case is held constant, while a dummy electrical load is used to maintain constant electrical demand. The latter is typically a set of heating coils that are switched on or off during electrical demand changes. For manual load governing, the dummy load switches are actuated manually by an operator, and for automated operation, sophisticated electronics are used.

Many community MHP systems utilize manual flow governing as it provides the simplest operation and maintenance and is often cheaper than other governing solutions. However, large changes in electrical demand are not permitted in manual flow governing. Therefore, the community needs to coordinate their electricity consumption. As such, administrative control on the use of the electricity for the entire community is often implemented, which includes regulated appliances, scheduled use of ironing, application of lighting without switches, and frequent workshops or seminars for the end-users.

Automatic governing, on the contrary, is able to mitigate all the disadvantages of manual flow governors as automatic governing systems are often equipped with safeguards and protections, such as overload and underload shut-off protection and short-circuit protection. Automatic governors are also able to adjust quickly to electrical demand changes, and therefore, very little administrative control is needed. The disadvantage of automatic governors is in its maintenance as it involves complex electronics which are often not repairable; replacement of the entire circuit board is often required.

4.9 Transmission

Transmission is the component that transmits the energy from the powerhouse to the consumers or to a distribution facility. The transmission may include step-up and step-down transformers, cables, poles and insulators. One of the high-value components of a transmission is the wires, which may have significant cost, and therefore, careful design and selection must be conducted.

5 Social Dimension in MHP

The greatest impact on the society that an MHP system can contribute is to provide access to affordable and clean energy for the rural communities. This is a prerequisite to achieving sustainable development. In far-flung areas where electricity is not available, poverty incidence is high. Access to electricity would not only improve the quality of life of the poor people significantly, but also has the potential to create wealth and resources for the community. The main objective of an MHP project is to improve the basic quality of life, which include health, education, income and environment. And as explained in other chapters in this book, energy influences socio-economic conditions of rural communities: having electricity significantly improves the life of people compared to situations where there is no access to power.

As MHP systems' sustainability relies on the social dynamics of the community, it is important to identify a natural leader from the community who can act as the MHP champion. This MHP champion must have the support of the people in the community and should be able to express to the people how the MHP can benefit the community. The MHP champion must therefore first have adequate understanding to the concept of MHP and must genuinely believe that it can benefit their community.

6 The Economics of Micro-hydro Power System

One of the most significant factors affecting the development of an MHP is the cost, specifically the installation cost. The MHP installation cost is usually quoted in terms of either total capital cost or unit cost, in units of currency per kilowatt (kW) capacity. The unit cost is said to be in the range from 750 to 2000 USD per kW installed capacity [11].

There are many factors affecting the cost of MHP such as site accessibility, technology, manpower capacity, site-specific characteristics and community dynamics. For community MHP, the technology applied is often simple and therefore cheaper. For instance, a community MHP may opt for a cheaper turbine with lower mechanical efficiency, while a commercial MHP will require state-of-the-art turbine (which may reach up to 3000 USD/kW despite higher capacity), offering a higher efficiency. This makes sense as community MHP will only require a working system regardless of its efficiency.

With the assumption that community MHP utilizes simple cheap technology, the two major factors that contribute to the cost are accessibility and site-specific characteristics. MHP projects that are situated in remote areas with limited road access will often result in higher cost due to hauling expenses. As a rule of thumb, MHP projects in the Philippines that require foot access of more than 4 h have to procure cement at twice the price in a more accessible location. Site-specific characteristics are those that directly affect the design of the MHP system in terms of materials cost. The major components that greatly affect the material costs are canal length, penstock length and transmission distance.

7 Case Study: MHP System in the Philippines

7.1 Introduction

The case study presented in this section is an actual implementation of an MHP system in the Philippines. The system was installed in a far-flung community in the northern part of the Philippines, in the middle of the mountains with no electricity or public transport to reach the place. The site has potential for hydro power due to the presence of naturally flowing water from the mountains down to the community. Initial discussion with the municipality officials showed much interest to cooperate in developing an MHP system. They view this as an opportunity to improve the quality of life of the people living in that area. The commitment of the local government and its people was paramount to the success of the undertaking.

7.1.1 Project Collaborators

The Parina MHP project was implemented by a university in Manila, Philippines, as a community-based technology deployment initiative. The institution provided the funding for the development and fabrication of the turbine for the MHP system. A local power company supported the project as part of their CSR programme, and they covered mainly the cost of travel, including transport, food and accommodation between Manila and the project site in Parina during the entire period of implementation. The local government unit (LGU) which governs the province and municipality and other major stakeholders, such as the local people, teachers, health workers and non-governmental volunteers, also played an important role in the success of the project.

The total project funding was USD 53,000, one-third of which was sourced from the university and the rest from company CSR, while the local community provided the sweat equity. The actual direct cost of the MHP in this case study was USD 35,000 which included administrative cost, logistical cost, professional fees, materials cost, hauling, skilled labour, and auxiliary costs. The remaining funds of USD 18,000 were utilized for capacity building, fabrication and maintenance training, and livelihood projects.

7.1.2 Project Site

Parina is a 55-household community of indigenous people in the municipality of Calanasan, Apayao province, which is 607 km from Manila. The trip to Calanasan is a gruelling 15-h travel by car, and to reach Parina, another three-hour ride is required. The mountain community is only accessible via rugged access roads, freshly cut through the mountainside. On good days, the mud stymies most vehicles and occasionally, a tractor is required to haul vehicles up the sharply inclined slopes. On bad days, the road is subject to landslides making travel impossible. Parina is verdant with green foliage, while in the distance fog envelopes the surrounding mountain peaks. The community is off-grid, does not have access to electricity or communication lines, but has ever-flowing streams and rivers with a tropical rainforest climate. Their means of livelihood are traditional farming and hog raising.

7.1.3 The Project Management

The overall project management was headed by the Project Leader from the academe and ably supported by staff from the partner company. The technical team was composed of nine engineers with backgrounds in mechanical, electrical and controls, civil, and chemical, all from the university. A social scientist was also part of the team whose main task was the mobilization of the local community and was assisted by the partner company's CSR staff.

Another significant contributor in the management is the community leader who organized the manpower and acted as the foreman of the MHP project. This community leader is the MHP champion for this case study mentioned in Sect. 5. This community leader has a college degree and is able to fully understand the concept of MHP as he had prior experience in hydro power through a previous pico-hydro implementation. Aside from organizing the manpower, the MHP champion became the eyes and ears of the university engineers throughout the construction of the project.

7.1.4 The Project Schedule and Implementation

The MHP project was carried out over a one-year period from June 2013 until May 2014. The timing is important so that during the rainy and typhoon season (June to November in the Philippines), no construction at the site is done. Activities during this time would primarily focus on the design and fabrication of the turbine and other components done off site. By the time the weather becomes dry, usually in the beginning of December, the deployment of the components and construction at the site could proceed and continue without interruption. Nevertheless, there were occasional bad weather conditions which necessitated reconstruction and delays in the overall implementation plan, but they were mostly manageable. It should be noted that the labour, i.e. sweat equity, is limited only to the availability of the local people which would normally be only on Saturdays and Sundays. During the weekdays, they are at work in farms.

7.2 Signing of the Memorandum of Agreement (MOA)

The cooperation is always strengthened through a memorandum of agreement (MOA) as it stipulates the roles and commitment of involved parties. The MOA signing

Fig. 9 MOA signing with local government, academe, industry and local community officials

is usually done with the presence of all the major stakeholders represented in the agreement as shown in Fig. 9. This is the kick-off for the cooperative project.

7.3 Community Engagement

Every member of the community where the plant would be located must be involved at the outset, so they are able to develop some kind of ownership to the project. This is particularly important as the share of the community would be sweat equity. They provide the labour required for the construction, especially of the civil works necessary to bring the flowing water to the powerhouse. The people feel more sense of belonging towards a project that they directly contribute to, including providing the workers shelter and food should they need to stay on-site for several days or weeks. Figure 10 shows the consultation with community leaders as part of the community engagement.

7.4 Social Mobilization

To effectively identify the available resources in the community, the mobilization of people is necessary. This would complement the technical resources of the implementors and developers. It is also during this time that the roles of women, and even young adults, are identified. This also allows the building up of good relations among all those involved in the project with the members of the community. Therefore, after getting the agreement of the community leaders, the rest of the community is also invited for discussion, as can be seen in Fig. 11.

(a) (b)

Fig. 10 Project orientation with the community leaders

Fig. 11 Project consultation with all the members of the community and other stakeholders

7.5 Hydrologic Survey

To establish the feasibility of an MHP system requires understanding the year-round availability of water, as without water no power would be produced. Based on the hydrologic assessment like in Fig. 12, the initial plant design capacity is determined. In this case study, the system design is 15 kW and the water output is 15 kW max and 10 kW average. Most MHP system will opt to design for average, but in this case, it was designed for max power output.

Hydrologic survey data:

Flow rate : 0.095 m^3/s
Head : 16.5 m
Average power output : 10.33 kW
System design : 15 kW

Fig. 12 Hydrologic survey and water flow measurements

7.6 Groundbreaking Ceremony

Once everything, including the funding and other resources required for project implementation, had been planned and agreed upon, then groundbreaking ceremony (Fig. 13) is done to signify the beginning of a noble community undertaking. This is usually initiated by the officials of the local government. All the leaders and the people are invited along with the project implementers who are introduced formally to the community by the Mayor. The MHP Project Leader presents the importance of the project and its value to them. Normally, a demonstration model of the MHP system is shown to illustrate how it would look like and how it would work. This enables people to visualize the MHP plant and to understand clearly what they can expect from the project.

Fig. 13 Groundbreaking ceremony

This is the best time to establish good relations and trust between the implementers of the project and the people whom they would be working with, especially since some implementers would live at the site during the course of building the power plant. The good relations built among the stakeholders during the groundbreaking ceremony would allow a smoother implementation of the project and is therefore an important occasion.

7.7 Building the Actual MHP System

This section presents the details of how the MHP system was built. It took about a year from the groundbreaking ceremony to the completion of the project. Some dates are shown in the figures to allow the readers to appreciate how fast or slow a particular task could be completed. The descriptions below follow a sequential flow of implementation activities.

7.7.1 Weir, Intake and Intake Barrier

The intake barrier serves as a barricade to protect the headrace canal especially during flood conditions where water coming from the source may form a pool just before the canal intake. Without an intake barrier, the water may overflow and enter the canal in an uncontrolled manner. The weir serves as an obstruction for water to accumulate water in an area just before the intake, just enough to maintain a controlled water supply especially during low supply and flood conditions. Figure 14 illustrates the building of the intake and weir.

Start of
Construction : July 2013
Completion : May 2014
Duration : 10 mos.
Total days of
actual labour : 48 days

Fig. 14 Intake and weir using stone masonry

(a) (b)

Construction started on May 2013; Completion date was on Sept 2013
Total days of actual labour: 40 days

Fig. 15 **a** Stone masonry canal and **b** concrete hollow block canal

7.7.2 Headrace Canal

The first part of the headrace canal, 10.4 m long, is made up of stone masonry and is located at the intake as pictured in Fig. 15a. The first part of the canal is made of stones, boulders and concrete because it receives the water from the source first, making it more vulnerable to concrete erosion and flooding. The rest of the headrace canal, 300 m long, is made up of concrete hollow blocks (Fig. 15b) since the construction process is faster compared to stone masonry. The headrace canal connects the source down to the forebay tank with a total slope of 10%.

7.7.3 Headrace Canal Setback

Landslide sometimes happens and destroys the constructed canal like in this project where 15 m of the canal was damaged at halfway through the total stretch due to heavy rains. Reconstruction had to be done immediately to resume the MHP operations. Typhoons can also exacerbate the landslide, which again happened in this case where

Fig. 16 Damaged portion of the canal due to landslide brought about by heavy rains. Landslide struck the 15-m-long canal located halfway through the total stretch on 2 October 2013, due to heavy downpour. Reconstruction immediately started on 10 October 2013

the adjacent part of the newly reconstructed canal, including the previously damaged canal, was washed away amounting to a total of 57 m destroyed canal length as shown in Fig. 16.

7.7.4 Reconstruction of the Headrace Canal

Due to two consecutive landslides at the same place, rerouting of the canal had to be done. The new route passes through the mountain, making a 5-m-high cut through land. Reconstruction took a month because of delay in the civil works. Concrete covers were provided this time so that future landslide would not cause clogging to the part of the canal. The new canal is 45 m long, 12 m shorter due to rerouting than the original canal that was destroyed due to landslides caused by unpredicted heavy rainfall. The reconstructed canal is visible in Fig. 17.

7.7.5 Flood Control Gate and Spillways

A spill way is provided just before the forebay tank for a way out for excess water especially during flood conditions. It is usually near the intake, immediately after the masonry canal, and acts as a canal flow regulator. Also, a gate is installed right after the spill way, as shown in Fig. 18, to provide additional safety measure and a means to empty the canal of debris and other foreign materials.

Fig. 17 Reconstructed canal and relocation site

(a) (b)

Fig. 18 **a** Forebay spillway and **b** intake flood control gate

7.7.6 Forebay Tank

Parts of the existing forebay tank were demolished for expansion purposes. Other parts were reinforced so as to add additional support, such as wall finishing and tank bed concreting, to the existing structure. The forebay during construction and upon completion are shown in Fig. 19a, b, respectively.

Fig. 19 **a** Concrete hollow block forebay during construction and **b** completed forebay

7.7.7 Penstock and Anchor Blocks

Six pieces of 600-kg steel pipes were laid out, welded and anchored, first using temporary supports, to the mountain side. The pipes connect the forebay tank to the turbine and are housed inside the powerhouse. The temporary wood supports were later replaced by concrete anchor blocks as demonstrated in Fig. 20. The parts were then painted with red oxide as primer, then enamel paint.

Anchor blocks were provided to constrain movement of the penstock especially when water is passing through it. It also prevents the pipe from being pulled apart due to longitudinal and lateral movements caused by water hammering. Hammering occurs during emergency shut-off situations where the shut-off valve is closed rapidly. Axial or longitudinal movements happen for straight penstocks, while lateral movement is experienced at bends. Scrap woods were temporarily used to anchor the penstock when it was being welded and when the anchor blocks were curing (Fig. 21a). Wooden forms were used to shape the anchor blocks out of concrete.

7.7.8 Turbine and Generator Foundations

The turbine was already connected to the penstock pipe, sandwiching the gate valve. Temporary supports were placed, while the turbine foundation was constructed. Generator foundation was constructed to restrict movements of generator due to vibrations. Figures 22 and 23 illustrate the construction of the turbine and generator foundations, respectively.

Fig. 20 **a** Hauling of the steel material and **b** completed penstock

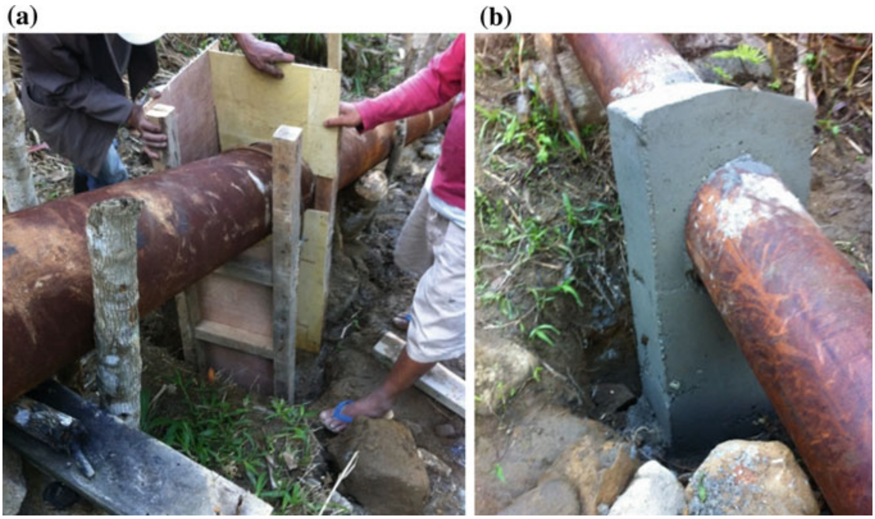

Fig. 21 **a** Anchor block wooden forms and **b** completed anchor block

(a) (b)

Fig. 22 **a** Turbine foundation using wooden forms, **b** completed turbine foundation

(a) (b)

Fig. 23 **a** Setting the generator foundation using reinforced steel bars and **b** curing of concrete

(a) (b)

Fig. 24 **a** Setting the powerhouse foundation and post and **b** completed powerhouse

7.7.9 The Powerhouse

The powerhouse (Fig. 24) consists of the turbine, generator, panel board and controller. The house has enough space for the operators of the plant. The operation involves servicing and maintenance of turbine, generator and controller, and is usually done by 2–3 workers. Some powerhouse has provision for operators' quarters. In this case, it was not required since the operators live nearby.

The generator can produce a maximum output of 15 kW which will be used as electrification for 55 households in the community. The generator specifications are 15 kW, 60 Hz, single phase, 230 V.

7.7.10 Tailrace Canal with Rectangular Open Weir

The tailrace canal receives the water that passes through the turbine and directs it back to the river. The port of the canal immediately after the turbine is made of concrete to avoid easy deterioration, but the canal leading back to the river is from earth, made to provide irrigation for nearby rice fields. An open rectangular weir is incorporated to the tailrace canal for flow rate measurement purposes as shown in Fig. 25. Although the open rectangular weir is optional, it provides easy method of flow measurement during monitoring.

Fig. 25 Tailrace canal with open rectangular weir for flow measurement

(a) (b)

Fig. 26 **a** Installation of transformer and **b** completed substation

7.7.11 Transformer and Transmission

The transformer used in this system is a single phase, silicone core, 15 kVA, outdoor type, with step-up 220 VAC to 1000 VAC, and step-down 1000 VAC to 240 VAC. The purpose of the transformer is to be able to transmit the power with a distance of 300 m with minimal power lost and minimal cost. This is possible due the high voltage transmission, in this case 1000 VAC, which will result in lower current given the power. Lower current allows the use of smaller diameter transmission wires. The transmission line is designed to compensate the estimated 10% power loss of the 15 kW system due to the distance of the powerhouse to the substation. The electrical copper wire used is #8 AWG THHN.

The 2.5-m-high substation (Fig. 26b) is placed at the centre of the community. It is located strategically to make it easier for the distribution lines to be installed in different directions, forming four cluster switches in the panel board. Colour coding was used for the distribution wires. Green, blue, yellow and white wires represent each of the four clusters for easy maintenance by the local community.

7.7.12 Electrical Post Installation

Local materials such as wood are used as electrical posts, as shown in Fig. 27. Grass, and even some trees, needs to be cleared to pave the way for the posts needed to bring electricity to the individual homes. In this case, a total of ten posts were put up; each is 8 m tall, 20 cm in diameter and weigh 300 kg. This needs to be carried by at least eight people during transportation and installation. Depth of excavation for the foundation is at 1.5 m. Transmission line stretches to about 400 m from the

Fig. 27 **a** Installation of electrical post and **b** wiring

powerhouse to the substation. Each post is 35–40 m from the next post to compensate for the cable sag.

7.7.13 Electrical Distribution Line

The community was divided mainly into four clusters from the substation. Each hexagon in the diagram represents 150 m of distribution wires. There were 53 houses inside the main four clusters. Figure 28 gives a rough outline of the village.

7.7.14 Reliability Testing

As soon as the entire MHP system was completed, a reliability test was done on the operation of the MHP system, as well as the transmission lines and household connections. This would ensure the smooth and trouble-free operation as soon as the local people take over the running of the affairs of the plant operation. The testing ran for 3 months until it was finally handed over to the community. No major technical

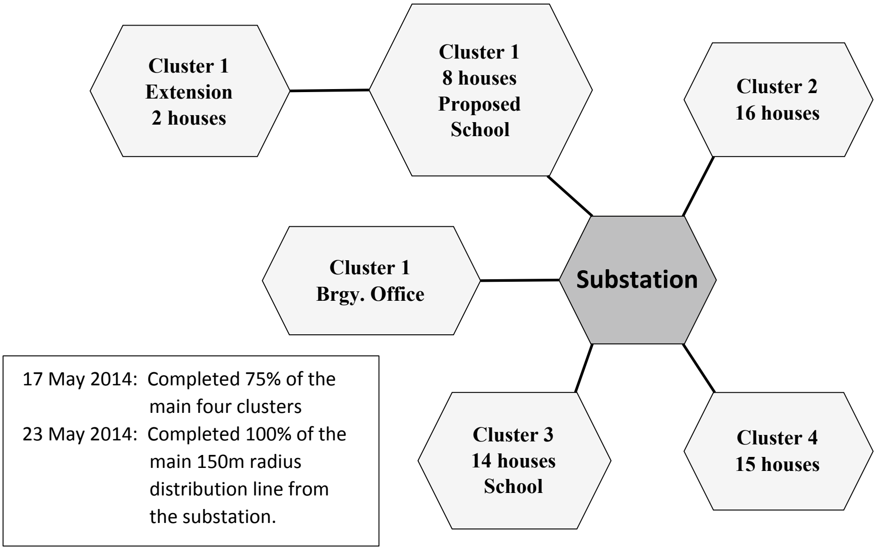

Fig. 28 Clustering of the houses, Barangay office and school. Barangay is the smallest administrative division in the Philippines

problems were encountered, and the MHP system was found to be reliable and safe to operate.

7.8 Sustainability and Benefits of the MHP Plant

The major challenge of any community project is to keep the facility in operation for a long time, i.e. throughout the theoretical system lifetime. One of the things that the project implementers have done was to conduct several technical and non-technical trainings on the fabrication, maintenance and operation of the whole MHP system as presented in Sect. 7.9. It had been emphasized to the community that they own the facility; it is theirs and therefore they have to take good care of it. A sense of ownership is needed to be built in the minds of the people in the whole community from the beginning of the project implementation.

However, there is also cost involved in sustaining the system to address the normal wear and tear, unexpected breakdowns, or even destruction of parts or components due to bad weather and poor operational practice. Thus, the local community was encouraged by the project management team to run the community-based MHP with a cooperative. This business set-up is designed to collect some kind of tariff for the use of electricity from the MHP plant. In some cases, this is equivalent to one Philippine Peso (equivalent to USD 0.02 at the time of writing) per watt per month consumed and is used for the operation and maintenance cost of plant. In this case study, the community adopted a fee per fixture scheme, where they charge PHP 20.00 (USD 0.40) per bulb and a television. They earn a net income of around PHP15,000.00 (USD 300) every month. The scheme had been employed by the community as their way of sustaining their plant, and the MHP is still in good working condition now, five years after its installation.

The main beneficiary of the project is the local community of Parina whose 55 households of 289 people are provided with electricity. Families use it for powering light bulbs and television as well as mobile phone charging. Most of the energy is only utilized in the evening. It is seldom used during the day; only when the community officials need to use their computers and printers, and when the school needs power for their teachers' and students' activities.

7.9 Capacity Building Programme

It is common that people in far-flung communities do not have much knowledge of technology. Without electricity, it is difficult for them to access information, education and formal training. It is therefore important that some villagers are trained to operate and maintain the facility on their own, without having to depend on expertise which is not easily available in the area.

In this case study, the team had to select the people who will run the system and thus would have to undergo a one-week training on operations and maintenance. More importantly, they have been trained to fabricate the turbine itself as demonstrated in Fig. 29. After the training, almost 90% of the turbine was finished. This gave everyone an excellent opportunity to gain understanding of how a turbine works and how it can be operated and maintained properly. In fact, this is the secret to sustainable operation of the system.

7.10 Inauguration, Commissioning of the MHP Plant and Launching of Livelihood Projects

The inauguration of the MHP drew together all the major stakeholders, such as the local government officials, leaders and the people of the community. This is the time that the whole community is waiting for: an occasion where they would see and experience electricity in their homes. It is a significant milestone for a place that never had any access to power. The photographs in Figs. 30 and 31 show the excitement of every member of the community as they witness the light turned on for the first time, signifying the end of dark night they all have been experiencing throughout their lives. To the developers of the technology, this is a fulfilment and gratifying experience to see their brothers and sisters in the far-flung community delighted to finally have electricity.

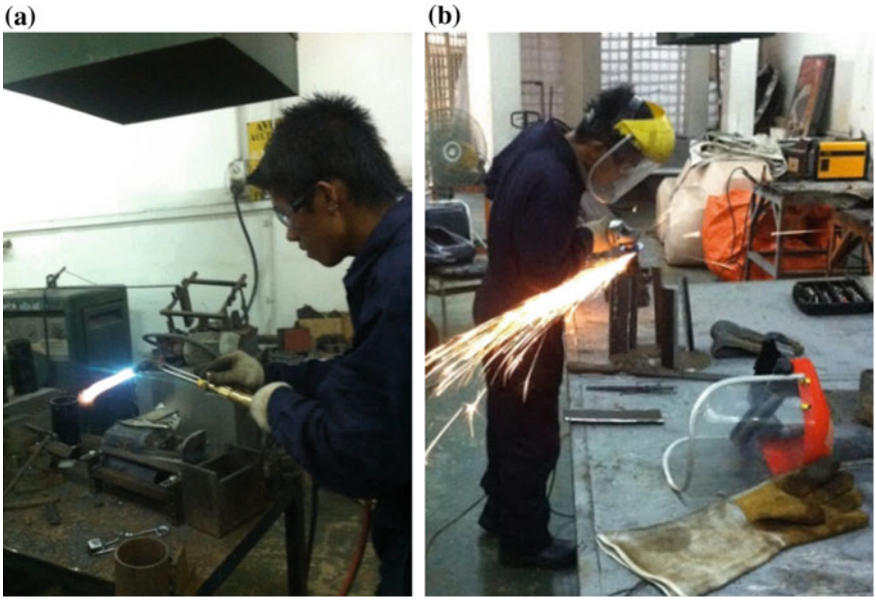

Fig. 29 Hands-on training in the **a** fabrication and **b** maintenance of MHP turbine

Fig. 30 Inauguration, switching on of the plant and turnover ceremony

The Mayor expressed his heartfelt thanks and appreciation to the developers of the MHP plant. A Resolution, passed and approved by its local government officials, was presented to the developers of the technology as a symbol of their gratitude for making their dream of having electricity a reality.

Fig. 31 Celebration and thanksgiving programme

8 Conclusion

The MHP system provides a sustainable solution to electricity needs of far-flung, off-grid communities as demonstrated in the experiences not only in the Philippines, but in many other countries as well. Small as it seems, MHP development is not straightforward. There are many important factors that need to be considered prior to deciding whether to pursue the project or not. Based on the authors' experience, the success of MHP implementation largely depends on the social factors rather than the technical ones.

Working with people in the local community is the biggest challenge of all. Trust and good working relations must be established first and foremost. This is developed through a series of consultations and discussion with major stakeholders until they fully accept the project's objectives. A written agreement is usually done to make it "black and white", and a formal ceremony is held involving all stakeholders of the project to allow for smoother implementation. A well-organized and carefully planned activity is crafted with clear goals and targets, as many of them require the commitment of the local community to provide the sweat equity to the project. Due to the proximity issues (e.g. distance and inaccessible roads) and also the weather conditions (i.e. typhoons) that implementers had to deal with, huge resources are given to logistics and people cooperation. To effectively carry out the critical activities of the project development, close communication and coordination have to be made with the local community. Yet, connecting to the community is challenging because mountain communities normally do not have telecom signal. Either costly satellite phones are used or people have to travel kilometres to find an area with phone signal. As such, getting feedback from the community takes a long time. The other major challenge is on logistics, including the transport of components such as the turbine and pipes which are fabricated in cities and have to be brought to the site.

System operation and maintenance are addressed by forming a technical support team composed of local people and are trained to handle these activities once the plant becomes operational. Overall management can be handled by the local leaders by organizing themselves, including the financial aspect of its operation. In the case study presented in this chapter, people pay a certain amount per month for every fixture or appliance they use in their houses.

Literature confirms that MHP system in rural, off-grid areas can bring many benefits to the community and its people—the electricity generated by MHP allows people to enjoy lighting and television in the evenings as in this case study—and can support the power needs of the community hall office which would have multiplier effects. The children in school can now study better at home, and even the school can use the power available during daytime for school activities and to have greater access to information. The people have various livelihood activities such as ice-making using their common freezer that uses the electricity after 10 o'clock in the evening. Air quality at homes has also improved because they no longer use kerosene for their lighting needs. First-aid services are now enhanced with the use of powered equipment devices. As MHP employs run-of-the-river scheme, no dams are required to store the water and thus, environmental impacts are minimized. Indeed, an MHP technology is truly a sustainable energy solution for the electricity-deprived remote areas.

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Tools Enabling the Solutions and Future Development

Assessment of Microgrid Potential in Southeast Asia Based on the Application of Geospatial and Microgrid Simulation and Planning Tools

Paul Bertheau, Martha M. Hoffmann, Andrea Eras-Almeida and Philipp Blechinger

Abstract Enabling access to energy is crucial for achieving the sustainable development goals (SDGs). A particular challenge for countries in Southeast Asia is to develop sustainable energy systems on their far-flung islands to increase energy security and improve living conditions. Here, renewable energy microgrids combined with other emerging energy technologies hold a large potential for sustainable remote-area electrification. With 45 million people in Southeast Asia lacking access to electricity and a large number of islands with insufficient and expensive fossil-based power generation, the need to increase renewable energy implementation is evident. To do so, a replicable way for planning and implementing renewable power systems is crucial to increase the implementation speed and achieve SDG7 in an efficient and least-cost way. We present a geospatial approach for characterising the island landscape of Southeast Asia. First, we apply geospatial administrative and demographic data, as well as renewable resource data to describe the island landscape. Second, we provide a comparison of state-of-the-art energy system modelling software. We conclude with the utilisation of selected energy system modelling software to simulate the cost-optimised renewable energy system for typical island groups based on the predefined island landscape. The findings of our analysis provide a detailed overview about the island landscape of Southeast Asia and the respective potential for renewable-energy-based microgrids to supply the remote islands with affordable, reliable, and sustainable energy as demanded by the SDGs.

Keywords Small islands · Renewable energy · Solar potential · Micro-grids · Energy system modelling · Open source · Levelised cost of electricity

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1 Southeast Asian Island Landscape

Southeast Asia is one of the world's regions with the most islands including the two of the largest archipelagic states, Indonesia and the Philippines [1], as well as other countries with their territories scattered over the sea. This geographic uniqueness brings certain challenges for infrastructure development, especially for providing access to clean energy. This relates to the UN's sustainable development goal (SDG) 7, which is to "ensure access to affordable, reliable, sustainable, and modern energy for all" [2]. In Southeast Asia, this can be best accomplished by renewable energy (RE)-based microgrid or "island" grid, given the availability of renewable resources [3] and the remoteness of many islands, which prevents other supply options like grid connection through submarine power cables [4]. In this chapter, we focus on understanding renewable energy supply options for microgrids on Southeast Asian islands and present different simulation and optimisation tools in order to assess the techno-economic feasibility of such systems.

The term "Southeast Asia" is used interchangeably for a group of ten (usually the ten member states of the Association of Southeast Asian Nations) [3] to twelve Asian countries [5] located between China and Australia, which are all characterised by a tropical climate [6]. For the analysis presented here, we are focusing on the following ten countries: Brunei, Cambodia, Indonesia, Malaysia, Myanmar, Philippines, Singapore, Thailand, Timor-Leste, and Vietnam. Laos, the only landlocked country, is excluded from further analysis. Most of these countries are characterised by dynamic demographic and economic growth [7]. As a consequence, their energy demand rose by 50% from 2000 to 2010 and is projected to triple by 2040 [8]. Simultaneously, the region is affected by the impacts of climate change, including the increasing frequency of extreme weather events [5] and less reliable monsoon patterns [9]. Therefore, the countries are challenged to meet an increasing energy and electricity demand and at the same time mitigate emissions to fulfil their climate protection targets [10]. This demonstrates that a decarbonisation of the energy sector is of high importance and that new generation capacities need to be more sustainable [11].

Currently, more than 45 million people lack access to electricity in Southeast Asia, of whom at least 50% live on small and remote islands [8]. Smaller islands often cannot be connected to the central grid, so if power is available, it is usually supplied by diesel generators [12]. The use of diesel fuel for power generation is one of the most expensive ways to supply electricity due to increasing world market prices and high local transportation costs [13]. In addition, the risk of local pollution by diesel fuel spills, noise, and exhaust gases is high. One solution to reduce the use of diesel fuel is the introduction of RE technologies into these diesel-based supply systems [14]. This results in the hybridisation of fossil-based energy systems, with energy storage systems facilitating high RE shares [15]. Key arguments for hybridisation are reduced diesel fuel consumption, which leads to decreased greenhouse gas (GHG) emissions and often also to reduced power generation costs. For islands without electric power supply, smart and hybrid energy systems comprised of RE, storage technologies, smart IT, and control systems provide a promising solution for electrification [16]. Overall, an implementation of RE strives towards the fulfilment of the SDG7, which can be met by an overall agenda of energy access and climate protection in the region [2].

Despite an existing potential for hybridisation and RE-based microgrids on Southeast Asian islands [15], the current status of RE implementation is rather low. Through our study, we want to support and increase implementation speed by removing barriers to project development and planning. The first barrier is the identification and overview of existing islands, which is currently missing. Here, we apply a geospatial analysis showing the socio-economic characteristics of all islands of Southeast Asia between 100 and 100,000 inhabitants and their solar and wind potential. The second barrier is to find the matching system configuration for hybridisation. This is addressed via three case studies, in which we show first the applicability of different simulation tools and second the techno-economic feasibility of solar-battery-based hybrid systems for island energy supply. The structure of this chapter follows the presented challenges.

1.1 Geospatial Analysis of Island Landscape

In order to characterise and describe the island landscape of Southeast Asia, we conduct a geospatial analysis. Initially, we identified the Global Administrative Areas (GADM) dataset (v. 3.6) as a suitable database of the contour of all land masses in Southeast Asia [17]. We limit the dataset to the ten case study countries and exclude the continental landmasses for Cambodia, Malaysia, Myanmar, Thailand, and Vietnam. Finally, the dataset yields a number of 13,387 islands with a total area of more than 2.4 million km^2. The disparity to other stated islands' quantities in literature, for example >17,500 islands for Indonesia [18] and >7400 for the Philippines [19], is due to simplifications of the GADM dataset. However, the GADM dataset provides land areas similar to official statistics [20], e.g. for Indonesia + 4.2%, Philippines −0.8%, Singapore −1.8%, and Timor-Leste +0.3%. To validate this data, we compare the applied GADM dataset for the example of the Philippines to a more detailed dataset provided by the Philippine National Mapping and Resource Information Authority (NAMRIA). We observe that the simplification of GADM merges smaller single islets and entirely misses some very small islands. This is illustrated for an example in Fig. 1, where the GADM dataset in red and the NAMRIA dataset in yellow. In conclusion, we found the GADM dataset sufficient for our analysis. It is the only dataset available for the entire Southeast Asian region, covers most of the island areas and only shows data gaps for very small and potentially uninhabited islands.

After identifying the location and size of each island, we calculate population statistics for each island based on the WorldPop datasets [21, 22] (applying the 2015 estimation) by using geospatial raster statistics algorithms. Based on the approach, we identify a population of more than 385 million distributed over the island landscape as

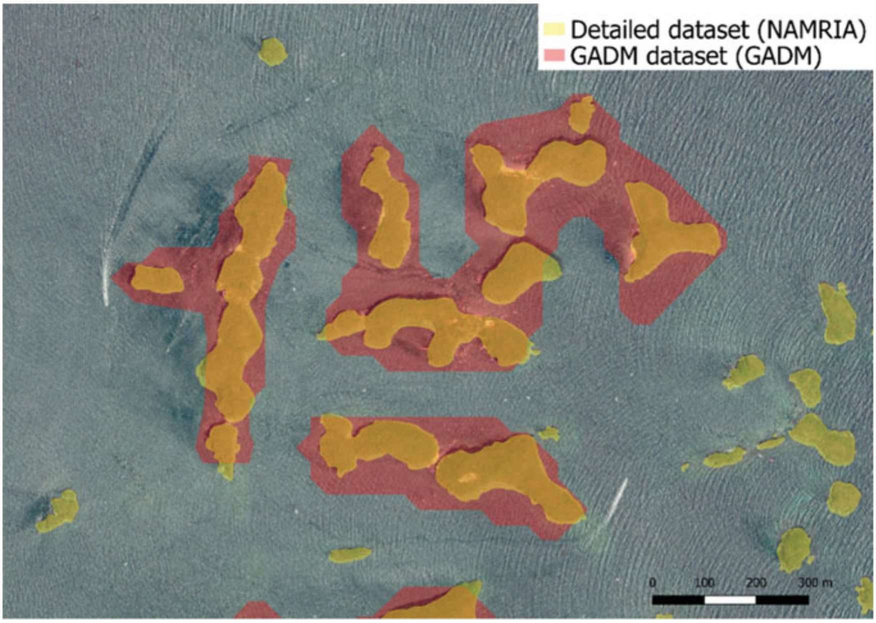

Fig. 1 Comparison of the applied island dataset (GADM) to a detailed island dataset for the Philippines (NAMRIA)

presented in Table 1. The analysis highlights that the major share of 70% of individual islands hosts only a minor share of the population. At the same time, the seven most populated islands comprise more than 82% of the population of all islands.

For our further analysis, we conclude that the first two groups of more than 11,400 islands hold no potential for microgrid deployment, since they are mainly uninhabited or only few people are living there (estimated maximum of 100). This

Table 1 Number of islands per population class and the respective total island population. Further analyses focus on population classes in the bold rows

Population class	Islands	% of islands	Total population	% of population
<10	9379	70.1	8517	0.002
<100	2037	15.2	75,592	0.02
<1000	**1224**	**9.1**	**420,701**	**0.1**
<10,000	**502**	**3.7**	**1,622,835**	**0.4**
<100,000	**181**	**1.4**	**5,868,787**	**1.5**
<1000,000	41	0.3	13,704,189	3.6
<10,000,000	17	0.1	47,361,254	12.3
>10,000,000	7	0.1	316,405,519	82.1
Total	13,388	100	385,467,394	100

means the electricity demands are small and the required effort for delivering the components and construction material of microgrids including distribution grids on site is very high. Instead, such islands could be provided with solar home systems[1] as an initial step to allow for basic electricity supply of households and small commercial customers [23]. Additionally, we apply an upper threshold and exclude islands with more than 100,000 inhabitants. Even though some islands with a population larger 100,000 are currently powered through microgrids, such islands are more likely to form major central electricity systems in the future. These systems require large base load and peak load capacities as well as reserve capacities and are more likely to be interconnected with submarine cables or form individual larger conventional power grids. In conclusion, we focus on islands with a population of 100–100,000 inhabitants, comp. [15]. This selection results in 1907 islands with a population of 7.9 million, which creates an interesting market for microgrids in Southeast Asia. Figure 2 provides an overview map of the considered islands.

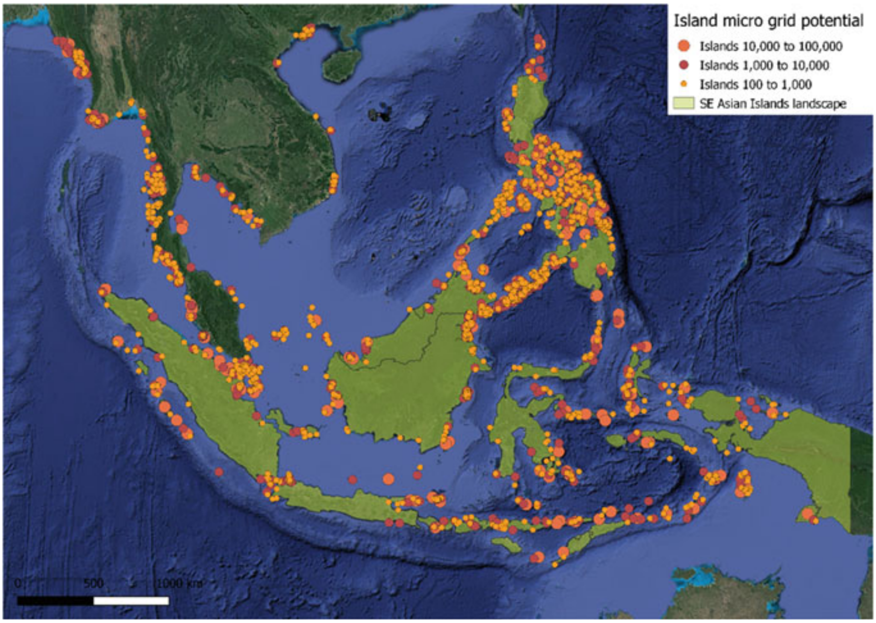

Fig. 2 Overview map of identified islands with microgrid potential

[1]More detailed discussion on SHS and its applications are explored in Chapter "Swarm Electrification: From Solar Home Systems to the National Grid and Back Again?" of this book.

1.2 Classification of Island Landscape and Implications for Microgrids

For the classification of the island landscape, we consider key socio-economic data for each island, specifically population, gross domestic product (GDP), physiographic data (area), accessibility data (remoteness), and renewable resource data (global horizontal irradiance (GHI) and wind speed). Geospatial raster statistics are applied to summarise population and GDP per island and to derive mean values for remoteness, GHI, and wind speed. The area per island is calculated applying the field calculator function in the utilised geospatial information software. The applied datasets are listed and described in Table 2.

For each of the three considered island population size classes, we highlight the characteristics per country. Countries with less than twenty islands are reflected in a summary group named "other".

For the least populated islands with a population between 100 and 1000 inhabitants (Table 3), we find a typical mean island population of around 350 for all considered countries. Most of these islands are located in the Philippines (501 islands) and Indonesia (435) with a total population of 420 thousand. Average GDP per capita for the smaller islands is mostly below the countries' average values, whereas mean island sizes are small in the Philippines, Malaysia, and Vietnam (<10 km^2), larger sizes are found in Thailand, Myanmar, and Indonesia (>10 km^2). The solar energy

Table 2 Applied datasets for classification of the island landscape

Parameter	Description	Unit	Source
Population	The applied dataset provides the number of inhabitants on a raster scale. Pixel resolution is approximately 100 m. The population is summarised per island.	#	[22, 21]
Area	Island size is calculated in square kilometres.	km^2	GIS calc.
GDP per capita	The dataset provides the spatially disaggregated gross domestic product (GDP). Information in million USD is provided in pixel resolution of approx. 1 km. For each island, the GDP is summarised and divided by the population to obtain GDP per capita	USD/capita	[24]
Remoteness	The applied dataset provides accessibility in minutes from the nearest city with more than 50,000 inhabitants on a raster scale. Pixel resolution is approx. 1 km	minutes	[25]
GHI	The dataset provides global horizontal irradiance (GHI) in kWh per m^2. Information is provided on a pixel scale of approx. 1 km	kWh/m^2/y	[26]
Wind speed	The dataset provides average wind speed in metre per second in 80 m hub height. Information is provided on a pixel scale of approx. 1 km	m/s	[27]

Table 3 Overview on islands with 100–1000 inhabitants per country

Country		Islands	Total Pop.	Island Pop.	GDP/capita	Area	Remoteness	Solar potential	Wind potential
		#	#	mean capita	mean USD/capita	mean km^2	minutes	mean $kWh/m^2/y$	mean m/s
Philippines	Value	501	164,446	328	424	1.7	234	1830	4.9
	Std. Dev.			221	2508	2.3	101	66	1.4
Indonesia	Value	435	157,890	363	1414	17.6	364	1788	3.5
	Std. Dev.			246	4011	26.4	306	157	0.8
Myanmar	Value	107	34,640	324	336	11.0	272	1820	3.8
	Std. Dev.			240	2669	21.9	150	22	0.6
Malaysia	Value	92	32,940	358	2114	2.9	223	1804	3.3
	Std. Dev.			223	8582	3.1	135	60	0.7
Vietnam	Value	37	12,678	343	2088	5.7	174	1567	5.9
	Std. Dev.			226	3896	6.1	69	262	0.8
Thailand	Value	35	12,631	361	6789	10.9	196	1836	3.9
	Std. Dev.			214	10,265	19.6	109	34	0.6
Other	Value	17	5475	287	11,427	9.1	330	1828	3.6

potential is very good for all islands with most values in the range of 1800 kWh/m^2/y. The mean solar potential for Vietnamese islands is lower than the average, but their wind power potential is the highest with 5.9 m/s wind speed.

For islands with a population between 1000 and 10,000 inhabitants (Table 4), we find an overall population of 1.6 million. Typical islands of this group have a mean population of approximately 3000–4000 island inhabitants, with a larger spread for Indonesian islands compared to other countries. The solar potential is similarly high for the island group (mean of 1800 kWh/m^2/y), the wind power potential is the highest in the Philippines with mean of 4.9 m/s.

Islands with a population between 10,000 and 100,000 inhabitants (Table 5) comprise the largest total population with 5.8 million. Of those, more than 4.7 million are living on Philippine and Indonesian islands. These larger islands hold a typical average population of 35,000. The Indonesian islands are more diverse in terms of economic activity and island area, compared to the uniform group of Philippine islands. The group of islands comprised as "other" islands are mainly comprised of larger islands in Myanmar (19) and Malaysia (15).

1.3 Implications for Future Microgrid Development

The classification reveals that there exist many islands in Southeast Asia, which are suitable for microgrid deployment in terms of their population size and renewable resource potential, especially for solar power. Most of the islands with a population lower than 1000 are likely not provided with electricity yet. As shown earlier, such islands are mostly very remote with low purchasing power (see Table 3), indicating that initial electricity demands will be low. Microgrid system designs need to address these preconditions. Based on the fact that most islands worldwide rely on diesel power systems to supply the electricity demand [28], we assume that the identified islands with a population of more than 10,000 are already supplied with such diesel generators. Here, the implementation of RE serves for the hybridisation of former fossil-fuelled island grids. The use of electricity for productive use facilitates the integration of RE, as the productive demand typically peaks in parallel with the highest daily solar yields. A stepwise implementation, e.g. to form a solar-diesel grid (RE share of 20–30%) and a later implementation of battery storage (RE share 40–100%) can facilitate the mitigation of diesel fuel combustion and minimise initial investment costs. In the group of islands between 1000 and 10,000 inhabitants, both cases, meaning no power supply yet and diesel-based power generation are likely to be found. Therefore, both implementing greenfield RE-based hybrid systems and stepwise implementation of RE capacities into diesel grids can be approaches for sustainable power supply and energy access.

Future microgrid planning efforts should focus on both providing electricity access as a large number of projects can be realised and on hybridisation as more beneficiaries may be reached. The Philippines and Indonesia clearly hold the largest potential for microgrids, so it is important to understand the market and regulatory framework

Table 4 Overview on islands with 1000 to 10,000 inhabitants per country

Country		Islands	Total Pop.	Island Pop.	GDP/capita	Area	Remoteness	Solar potential	Wind potential
		#	#	mean capita	mean USD/capita	mean km^2	minutes	mean $kWh/m^2/y$	mean m/s
Philippines	Value	191	589,396	3086	773	15.4	221	1848	4.6
	Std. Dev.			2299	662	24.2	104	73	1.5
Indonesia	Value	183	579,899	3169	2231	95.0	358	1801	3.4
	Std. Dev.			19,102	5179	284.6	198	1	0.0
Myanmar	Value	56	177,062	3162	220	48.6	323	1821	3.4
	Std. Dev.			2123	236	69.8	171	24	0.5
Malaysia	Value	39	170,792	4379	4355	36.1	251	1800	2.9
	Std. Dev.			2597	7748	50.8	156	70	0.6
Other	Value	33	105,686	4040	48,900	285.1	301	1697	3.5

Table 5 Overview on islands with 10,000–100,000 inhabitants per country

Country		Islands	Total Pop.	Island Pop.	GDP/capita	Area	Remoteness	Solar potential	Wind potential
		#	#	mean capita	mean USD/capita	mean km^2	minutes	mean $kWh/m^2/y$	mean m/s
Indonesia	Value	77	2,674,521	34,734	2142	972.6	334	1761	3.3
	Std. Dev.			24,680	3422	1,533.2	290	140	0.7
Philippines	Value	61	2,036,667	33,388	831	135.9	253	1826	4.4
	Std. Dev.			26,536	1409	173.6	120	73	1.3
Other	Value	43	1,157,599	39,589	12,834	202.5	336	1792	3.8

that could cause potential bottlenecks for implementation in these two countries followed by Malaysia, Myanmar, Thailand, and Vietnam. Additionally, the deployment of microgrids needs to account for the rising impact and risk of climate change effects in Southeast Asia. This includes droughts, floods, extreme weather events, and sea-level rise [10]. Therefore, microgrid designs should incorporate flexibility and resilience to the above-mentioned threats.

2 Application of Energy System Modelling Tools

The GIS analysis results in a pre-selection of islands in Southeast Asia, which are potential microgrid project sites. To determine the actual feasibility of a microgrid at these project locations, a more detailed analysis of the islands has to be performed. This means the load demand needs to be understood so that potential supply options can be suggested. There is a large variety of software tools to determine pre-feasibility of microgrid projects as well as to simulate and optimise energy power systems and sizes of components [29]. These tools optimise the sizes of components of energy systems and use dispatch strategies to supply the demand for the specific case study. In order to identify possible renewable energy investments, we apply different software tools to simulate hybrid microgrids for a selection of three case studies. The results are useful for planners and decision makers to understand typical solutions for RE microgrids and to find the most suitable tool for their use case.

The simulation tools selected have been developed or used by the authors and are comprised of: the simplified planning tool for hybrid systems (SPT), developed by researchers of the Reiner Lemoine Institute (RLI) initially for the Philippine context, which is implemented in Microsoft Excel. The Python 3-tool Offgridders—available open source—and the proprietary software Hybrid Optimization of Multiple Energy Resources (HOMER). They are applied to three exemplary Southeast Asian islands, distinguishable by population and economic activity and representing small, mid-size, and large islands (in terms of population). The simulation results of the tools for each case study island are presented comparatively.

2.1 *Literature Survey on Simulation Tools*

The three energy system modelling tools applied are only a selection of a diverse group of existing energy system modelling tools that have been developed for many purposes. Scientific literature provides several review studies to describe and categorise such tools: Ringkjøb et al. reviewed 75 modelling tools for analysing and planning energy and electricity systems [30]. Sinha and Chandel explicitly focused on tools for hybrid renewable energy systems and reviewed 19 software tools [29]. Connolly et al. highlighted 68 computer tools for analysing the integration of RE in energy systems and analysed 37 of those in more detail [31]. Anoune et al. compared

11 different sizing tools for PV wind-based hybrid renewable energy systems [32]. Sharma et al. compared the environmental assessment methodology in five hybrid system simulation software tools [33].

HOMER is considered for review in all of the above-mentioned studies and applied in many case studies, e.g. [34–39], highlighting its widespread use. It is therefore applied in our case studies and can serve as a reference tool. As it is a relatively new tool, Offgridders has only been used once for scientific papers [40]. Building up on the open source python-library Open Energy Modelling Framework (oemof) [41], the core optimisation methodology of Offgridders has been scientifically validated through the oemof developer and open modelling community. Other software tools mentioned for the application of hybrid and microgrid modelling with significant users are RETScreen [29, 31], H_2RES [30], INSEL [29], iHOGA [33], and TRNSYS [30, 33]. A particular challenge mentioned is that most proprietary software does not allow for customisation of its internal computation method and are therefore a "black box" for users [29]. Additionally, license fees limit the applicability of such tools [42]. Both contradict the scientific criteria of replicability, accessibility, and reproducibility of research results and approaches [41]. Open source software tools comply with the above-stated criteria and are increasingly considered as sufficiently reliable for policy advice [43]. As the group of developers is diverse, tools are developed based on many different motivations and their functions differ widely [43]. However, open source software tools require a large and active community of developers and users to incorporate and update necessary functions [42]. Otherwise, such tools tend to become outdated quickly and limited software support discourages application [29].

For future improvements of tools, the scientific community recognises the necessity to improve energy system modelling tools, including sustainability criteria. Such critique includes the capability of the tools to inform users about the environmental impact of the suggested system designs [33]. Most tools consider emissions—if at all—solely during the operational phase as a proxy of the combusted diesel fuel. Here, the inclusion of life cycle assessment approaches could add information for developing sustainable energy systems [33]. Most microgrid tools neglect the grid impact and network constraints [43], whereas the integration of intermittent RE sources can pose a larger challenge in island grids than larger grid networks [44, 45]. Other concerns address the user-friendliness, incorporation of emerging energy technologies, and more flexible control techniques [29].

2.2 Description of Tools Applied

Microgrid design and simulation tools can make use of multiple methods and levels of detail to determine both microgrid architecture and performance. This, in turn, can lead to significantly differing design and feasibility results of single project locations. It is therefore essential to choose a simulation tool according to the needs of the study at hand and be aware of the effects and uncertainties introduced by this choice. According to Moretti [46], tools can be divided into three main classes: an *analytical* *model* simplifies the simulation of the microgrid for a limited time period and makes use of aggregated factors to determine the system architecture. The influence of dispatch on system design is not addressed, and as such, both resulting economic and technological feasibility remain an estimate.

Two-layer models add a level of detail by addressing design as well as dispatch. Still, these two layers are optimised separately, determining first an architecture and then, according to a previously defined set of dispatch rules, evaluating system performance. Hence, the optimal system design is determined by iteration. Simulation tools integrating the optimisation of design and dispatch can be labelled *single-layer models*. The optimisation of this intertwined problem requires powerful tools, for example mixed integer linear programming.

Analogously, in order to show the applicability of and compare different simulation tools, we selected three different tools for a comparative evaluation of the case studies. The SPT is a simplified excel-based tool, which targets project planners and decision makers for pre-feasibility analyses and can be categorised as an analytical model. HOMER targets commercial developers of hybrid projects and is a typical two-layer tool [33]. Offgridders is an open source tool [47, 48], which targets the scientific community of researchers and tool developers and is representative for the single-layer type. It makes use of oemof [41] to generate a model of an electricity supply system to be designed, and to solve the resulting set of linear equations. All tools follow the same principle of inputs, processing (simulation/optimisation), and output as shown in Fig. 3.

The tools can be distinguished along those steps and by other categories. Table 6 gives an overview of the specifics of the three applied tools. It provides detailed information about input and output data, processing, flexibility, accessibility, and developers. The main input data that these tools require are load, resources information, component costs, and project features. In a simulation scenarios (dispatch simulation), the energy flows are simulated along predefined dispatch strategies (SPT, HOMER) or are simulated including the optimisation of dispatch strategies (Offgridders). Meanwhile, in the optimisation scenarios (dimensioning of system components

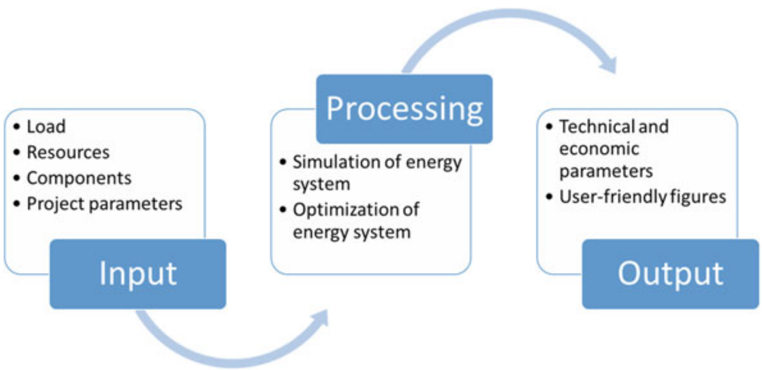

Fig. 3 Conceptual flow of energy system simulation tools

Table 6 Comparison of applied tools

Category	Detail	SPT 3.0	HOMER 3.13.1[a]	Offgridders
Input	Load	Electricity demand per hour for one reference day	Hourly data (handling capacity) for one year	Hourly demand profile for a reference period, i.e. a variable number of days, ideally a year
	Resources	Based on average values	Data with time steps of different sizes from 60 min to one minute. Solar and wind data can be downloaded from national renewable energy lab or NASA sources. These resources and others such as fuel, hydro and biomass resources can be imported or manually introduced by the user	Hourly time series for potential solar or wind plant electricity output for the reference period
	Components	PV, wind, hydro, battery, diesel	PV, wind, hydro, battery, converter (inverter/rectifier), generator (diesel, natural gas, methanol, and others), controller, boiler, electrolyser, hydrogen tank, grid, thermal load controller	PV, wind, battery, converters (inverter/rectifier), transformer station connecting to the national grid (in/out), diesel
Processing	Simulation	Calculation of dispatch for one reference week in hourly increments	Calculation of dispatch for one reference year in hourly increments (can be adjusted to minutes)	Parallel optimisation of capacity and dispatch of system assets Cost-optimal dispatch, not rule-based

(continued)

Table 6 (continued)

Category	Detail	SPT 3.0	HOMER 3.13.1[a]	Offgridders
	Optimisation	No dispatch/system optimisation	Dispatch strategy to control the operation of generators and storage banks to supply the demand. Two dispatch strategies can be used: load following and cycle charging suitable for systems with high and low renewable power, respectively	
	Optimisation algorithm	Scenario analysis to compare configurations	Design process to identify the least-cost option between different scenarios or optimisation using the "HOMER Optimizer"	Solving of a set of linear equations describing the whole system
Output	Technical and economic parameters	Key parameters for selected years (LCOE, CAPEX, OPEX) No detailed energy flows	Detailed parameters (cost and technical) for each component and the project, renewable energy share, emissions. Detailed energy flows	Detailed cost parameters for each component and the project, asset sizing and technical and economic system performance (NPV, LCOE, reliability, renewable share and other)
	Visualisation	Simple figures	Detailed and customised figures	Figures of the system's electricity flows
Flexibility		Fixed tool	"Black box" code used, but control strategies can be implemented via MATLAB Link module	Flexible tool, open-source, adaptable electricity system configurations, other components or energy vectors can be added

(continued)

Table 6 (continued)

Category	Detail	SPT 3.0	HOMER 3.13.1[a]	Offgridders
Additional features		–	Additional modules to design or improve dispatch strategies: generator order, combined dispatch, homer predictive. Multi-year and sensitivity analyses are also possible	Central grid connection can be subject to blackouts, blackout randomisation, batch-analysis of a number of project locations, automated sensitivity analysis
Developer		Reiner Lemoine Institut	National Renewable Energy Laboratory	Hoffmann, Reiner Lemoine Institut
Accessible via		https://reiner-lemoine-institut.de/en/	https://www.homerenergy.com/ (For testing: the software is available for 25 days)	https://github.com/smartie2076/Offgridders

[a]www.homerenergy.com (accessed: July, 31 2019) HOMER Pro. Version 3.13.1

and dispatch simulation) system designs are identified based on least-cost energy supply (Offgridders, HOMER). The open source tool Offgridders provides the flexibility to perform code modifications, adjusting to the specific conditions of the performed case study. Finally, the output data, which can be used to make comparative analyses, are Levelised Cost of Electricity (LCOE), RE share, and fuel consumption among others. Depending on the chosen simulation tool, the extent of output information varies.

2.3 Description of Case Study

We apply the three outlined energy system modelling tools for each of the pre-identified island classes. The application serves to better understand the techno-economic potential for hybrid microgrids on these islands and to compare the usability of the different tools. The three case study islands are chosen from real project sites for which data are available. The selection is conducted to be representative for small, mid-size, and large Southeast Asian islands.

- Small island: Islands with 100–1000 inhabitants

This case study island represents the most numerous island group characterised by low populated islands with few productive loads. Many of the considered islands are not yet electrified. The selected case study island has a population similar to the average of 350. The electricity demand is characterised by a high evening peak and low average demand (Fig. 4). The peak load is 12.6 kW, and the average solar potential is 1807 kWh/m^2/y. The island is served by one diesel generator with a size of twice the peak load. Such oversizing can be commonly observed in small island grids serving one or few villages.

- Mid-sized island: Islands with 1000–10,000 inhabitants

This case study island has a population of around 3000, which is in the typical size range for islands of this class. The load profile is as well characterised by an evening peak load but with a higher average load (Fig. 4). Peak load is 138 kW, and the average solar potential is 1802 kWh/m^2/y. Two diesel generators each with a capacity equal to the peak load provide power supply on the island. By implementing two generators, the security of supply is increased as one diesel unit can supply all of the demand while the other one is under maintenance.

- Large island: Islands with 10,000–100,000 inhabitants

We select a case study representing a population of approximately 40,000 with a peak load of 1.8 MW. In contrast to the two former island groups, this island has a midday peak due to productive and economic activities during the day (Fig. 4). The solar potential is 1840 kWh/m^2/y. Three diesel generators are implemented with a capacity of 1.2 MW each.

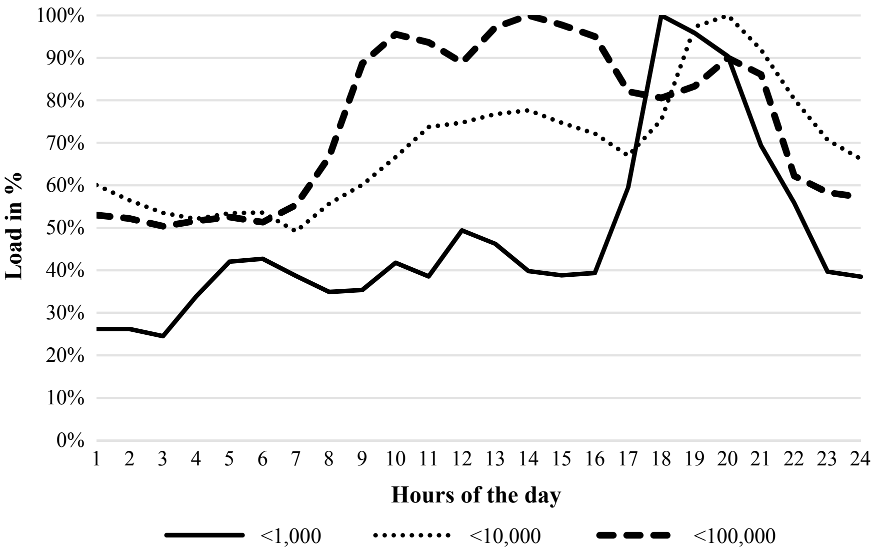

Fig. 4 Applied load profiles for the three applied case studies

As wind power potential is largely dependent on local island conditions and relatively low along the tropics, it cannot be easily generalised and will not be considered in the energy systems of our exemplary case studies. Since we identified a high potential for solar PV for the entire island landscape, we consider solar-battery-diesel hybrid microgrids for the modelling of energy systems. Given the objective of comparing the energy system modelling tools described, we insert the input parameters in the most similar way possible. However, due to different input schemes of the individual tools this is not possible for some of the parameters. An example is the solar generation per hour, which is inserted as an annual profile for Offgridders and HOMER and as a weekly profile in SPT. The same holds true for the electricity demand profile. Another difference is that no minimal loading and fixed efficiency for the diesel generator is applied in Offgridders, in contrast to a minimal loading of 30% and variable efficiency depending on the loading of the diesel generator in HOMER and SPT. Table 7 provides the applied economic and technical parameters.

We apply researched projected cost and technical assumptions for describing the specific components of the microgrid in terms of initial costs, operational expenditures, lifetime and further specified technical parameters. For solar PV plants, we apply initial investment costs of 1000 USD/kWp, 2% OPEX and lifetime of 20 years [49]. We consider lithium-ion battery technology as energy storage system, considering it as the most suitable energy storage technology on islands, given the expected cost reduction, high efficiency, and longer life cycles compared to other technologies [50, 51]. CAPEX are 500 USD per kWh installed capacity, OPEX are 5 USD/kWh per year, and the assumed lifetime is 10 years; other technical parameters are round-trip

Table 7 Economic input parameters for case study analysis

	Parameter	Unit	Value
PV	CAPEX	USD/kWp	1000
	OPEX	USD/kWp/y	20
	Lifetime	y	20
	Solar output	kW/kWp/h	Year (Offgridders, HOMER) Week (SPT)
Battery	CAPEX	USD/kWh	500
	OPEX	USD/kWh/y	5
	Lifetime	y	10
	C-rate	kW/kWh	1
	Max. depth of discharge	%	80
	Charging efficiency	%	90
	Discharging efficiency	%	90
Diesel	Installed capacity	kW	2 times peak demand
	CAPEX	USD/kW	500
	OPEX (fix)	USD/kW/y	6
	OPEX (var)	USD/kWh	0.03 (SPT, Offgridders) var. (HOMER)
	Lifetime	Y	10
	Minimal loading	% of max power	0 (Offgridders) 30 (SPT, HOMER)
	Fuel use per kWh	l/kWh(el)	0.33
	Generation efficiency	%	30.9 (Offgridders) var. (SPT, HOMER)
Other	Fuel price	USD/l	0.8
	Project lifetime	Y	20
	WACC	%	10
	System stability criteria	%	30
	Demand	kW, hourly	Year (Offgridders, HOMER) Week (SPT)

efficiency of 81% and a maximum depth of discharge of 80% [52, 53]. For designing the diesel generator system, we assume a fixed capacity twice the peak load for each case study [54]. We apply CAPEX of 500 USD/kW, fixed operational costs of 6 USD/kW/y and variable operational costs of 0.03 USD/kWh in Offgridders as well as SPT [13]. For HOMER, we apply default values of 0.25 USD per operating hour for diesel generators <100 kW, 2 USD per operating hour for diesel generators <1000 kW, 10 USD per operating hour for generators >1000 kW. A stability criterion is applied which ensures that 30% of the hourly load can be supplied by using the generator or by having sufficient battery capacity and power as backup. We set diesel costs at 0.8 USD/l, reflecting procurement costs plus additional transport costs [13]. Project lifetime is set to 20 years with an interest rate of 10%.

2.4 Case Study I: Small Island

At first, we present a diesel-only and hybrid scenario for the small case study island. Evaluating the likely current electricity supply system of the smallest island, a sole diesel microgrid with only one single generator of 25 kW capacity, the simulation tools result in a wide range of LCOE: The electricity supply costs vary from 34 USDct/kWh (Offgridders), 59 USDct/kWh (HOMER) to up to 60 USDct/kWh (SPT). A closer look into the cost components reveals that these differences spring both from differing fuel consumption and from annual operational costs of the generator (Table 8). This highlights the differences of the simulation tools with regard to their diesel generator models: while Offgridders assumes constant efficiency and no minimal loading, both SPT and HOMER take into account the dependency of the generation efficiency on the diesel generator's load factor and a minimal loading, resulting in twice as high fuel consumption. The generator constantly operates in part load, which leads to very low efficiencies in the SPT and HOMER simulations. Excess generation in times of low demand, resulting from the generator's minimal loading, increases the fuel consumption additionally.

When designing a hybrid microgrid for the smallest island, all three tools result in an optimal renewable share of about 30%. However, the capacities to reach this percentage vary: while the SPT suggests an installation of 20 kWp PV combined with 8 kWh lithium-ion battery, Offgridders reaches the renewable penetration with only 14 kWp PV and 2.6 kWh battery. In contrast to this, HOMER recommends an installation of 20 kWp PV and a larger battery capacity of 28 kWh. In case of Offgridders, the low installed capacities are caused by its methodology: with perfect foresight and constantly high diesel efficiency, low PV, and battery capacities pose the least-cost option. HOMER is able to use the battery capacities to decrease diesel operational hours, and as such, the diesel generator's operational costs.

The investment into hybridisation (SPT: 24,000 USD, Offgridders: 15,300 USD, HOMER: 34,000 USD) allows to decrease the island's system's estimated fuel consumption by a large margin—by half in the case of SPT and HOMER. This saves 4,000–16,000 USD/a in fuel expenditures, leading to lower LCOE. The SPT shows

Table 8 Results of energy system modelling tools for the three case studies

	System type	Tool	LCOE	Diesel units	Fuel consumption	Fuel cost	Annual O&M costs diesel
			[USD/kWh]	[#]	[thousand litre/a]	[kUSD/a]	[kUSD/a]
Small island	Diesel	SPT	0.60	1	34.2	27.4	2.3
		Offgridders	0.34	1	17.5	14.0	1.7
		HOMER	0.59	1	33.8	27.1	2.2
	Hybrid	SPT	0.39	1	17.6	14.1	1.3
		Offgridders	0.29	1	12.4	10.0	1.3
		HOMER	0.35	1	14.2	11.3	0.7
Mid-sized island	Diesel	SPT	0.34	2	298	238	26.7
		Offgridders	0.32	1	276	221	26.7
		HOMER	0.36	2	326	260	24.8
	Hybrid	SPT	0.29	2	201	161	18.2
		Offgridders	0.27	1	183	146	18.3
		HOMER	0.28	2	192	154	9.4
Large island	Diesel	SPT	0.32	3	3921	3136	374.4
		Offgridders	0.32	1	3881	3105	374.4
		HOMER	0.34	3	4191	3353	350.4
	Hybrid	SPT	0.26	3	2344	1875	226.5
		Offgridders	0.26	1	2283	1826	229.1
		HOMER	0.26	3	2071	1657	121.4

electricity costs of 39 USDct/kWh, Offgridders of 29 USDct/kWh and HOMER of 35 USDct/kWh.

2.5 Case Study II: Mid-Sized Island

For the second case study, similarly, we simulate a diesel-only and a hybrid system. Powering a mid-sized island with a diesel-based microgrid is cheaper than powering a small island, with LCOE ranging from 32 USDct/kWh (Offgridders) to 36 USDct/kWh (HOMER) (Table 8). Splitting the diesel generator capacity in two units allows for a more appropriate supply of the hourly load. Annual fuel consumption also varies to a lower degree. It is important to underline that this is achieved through two generators of 138 kW being installed in case of SPT and HOMER, as it is often the case in microgrids with increasingly high peak demand. As such, the average generation efficiency is increased dramatically—as one of the generators can even operate on full load during peak demand times.

The costs of electricity supply for the mid-sized island can further be decreased if a hybrid microgrid is installed, with LCOE of 27 USDct/kWh (Offgridders), 28 USDct/kWh (HOMER), and 29 USDct/kWh (SPT). This is achieved with an increased renewable share between 32 and 39% (Fig. 5). The PV capacity installed exceeds the peak demand in all three cases and is almost twice the peak demand (Fig. 7). Overall, the SPT estimates that 276 kWp PV and 57 kWh battery should be installed, Offgridders recommends 267 kWp PV and 44 kWh battery, and HOMER results in 266 kWp PV and 180 kWh battery capacity. Such an installation sums to capital costs of 305,000, 289,000, and 356,000 USD, respectively, compared to diesel generator capital costs of 138,000 USD. This decreases fuel consumption and fuel costs by about a third in all simulation tools. HOMER, again, uses the large battery capacity to decrease the operation hours of the diesel generator (Fig. 6). We assume

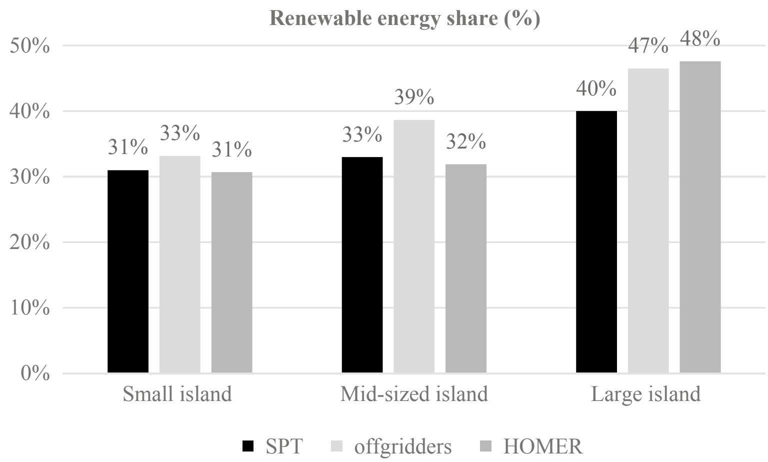

Fig. 5 Renewable energy share for the three applied case studies

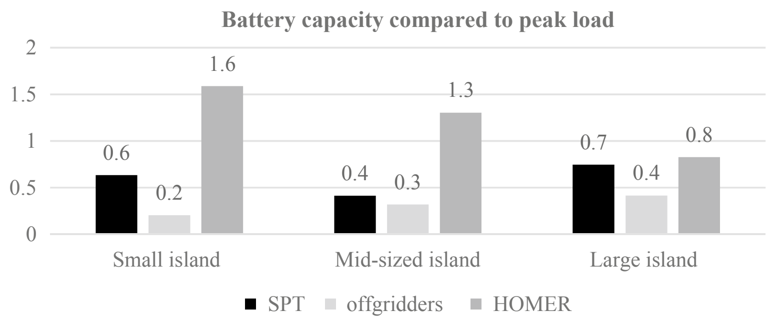

Fig. 6 Battery capacity compared to peak load for the three applied case studies

this is based on the detailed modelling of diesel and battery dispatch and optimising the battery lifetime through cycle charging. This results in higher required battery capacities.

2.6 Case Study III: Large Island

For the final case study, a diesel and a hybrid system configuration is simulated analogously to the case studies described earlier. Microgrids on large islands often consist of multiple generators. As such, in SPT and HOMER, we assume three generators with a peak power of 1.2 MW each to be already installed on the island. This also allows increasing the times a specific generator runs on a high load factor and may decrease excess generation by running generators on low load factors when demand barely exceeds multiples of 1.2 MW. The fuel consumption estimated by SPT and Offgridders is therefore comparable, while HOMER has the highest fuel consumption due to the most detailed simulation of the individual diesel gensets (Table 8). Supplying the island with electricity through a diesel-powered microgrid is therefore possible at an LCOE of 32 USDct/kWh (SPT, Offgridders) to 34 USDct/kWh (HOMER).

Still, hybridisation of the microgrid enables to decrease the electricity costs further to 26 USDct/kWh (SPT, Offgridders, HOMER). This is possible by replacing 40–48% of fossil-fuelled electricity with renewable generation. SPT and Offgridders estimate a PV capacity of 230–250% of the peak demand (Fig. 7). As such, the SPT would recommend installing 4.1 MWp PV and 1.3 MWh battery at costs of 4.8 million USD, while Offgridders suggests the installation of 4.5 MWp PV and 750 kWh battery investing 4.9 million USD. HOMER's simulation results recommend the

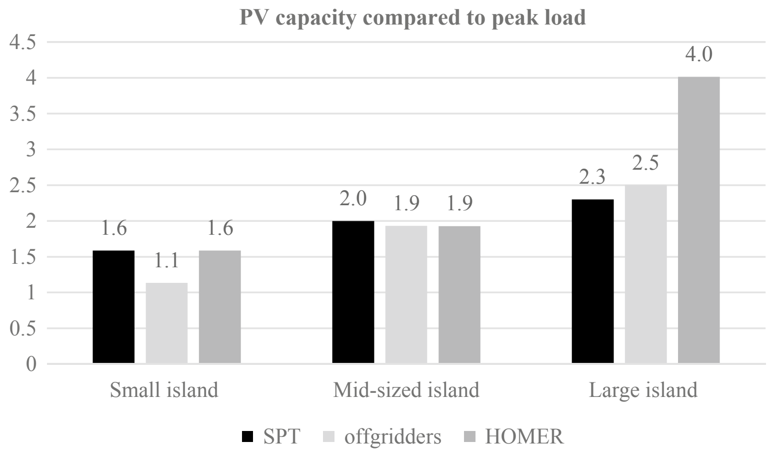

Fig. 7 PV capacity compared to peak load for the three applied case studies

installation of a PV capacity four times the peak demand (7.2 MWp) and 1.5 MWh battery capacity, with capital costs of almost 8 million USD. This large capacity decreases operational hours of the diesel generator almost by half (compared to SPT and Offgridders) and thereby decreases diesel generator operational costs. Judging from the comparably low fuel consumption decrease, these savings are achieved by replacing diesel generator utilisation not only during the day, but also at times at low demand in the evenings or mornings through batteries charged using PV generation.

2.7 Comparative Discussion

The presented case study analysis of the simulated islands shows that microgrid hybridisation is favourable for small, mid-sized, and large islands. While these prospects can be, as a simplification, linked to an islands' population, the actual driver can be found in the demand profile's shape. High evening peaks, common on islands with lower population, disadvantage high PV penetration as the batteries required to supply evening demands are not always economically competitive to fossil-fuelled power generation. With increasing population and business activity, the demand peaks move towards noon, while at the same time, the daily average demand increases and the demand profile flattens. This leads to cheaper systems, in which diesel generators run on higher efficiencies, and PV can be used not only to supply daytime demand, but also to decrease diesel operational time. The second driver to lower LCOE of diesel and hybrid systems is the flexibility of the diesel generators operation and dispatch. Instead of using one generator (first case study), we use two and three generators (cases II and III) to show the effect of increased flexibility and reduced overall minimum load of the power plant.

Especially HOMER showed that microgrid hybridisation could not only replace daytime diesel operation, but also decrease diesel operational hours and increase its efficiency, thus decreasing system costs. Attention has to be paid to the assumed diesel fuel price. Here, a conservative estimation without accounting for future fuel price growth was used, displaying the competitiveness of PV and batteries today but underestimating their benefits in the future.

As presented, the simulation tools displayed similar tendencies but also differing simulation results. While the general tendency of decreasing LCOE and increasing renewable share with increasing population remains true for each tool individually, the actual values can differ largely, especially with regard to optimal capacities and fuel usage. This originates from the different component models and possible settings of each simulation tool, which the user should take into account.

The simulation tools, therefore, have different areas of application. The SPT is able to perform a pre-feasibility study of individual locations with a low need for inputs and a clear interface for the results, which makes it accessible to non-experts. Offgridders has a very low computation time, but relies on simplifications for system assessment. With its ability to evaluate a great number of locations and perform sensitivity analyses, it can identify tendencies and highlight project sites with high potential for future detailed analysis. With its adaptability, it can be used in research. Using HOMER, on the contrary, requires expert knowledge and a long computing time but is able to provide a detailed and implementable system design for a specific project location.

2.8 Advantages and Disadvantages of Applied Tools

The literature review has shown that HOMER can be seen as the current state-of-the-art simulation tool for microgrids. With the SPT and Offgridders, we suggest two alternatives, which are free of charge and can be further developed and adapted by the users. In the following table, the advantages and disadvantages of each applied tool are summarised from the users' perspective.

As stated in Table 9, each tool has certain advantages and disadvantages for different user groups. They can be summarised as follows:

Table 9 Simulation tool comparison from a user's perspective

Tool	Advantages	Disadvantages
Offgridders	• Open source tool which allows for changes in the programming code by the users • Highly flexible tool; any components and dispatch strategy can be added • Allows automated simulation of many islands/scenarios which is beneficial for pre-feasibility studies • Linear optimisation of components' sizes and dispatch allow an outlook on optimal hybrid system's performance	• Limited reference cases • Limited output functions for visualisation and comparison of results • Simulations are currently simplified due to generic diesel generator with fixed efficiency
HOMER	• Industry standard for microgrid simulation • High user-friendliness due to graphical user interface • Wide range of system configurations can be simulated and optimised • Various presentations and illustrations of outputs	• Proprietary software with high license costs • Black-box simulation does not allow for detailed analysis of results • Structure of tool and simulation and optimisation algorithms cannot be changed by the user • Detailed settings need experienced users for correct application of HOMER (high barriers of entry for users)
SPT	• Excel-based user interface allows for quick understanding of tool application • Simplification of inputs and simulation algorithm allows for quick application and simulation	• Simplification reduces reliability of results • Use cases are currently limited to the Philippines

Offgridders can be seen as most suitable for academic users and planners. The advantages are that it is the most flexible tool in terms of changes and use cases and that it can be automated to simulate hundreds or even thousands of microgrids or scenarios with reasonable effort. Disadvantages lie in the higher complexity of usage, as users need to be proficient with the programming language Python if they want to add new functions. Another disadvantage lies within the simplification of the diesel genset, which may be overcome by the developers' community in the future.

HOMER is most suitable for project developers and detailed case studies. It can be seen as industry standard and is globally the most applied tool for project developers and researchers. The advantages of HOMER include the user-friendliness of the tool, as well as the many functions in terms of system settings, output tables, and illustrations. The main disadvantage of HOMER is the commercial and proprietary nature of the product. Thus, users need to pay a license fee and tool developers are not able to change the coding of HOMER and need to trust the black-box-based results.

SPT is a tool for less experienced project developers and planners. Thus, its main advantage is the simplification of inputs and calculation processes, which lowers the barriers of entry for users. Furthermore, it is implemented in Microsoft Excel, a very widespread software. The disadvantages lie also in the simplification of the tool. As only one reference week is calculated in the SPT, it remains a rough first estimate of project cost and potential. Even though the diesel gensets are simplified, results have been shown to be similar to HOMER.

In conclusion, we recommend the use of HOMER for detailed planning of projects and the SPT for pre-feasibility studies. Offgridders should be used by researchers and planners to perform a pre-feasibility analysis of a large number of locations, after which a selection of promising locations can be simulated in more detail with other tools. During application, the scientific open source community could also improve it further for future use.

3 Conclusion

Microgrids are appropriate sustainable energy solutions for remote areas in Southeast Asia. We quantify insular remote areas through a geospatial analysis and consider more than 1900 islands with a population of 7.9 million as potential locations for microgrid implementation. Such microgrids need to be based on RE to address climate change mitigation, and simultaneously need to be designed in a resilient way to address climate change adaptation. We identify solar power as most suitable for implementation on Southeast Asian islands since excellent solar resources are available throughout the region, whereas good wind potential is limited only to certain areas. This emphasises the techno-economic feasibility of solar power systems. Finally, the illustrated remoteness of many regions demands for sustainable energy systems. This implies less or even zero fuel dependency for electricity generation.

Key countries to focus on for microgrid deployment are the Philippines, Indonesia, Myanmar, and Malaysia, as these countries comprise the majority of the island landscape.

We cluster the considered islands in the population classes by the following characteristics: lower than 1000; 10,000; and 100,000 inhabitants. Microgrid deployment needs to be adapted to the characteristics of each island group. The least populated islands are characterised by few settlements with a population of around 350. Most of the islands are not yet electrified, and many communities are rather poor. Consequently, the electricity demands are small and the ability to pay for electricity is low. Overall, islands are small in area (only a few km^2) and are remotely located.

Applying different energy system modelling tools highlights that expected diesel-based power generation costs are very high for such islands, due to a large difference between peak and average load causing inefficient diesel generator operation. Hence, all applied tools project huge cost savings through RE-based hybridisation, which allows the reduction of fuel consumption. An appropriate solution for such islands could be containerised PV-battery-diesel systems, which allow for easy transportation and installation. A standardised system could be deployed for the group of more than 1200 islands comprising a population of 420,000.

Mid-sized islands have a typical population of 3000–4000. With 1.6 million, their population is four times larger than the group of least populated islands. The remoteness of such islands decreases while economic activity and island area increase compared with the aforementioned group. The modelling of RE-based microgrids for this case study group reveals cost savings and recommends installing solar capacities equal to twice the peak load (under the applied cost assumptions). For a substantial increase of renewable penetration, and thus potentially decrease of power generation costs, it is necessary to implement solar PV with battery storage, given the higher electricity demands in the evening.

The group of larger islands, in the range of 10,000–100,000 inhabitants, is comprised of only 181 islands, but is home to a large population of 5.8 million. Typically, such islands have a population of more than 35,000 with economic activities and productive use increasing the demand for electricity during the day. The assessment of RE-based microgrid options finds highest RE shares for this island class, because the electricity demand profile matches with the solar resource availability. Here, a possible implementation strategy could be to implement solar PV for fuel-saving purposes during daytime initially and then stepwise increasing solar and battery capacities to increase the RE share.

In summary, this chapter has shown the usefulness of GIS and simulation tools for planning microgrids as they enable the evaluation of the economic feasibility and environmental impact, before embarking on costly site visits to the remote islands. Different tools exist for different user needs and a focus on openly accessible tools can further enable a widespread use in the future to accelerate project development and implementation of renewable microgrids.

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Solar Project Financing, Bankability, and Resource Assessment

Dazhi Yang and Licheng Liu

Abstract This chapter deals with issues involved during solar project financing and resource assessment. In the first half of the chapter, an overview of financing and bankability of utility-scale photovoltaic (PV) plants is provided, with a slight touch on microgrid PV financing. The discussion revolves around risk management, which requires rigorous assessment of the financial viability. Since a robust solar radiation dataset is essential for securing competitive financing for solar-power projects, the second half of the chapter discusses solar resource assessment—a data-oriented exercise. The best practices on solar resource calculation are exemplified through various case studies using data collected at a tropical site: Singapore. Subsequently, 5 latest satellite-derived irradiance products and 2 latest global reanalysis products are reviewed. Detailed instruction for data downloading is also provided to facilitate the worldwide uptake of these high-quality data. Latest scientific methods on site adaptation—a class of procedures to reduce the uncertainties embedded in gridded products—are presented with a Brazilian case study.

Keywords Project financing · Bankability · Resource assessment · Solar energy; Ensemble method · Site adaptation · Remote-sensing data · Reanalysis

1 Introduction

In recent years, the adverse impacts of climate change, such as catastrophic natural disasters, rising sea levels, or elevated mean surface temperatures, have led to growing interests and concerns in the global community to dive deeper into various efforts

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to reduce or limit carbon emission. Many countries are closing in on the commitment targets that they had previously pledged in the fight against climate change. Considerable effort has been made in promoting the electricity production from renewable energy sources, such as solar photovoltaic (PV), wind, or hydropower. In particular, the development of solar PV has been thriving—it becomes increasingly commercially viable—in places that have readily available access to state-owned power grids. Financial institutions are now comfortable with making the commercial decision to finance grid-tied PV projects, may they be ground-mount or commercial and industrial rooftop PV plants.

That said, there is also a high energy demand in remote and rural areas, where state-owned power grids are unable to reach and therefore supply electricity to, due to cost or infrastructural constraints. In order to bridge the disparity in energy supply and demand in such areas, microgrid solutions have been proposed and considered, in which variable renewable energy generators are combined with controllable diesel generators [1, 2]. However, many technical, financial, as well as regulatory challenges for such microgrid solutions have yet to be fully solved, which impedes the establishment of a commonly practiced financing solution. As a result, many microgrid PV plants are financed with an on-balance-sheet structure. In other words, the capital or debt raised by companies to develop and build the microgrid PV plants is highly dependent on their financial health, which becomes a barrier to the sustainable growth and implementation of microgrid solutions. Nonetheless, it is crucial to continue exploring ways to establish microgrid financing, and similarities can be drawn from the more matured financing of grid-tied PV projects. To that end, the first goal of this chapter is to briefly introduce various existing practices to ensure healthy financing and bankability of solar projects.

> Important

The risk in financing a solar project can be mitigated with proper assessment of the financial and technical viabilities. While the financial viability depends highly on the financing structure and contractual terms, confidence in the technical viability mostly comes from the solar resource assessment exercise.

To minimise the financial and technical risks of solar projects, knowledge of the solar resource is of the utmost importance. In solar resource assessment—a subdomain of energy meteorology—three solar radiation components are commonly referenced, namely, global horizontal irradiance (GHI), beam normal irradiance (BNI), and diffuse horizontal irradiance (DHI). At this early stage, it is important to point out that solar radiation is never available “on demand” but varies naturally on various timescales, ranging from a few seconds (ultra-short-term variability caused by moving broken clouds) to a few decades (global dimming or brightening due to anthropogenic climate change). To that end, the notion of uncertainty must be put forward. In the second half of the chapter, various long-term solar radiation databases, either for free or for pay, are reviewed. These data provide the cornerstone for the bankability of solar projects, as well as ways to secure competitive financing.

> **Important**

One should never rely on a single source of data when there are more options available, even if data from that source is known to be superior to others. Formally, this is related to ensemble modelling, which seeks an optimal combination of different data, parameters, and models, to make the inference as accurate as possible. The central idea in ensemble modelling is to allow cancellation of random errors and removal of systematic errors.

2 An Overview of Solar Project Financing and Bankability

Risk management is a central consideration in financing a solar project. Building sizeable PV plants usually requires high initial capital investment, which is a key risk factor for companies that intend to build them, regardless of the internal financial capacity to absorb the cost. For this reason, external financing from financial institutions such as banks or private equity investors are sought in the forms of debt and equity. There are many types of financing structures that can be applied to PV projects, such as corporate financing, which typically has an on-balance-sheet structure as aforementioned, project financing, crowd sourcing, or even personal credit lines. A key consideration for banks and investors when making the commercial decision to provide a loan to finance any project is to assess the borrower's ability to repay the loan. It is also critical that the project provides an attractive return on investment, which can be rather subjective and vary with the type of investors, the type of financing and the corresponding security or collateral requirements.

The most ideal financing structure for a PV project is non-recourse project financing, in which a bank typically takes on the role of the lender to provide a loan; a special purpose company or special purpose vehicle (SPV) is set up by the parent company that intends to develop and build the project to hold the rights and assets specific to the project, and to act as the borrower of the loan. The ability to repay the loan is assessed purely based on the cashflow of the SPV; its non-recourse nature dictates that the loan shall be secured only by a set of predefined collaterals such as project rights, land rights and assets that are specific to the project. In other words, even in the event of default, the lender cannot seize any asset of the SPV nor of the parent company beyond the project-specific collaterals to recover any loss incurred. Such a financing structure, at first glance, seems to be a risky investment. Therefore, in order to obtain enough security to provide non-recourse project financing, it is extremely crucial for the lender to carry out its due diligence to assess the bankability of the project.

2.1 Bankability of Solar Projects

There are many factors that contribute to the overall bankability of a project. First and foremost, the lender will have to go through an evaluation process of the project-related entities, also known as “know your customer” (KYC). The KYC process usually involves the SPV, the parent company, as well as any other equity investor in the SPV, and evaluates the legal, structural, and financial health of the respective entities. The evaluation looks into information such as the articles of incorporation, financial statements, list of directors, or tax declaration forms. It is also important to be transparent to the lender about the project structure, which shows the shareholding structure in the SPV by the parent company and the equity investors. Eventually, the project structure will reflect the injections via equity and loan that constitute the debt ratio, as well as the entity into which each injection goes. The main objective of KYC is for the lender to mitigate, if not eliminate, any potential risk of illegal intentions such as money laundering by any party through the project.

In principle, non-recourse project financing is secured only by the project-specific collaterals. The most important collateral is the land rights to the project site, the grid connection path, and the grid connection point. Grid connection points, in many cases, are not on the project site. The typical land rights being pledged as collateral to the lender are land ownership, surface rights, easement rights, and lease rights. The most bankable land rights are those that can be registered on the land registry, which are typically ownership and surface rights. In some cases, easement rights can also be registered. Public land and roads are generally owned by the government, which grants neither land ownership nor surface rights. In such cases, leases and road use permits can be obtained from the government but cannot be pledged as collateral. If the project is on a feed-in tariff (FIT) scheme, the government will pay the SPV a unit price for every kilowatt hour (kWh) of electricity produced, through a state-owned utility company. In this case, the project rights to be pledged as collateral to the lender are the project ID granted by the government and the power purchase agreement (PPA) between the SPV and the utility company. The bankability of these project rights depends highly on the credit rating of the government. If the project is developed based on a corporate PPA, then the key project right to be pledged is the PPA between the SPV and the off-taking company. The lender will examine the credit rating of the off-taking company and check the sustainability of its business in order to assess the bankability of the PPA.

Two other major areas into which the lender will typically look, to assess the bankability of the project, are the engineering, procurement and construction (EPC), and operations and maintenance (O&M) aspects of the project. The lender will review the track records of the EPC and O&M contractors, to ensure that the project will be designed, built, operated, and maintained by experienced professionals in accordance to local regulations. The EPC and O&M contracts will also be evaluated for the scope of work, warranties, and clauses on liquidated damages in the event of late project delivery and underperformance. In terms of bankability of the components and equipment, reputable suppliers and manufacturers tend to be favoured, owing to their stable production capacity, punctual product delivery, and reliable operational support.

Although non-recourse project financing is ideal, it is unlikely to be achieved for every project, commonly due to issues such as market instability, low credit rating of the off-taking company, insufficient experience of the EPC contractor, or adoption of new and unproven technology for components. In this regard, solutions with partial or full recourse, such as parent guarantee, construction guarantee, or performance guarantee will have to be taken into consideration by the parent company as financing securities. Furthermore, the amount of loan provided by the lender also varies according to the targeted market and the form of recourse.

2.2 Determining Loan Amount

A key indicator that lenders use to determine the financeable loan amount for a project is the debt service coverage ratio (DSCR). The DSCR is the ratio of net operating income, which is revenue minus operating expenses excluding depreciation, versus total debt service, which includes principal repayment, interest, and any other loan related administrative fees. The DSCR indicates the ability of the SPV to pay for the debt obligations, and it typically ranges between 1.2× and 1.6× depending on the market and bankability of the project. The higher the DSCR, the healthier the cashflow of the project. In general, projects in more stable markets with higher bankability will have a lower interest rate and a lower DSCR requirement. Therefore, having a stable revenue stream is very crucial for financing.

Revenue is essentially pricing multiplied by volume. Pricing varies with different business models. The FIT model, adopted by many countries such as Germany, Spain, or Japan, provides a reliable unit price per kWh of electricity generated over an extensive period of time, typically around 20 years. The FIT model offers a stable source of revenue and is typically used to attract investors and stimulate market growth during the initial phase. However, it utilises taxpayers' money, which can be otherwise spent on areas such as healthcare, education, or infrastructure, and is therefore not a sustainable long-term solution. As a result, many other innovative solutions, such as off-site corporate PPA or distributed solar leasing, emerged over the years, which can achieve win-win situations and cater to the interest of both the energy producers and the off-takers.

Volume is the counterpart of pricing married to the revenue equation. It is the total amount of kWh or yield that can be generated by the PV plant, which depends on the long-lead forecasts (climatology) of the available solar resource, as well as the performance ratio of the PV plant. The solar resource is estimated via statistical analyses of historical data to provide an accurate representation of the plausible amount of solar radiation in the long term. As mentioned earlier, the availability of solar resource at a project site depends on climate and weather conditions, see [3] for the worldwide Köppen–Geiger–PV climate classification. The performance ratio of a PV plant is a commonly used indicator to represent the overall efficiency of the plant from a technical perspective—for the tropics, performance ratio typically ranges from 0.75 to 0.825 [3]. It is highly affected by *design factors* of the PV plant such as tilt angle, azimuth, fleet distance, site surrounding conditions (shading, slope, or elevation), as well as component-driven factors such as quality, efficiency, or losses. Clearly, the list of design factors is long. Therefore, typically, two to three reputable independent technical advisors are engaged by the lender of a project to carry out the energy yield assessment (EYA) to provide an unbiased calculation of the yield.

With pricing and volume, it is easy to calculate the revenue stream for the project over a specific period, and thereby deriving the DSCR requirement and the loan amount comfortable for the lender to provide. For projects under the FIT scheme, pricing is not within control of the PV owners, volume thus becomes the deciding factor for the overall viability of the projects. In subsequent sections, the technical aspects of solar resource assessment will be discussed in details.

2.3 Financing Microgrid PV

Although the set of best practices for financing microgrid PV plants has yet to be standardised, many bankability factors for grid-tied PV projects can already be applied to microgrid PV projects. The first checkbox to tick is land rights. The strongest form of land security, which is registrable land rights, shall always be sought when developing a microgrid PV plant. Next, the EPC and O&M aspects of projects are also transferrable. Experienced contractors and reputable component manufacturers shall be engaged; legally sound and secured contracts shall be negotiated and inked. This is especially important for developing and financing microgrid PV plants in remote and rural areas, in order to ensure the availability of professional services and continuous support during the operational phase of the project, despite the inaccessibility of the site. For similar reasons, the KYC process will have to be carried out in greater detail. The more inaccessible an investment is located, the better the lender will need to know about the borrower.

There are some major challenges that must be overcome in order to minimise the financing recourse. A critical one is to ensure a steady and sustainable revenue stream. Although there are high demands for electricity in remote and rural areas, the spending power of the local people is limited, which makes it difficult to determine an optimal unit price for the electricity provided that is affordable to the people, and yet guarantees an attractive return on investment. Furthermore, a PV plant might play a more pivotal role in a microgrid environment as compared to that in a grid-tied environment. Hence, it is probably more crucial to include a back-up energy source that complements the fluctuative nature in energy generation by the PV plant, which leads to the question of whether the PV plant should be financed with or without the back-up energy source. If a back-up energy source, for example an energy storage system, were to be included in the financing, a more detailed and representative breakdown of the capital expenditure (CAPEX) must be taken into account, and a more accurate and effective EYA must be carried out to determine the overall yield.

Moreover, microgrids are technically considered as electrical infrastructures as they are designed and built for the provision of electricity to the public. The question of who is going to be the off-taker that can provide enough security to the lender over an extensive period of time begs clarity. If the electricity generated is being sold directly to the local people, it is hardly possible to establish any long term PPA or bilateral agreements for bankability purposes. One plausible solution is to get state-owned utility companies involved as the intermediate off-taker to bridge this lack of security, which in turn raises numerous questions on the regulatory framework that should govern the development, building and operation of microgrid PV projects. How should microgrid PV projects be regulated? Who should own the project rights? Should state-owned utility companies be part of the ownership or operational structure? And what concessions can state-owned utility companies make in light of bankability?

All these are pressing issues that need to be resolved in order for the financing of microgrid PV projects to develop. Since these topics are already gaining considerable traction in the industry, we hope to see light soon at the end of the tunnel. On the other hand, most technical aspects of microgrid PV resource assessment have already matured. Within the scientific community, a consensus on the best practices and models for solar resource calculation is forming, owing to the recent advances in radiometry, remote sensing, data science, and energy meteorology.

3 Solar Resource Calculation

Calculating, or rather estimating, the available solar resource is the foremost step in PV energy system design, financing, and commission. Most software packages and tools, such as the free PVLIB,[1] System Advisor Model,[2] or the paid PVsyst[3] (see [4] for a comparison of some of these tools), take time series of irradiance and other meteorological variables as input. Using these input data, the long-term performance of the system is simulated based on other system-level design data, such as location and layout of the system, module characteristics, inverter specifications, or profiles for various loss mechanisms. Generally speaking, the technology in the latter simulation steps, i.e., solar irradiance to PV power conversion,[4] is quite mature, and most professional companies are well versed in the above-mentioned design tools. However, relatively little attention has been placed on the quality of the input meteorological data, which in turn becomes the most significant source of uncertainty.

[1] https://pypi.org/project/pvlib/.

[2] https://sam.nrel.gov/.

[3] https://www.pvsyst.com/.

[4] This is a collective term for various models including, but not limited to, cell temperature models, I–V characteristics of the PV module, DC wiring and mismatch losses, DC/AC conversion losses, and AC wiring and transformer losses.

3.1 Transposition Models

PV is often installed on a tilt that is equal to the site's latitude, to maximise its annual electricity production. Hence, the global tilted irradiance (GTI), or sometimes referred to as irradiance on the collector plane, plane-of-array irradiance, or in-plane global irradiance, is the key parameter governing PV energy production. Mathematically, GTI, or G_c, can be decomposed into three terms:

$$G_c = B_c + D_c + D_g, \tag{1}$$

where B_c, D_c, and D_g are beam tilted irradiance (BTI), diffuse tilted irradiance (DTI), and irradiance due to ground reflection, respectively. Since these tilted irradiance components are rarely being measured, they have to be estimated using the horizontal irradiance components. More specifically, one can write

$$G_c = B_n \cos\theta + D_h R_d + \rho G_h R_r, \tag{2}$$

where GHI, BNI, and DHI are denoted using G_h, B_n, and D_h, respectively; θ is the incidence angle, which can be calculated using solar positioning algorithms (SPAs); R_d is called the diffuse transposition factor; R_r is known as the transposition factor for ground reflection; and ρ is foreground's albedo, a (time-varying) factor describing the reflectivity of the surface.

Equation (2) is called the *transposition model*. In order to estimate G_c, every term on the right-hand-side of that equation needs to be known. Since the relationship among the three horizontal irradiance components is governed by the *closure equation*:

$$G_h = B_n \cos Z + D_h = B_h + D_h, \tag{3}$$

with Z being the solar zenith angle, when two components out of three are known, the third can be deterministically constructed. It is common to assume a constant value of $\rho = 0.2$ for tropical regions. Moreover, it is typically reasonable to assume isotropy in the ground-reflected irradiance, that is, $R_r = (1 - \cos s)/2$, where s is the known collector tilt. Hence, the only parameter requires attention is R_d.

In the literature, there are about 30 different models proposed to calculate R_d. The model complexity varies by quite a lot. Notwithstanding, the Perez model [5] proposed in 1990 is commonly perceived as the most accurate one. The Perez model views the hemispheric sky dome as a three-part geometrical framework that consists of (1) an isotropic background, (2) a circumsolar region, and (3) a band near the horizon. Although the model is intricate, it is implemented in most, if not all, software tools, owing to its popularity in the solar community. That said, there are many versions of the Perez model, and it is generally unclear which version is being implemented in which software tool. Thus, even when the same data is used, different tools usually give different values of R_d. This is not a problem unique to the industry, as even in research, scientists frequently make mistakes, see [6] for a discussion. Since those mistakes tend to propagate in the literature, the reader's attention is required.

Next, a case study is presented using a research-grade dataset collected at a tropical site—Singapore—by the Solar Energy Research Institute of Singapore (SERIS). The dataset consists of one year of 15-min G_h, B_n, and D_h measurements from 2013, as well as 8 sets of temporally aligned G_c measurements on surfaces with different orientations. Subsequently, 26 transposition models are applied to predict G_c on each tilted plane, and the actual measured G_c is used to gauge their accuracies under squared loss. Table 1 depicts the root-mean-square errors (RMSEs) of each scenario, over all daylight timestamps (herein defined as $Z > 85°$) in that year. These RMSEs

Table 1 Root-mean-square errors (RMSEs), in percentage, of 26 transposition models. One year of 15-min data collected in Singapore, on 8 different orientations (tilt $s°$ and azimuth $\gamma°$) are used. Column-wise smallest RMSEs are in bold. The details of each model and the corresponding original reference are provided in [6]

Model	(10, 64)	(20, 64)	(30, 64)	(40, 64)	(90, 90)	(90, 180)	(90, 270)	(90, 0)
LIU	4.3	7.1	11.0	13.0	25.0	24.2	24.6	23.8
TEMPS	7.3	7.2	10.2	11.7	30.1	39.0	33.1	38.5
BUGLER1	4.9	6.2	10.1	11.6	23.2	24.3	23.3	23.8
BUGLER2	3.9	6.5	10.0	11.7	23.1	22.3	22.9	22.2
KLUCHER	5.3	5.8	9.0	10.3	25.7	33.3	27.8	32.3
STEVEN1	3.7	6.1	8.6	10.8	24.1	22.8	25.4	18.9
STEVEN2	3.6	6.0	8.4	10.8	23.7	23.2	25.2	18.8
STEVEN3	4.3	7.3	11.3	13.4	25.8	18.7	24.1	17.6
STEVEN4	3.0	4.7	6.5	8.3	19.7	21.2	20.4	17.7
HAY1	3.0	4.5	6.8	7.7	16.1	18.5	17.0	18.2
HAY2	3.0	4.5	6.7	7.6	16.0	18.4	16.9	18.2
WILLMOTT	3.3	5.7	7.5	8.6	16.0	18.4	16.9	18.2
KORONAKIS	4.3	6.9	11.0	13.1	31.0	38.0	33.3	37.7
PEREZ1	2.7	**3.4**	**4.9**	**5.2**	**12.6**	17.3	12.8	14.9
PEREZ2	2.9	**3.4**	**4.9**	5.3	12.9	16.8	12.5	14.8
PEREZ3	**2.8**	3.6	5.0	5.3	**12.6**	**16.2**	**12.2**	**14.3**
PEREZ4	**2.8**	3.6	5.1	5.3	**12.6**	16.7	12.5	14.6
SKARTVEIT	3.0	4.6	6.8	7.9	16.6	17.9	17.1	15.8
GUEYMARD	3.3	4.7	7.2	8.1	17.1	21.1	17.3	19.4
MUNEER1	3.0	4.5	7.0	8.2	16.0	22.4	17.1	19.1
MUNEER2	3.1	4.4	7.0	8.1	17.2	24.2	18.3	20.6
REINDL	3.0	4.5	6.7	7.7	18.0	23.7	19.7	23.3
OLMO1	5.0	7.5	10.1	12.7	25.6	29.5	26.7	28.1
OLMO2	7.6	9.6	9.9	12.3	21.7	22.3	22.8	21.3
TIAN	5.6	10.3	13.7	15.8	25.0	24.2	24.6	23.8
BADESCU	4.3	7.8	12.1	15.1	25.0	24.2	24.6	23.8

are expressed in percentage, normalised using the tilt-specific mean G_c values for the daylight hours. Clearly, the Perez family of models performs the best. Particularly interesting is that PEREZ3, which is the 1990 version of the Perez model [5], has the smallest RMSE for 5 surfaces out of 8. The details of this case study can be found in [6], and interested readers are referred to the original publication.

Another interesting observation made from Table 1 is that the transposition accuracy decreases with increasing tilt angle. In other words, the errors for all models are found to be smallest for the 10° tilted surface and highest for the 90° (vertical) surfaces. This is the case for not only tropical areas, but the whole world in general. However, as discussed earlier, the rule-of-thumb is to have the PV array tilt angle comparable to the site latitude, thus high-tilt installations are usually not seen in the tropics. One exception is those projects involving bifacial PV technologies, where bifacial modules are sometimes installed vertically. However, that does not affect the present conclusion—the Perez model should be used whenever possible, with no reservation. For further reading on transposition modelling in a tropical environment, the reader is referred to [7, 8].

3.2 Separation Models

Recall Eqs. (2) and (3), to predict G_c, at least two of three horizontal irradiance components are required. However, BNI and DHI data are less common than GHI data. If both are unavailable, one needs to separate them from GHI, and hence the name, *separation modelling*. Stated simply, a one-parameter separation model is in the form of

$$D_h = f(G_h), \tag{4}$$

where $f(\cdot)$ is some function that maps G_h to D_h. It is known, a priori, that the function $f(\cdot)$ is not injective. In other words, for a given G_h value, there are an infinite number of D_h that can correspond to it, see Fig. 1. Consequently, the one-parameter separation models are inferior to those multi-parameter models. Typically, the parameters involved in separation modelling are clearness index (the ratio between GHI and the extraterrestrial GHI), apparent solar time, solar zenith angle, temperature and air mass, among others.

Similar to the case of transposition models, there are many separation models available—in fact, there are a lot more. In 2016, Gueymard and Ruiz-Arias performed a worldwide comparison of 140 separation models [9]. It was found that the Engerer model [10] was the most accurate one at that time. As of today, the best model is believed to be the Yang–Boland model [11], which has been shown to outperform the Engerer model by significant margins. Although the Yang–Boland model has only been verified in the United States and Europe, its universality can be assumed at once. The reason for such improvement is attributed to the fact that the Yang–Boland model leverages satellite-derived diffuse irradiance, which leads to substantial uncertainty reduction.

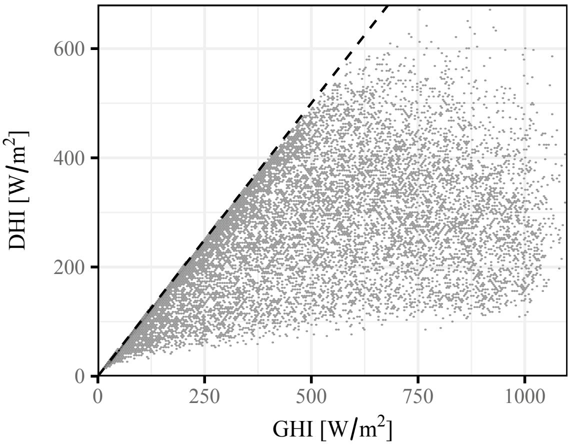


Fig. 1 The non-injective mapping between GHI and DHI. One year of 15-min data collected in Singapore (1.301° N, 103.771° E) are depicted. For any GHI value, DHI can take a range of values. The dashed line shows the identity line

Nonetheless, even the best separation models can result in fairly large errors in the predicted BNI and DHI. Based on the report in [11], at 7 locations in the United States and 5 locations in Europe, the RMSE of the Yang–Boland model ranges from 10–25% for BNI and 25–35% for DHI. For instance, if the site-specific mean measured BNI is 400 W/m^2, then the predicted BNI will miss the actual value by 40–100 W/m^2 on average. The RMSE for the Engerer model is even larger, which can reach up to 35% for BNI and 50% for DHI. On the other hand, under the current best practice, the expanded uncertainties for measured BNI and DHI are only 2% and 5%, respectively. Obviously, there is no reason to use separation models, unless it is absolutely necessary.

3.3 Optimal PV Orientation

Using a set of horizontal irradiance components, with a predefined PV orientation—tilt and azimuth angles—GTI can be estimated through transposition and separation models. In that, an optimisation issue naturally arises. While the conventional wisdom suggests placing the PV arrays at a tilt equal to the site's latitude facing the Equator, due to location-dependent climate and weather regimes, such placement strategy may not be optimal. Therefore, solar engineers usually seek an optimal orientation that can maximise the annual PV yield, by perturbing the tilt and azimuth angles of the PV arrays. Mathematically, the optimisation is written as:

$$\arg\max_{s,\gamma} \sum_{t=1}^{n} \hat{G}_{c,t}, \tag{5}$$

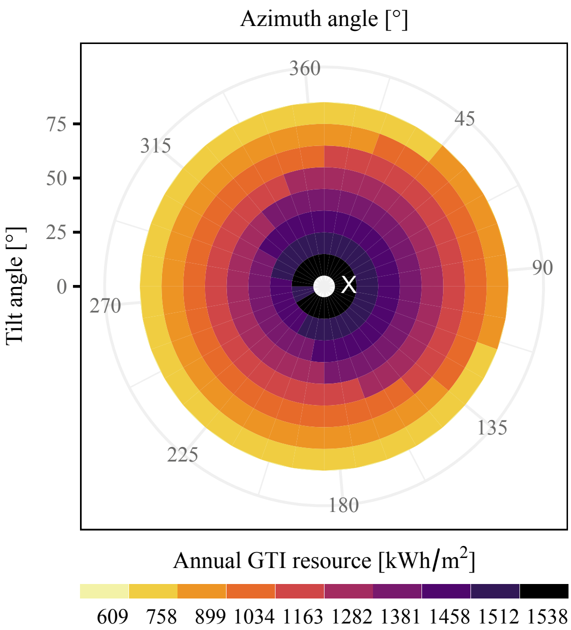


Fig. 2 Perturbing PV orientation to maximise annual yield. One year of 15-min data collected in Singapore (1.301° N, 103.771° E) are input to the Perez transposition model to predict G_c. Both tilt and azimuth angles are perturbed with an increment of 10°. A maximum annual tilted solar energy of 1538 kWh/m^2 occurs at $s = 10°$ and $\gamma = 80°$ E, marked with "X" on the plot. The heat map shows that the mornings in Singapore are sunnier than the afternoons, since placing the panel facing East is awarded with more yield

i.e., to find the optimal values for tilt s and azimuth γ, such that the arithmetic sum of the predicted $G_{c,t}$ for a period of time, $t = 1, \ldots, n$, is largest.

A Singapore case study is used to demonstrate the selection of the optimal PV orientation during solar resource assessment. One year (2013) of 15-min G_h and D_h data collected at (1.301° N, 103.771° E) are input to the 1990 version of the Perez model. The tilt angle is perturbed from 10° to 90° with a step size of 10°. The reason for not starting the perturbation from 0° is because a horizontally placed PV array accumulates dust more easily, whereas a tilted array allows self-cleansing by rain. On the other hand, the azimuth angle is varied from 0° to 350° with a step size of 10°. As a result, a total of $9 \times 36 = 324$ unique pairs of tilt and azimuth angles are tested. For each pair, the Perez model is used to estimate $\hat{G}_{c,t}$ for all 15-min timestamps in 2013, and subsequently, $\sum_{t=1}^{n} \hat{G}_{c,t}$ is evaluated.

Figure 2 shows the optimisation result. It is found that the orientation with $s = 10°$ and $\gamma = 80°$ E has the maximum annual tilted solar energy, namely, 1538 kWh/m^2. Stated differently, the yield of a PV system is maximised if it is placed towards East, rather than facing the Equator. This result is consistent with that reported in an earlier study [12]. It is thus immediately clear that mornings in Singapore are sunnier than its afternoons. From a meteorological viewpoint, on a hot afternoon, the Sun heats the ground which in turn heats the immediate layer of air. This layer is known as the planetary boundary layer, which is the lowest part of the atmosphere and responds to surface forcing in a timescale of an hour or less. Hot air rises to produce convective clouds, and these convective clouds in turn give rise to thunder showers. This type of analysis falls within the domain of energy meteorology, and offers critical information on configuration of numerical weather prediction models in a tropical environment [13]. Solar engineers must be able to integrate such knowledge into the processes of design, simulation, and performance evaluation of PV systems.

4 Solar Radiation Data Sources

Solar radiation data[5] can be obtained from three complimentary sources: (1) ground-based radiometers, (2) instruments onboard geostationary satellites or polar orbiters, and (3) reanalyses [14]. Among these three sources, reanalyses have the highest uncertainty, whereas ground-based measurements through regularly calibrated radiometers have the lowest uncertainty. Terminology wise, only the ground-based data are referred to as *measurements*, and the gridded irradiance products—satellite-derived and reanalysis irradiance—are called irradiance *estimates*. This is because the gridded datasets are produced using either satellite-to-irradiance models or data assimilation.

4.1 Ground-Based Data

Ground-based solar radiation data is measured by radiometers. The instrument that measures GHI is called pyranometer. The instrument that measures BNI is called pyrheliometer.[6] Since a pyrheliometer should always be pointed at the Sun, a tracker that can follow the Sun's position in the sky is needed. Lastly, DHI is measured with another pyranometer accompanied by a shading ball, blocking the direct sun-ray from reaching the thermopile, and thus only measuring diffuse radiation. Interested readers are referred to some of the latest scientific reports on calibration and performance of radiometers [15–17].

Long-term, high-quality, publicly available, ground-based solar radiation data are extremely rare. At the moment, the largest research-grade solar radiation monitoring network is the Baseline Solar Radiation Network (BSRN). BSRN started collecting data in 1992 with 9 initial stations. As of 2019, it has a total of 76 stations located around the world, among which 9 are candidate stations that have yet to collect any data, and 12 are closed due to lack of funding [18], see Fig. 3. For the tropics, there are fewer than 10 active stations, which clearly do not provide sufficient coverage for accurate resource assessment—data from a ground-based station can be used for effective resource assessment within a radius of $\approx$50 km, beyond which the

[5] Solar radiation data are necessary inputs to the microgrid planning tools described in Chapter "Assessment of Micro Grid Potential in Southeast Asia Based on the Application of Geospatial and Micro Grid Simulation and Planning Tools" of this book.

[6] The absolute-cavity radiometer is the most accurate instrument for BNI measurements. However, cavity radiometers are very expensive and are not truly designed for continuous field measurements. Hence, pyrheliometer is the usual option.

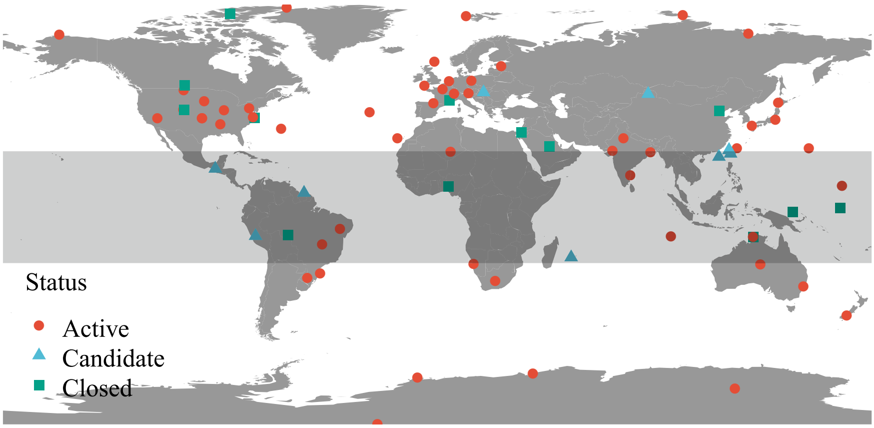


Fig. 3 Station locations of the world's largest radiation monitoring network—BSRN. Active, candidate and closed stations are annotated with different symbols. The tropics are annotated with shade

climatology might be different. The lack of ground-based data can be attributed to one simple reason: collecting long-term, high-quality, ground-based radiation data is highly technical and costly.

To give perspective, Table 2 shows an approximate price breakdown of a monitoring station, following the BSRN standard. Since one aim of BSRN is to measure data permanently and uninterrupted, each item in the monitoring station requires spare parts. As a result, to have one of these highest-quality station, the setup cost is around €164,000 Euro, or equivalently, $182,000 USD. If other O&M costs, such as cost for building a fence around the site or cost for sending instruments for calibration, are considered, the total cost would be even higher.

By now, it should be clear that owning a high-quality solar radiation monitoring system is not for everyone; this is particularly true for private PV owners, who may have a tight budget when it comes to resource assessment. Even if the budget allows, one would not have a reliable local climatology in 15–20 years after the station is built. To that end, resource assessment for solar project is *ubiquitously* carried out using gridded data, either through remote sensing or using reanalysis.

4.2 Publicly Available Satellite-Derived Solar Data

The region between ±65° latitudes is jointly covered by several geostationary weather satellites. In almost every case, the raw data from the infrared and visible channels of the instruments onboard those satellites are made freely available. The latest satellites sample these images every 10 min, at a spatial resolution of a few kilometres. The older ones sample images every 30 min or 1 h. By using the

Table 2 Price breakdown of a BSRN station. All prices are in Euro, € [This information is provided on 2019-11-05, by Bernd Loose from Alfred-Wegener-Institut, Bremerhaven, Germany, who is the station scientist for the Neumayer station of BSRN]

Item	Number	Unit price	Total price	Note
Pyranometer	7	7000	49,000	3 in the field, 4 spare
Pyrheliometer	3	3000	9000	1 in the field, 2 spare
Pyrgeometer[a]	5	6000	30,000	2 in the field, 3 spare
Sun tracker	2	25,000	50,000	1 in the field, 1 spare
Ventilation unit	6	1500	9000	5 in the field, 1 spare
Housing	2	5000	10,000	1 set of electrical cabinet with data logger, power supplies, data transmission hardware in the field, 1 set spare
Computer	2	1500	3000	1 in service, 1 spare
Miscellaneous	–	–	4000	Mast for solar tracker, mounting material, cables
Total price			164,000	

[a] A pyrgeometer is a device that measures infra-red (longwave) radiation

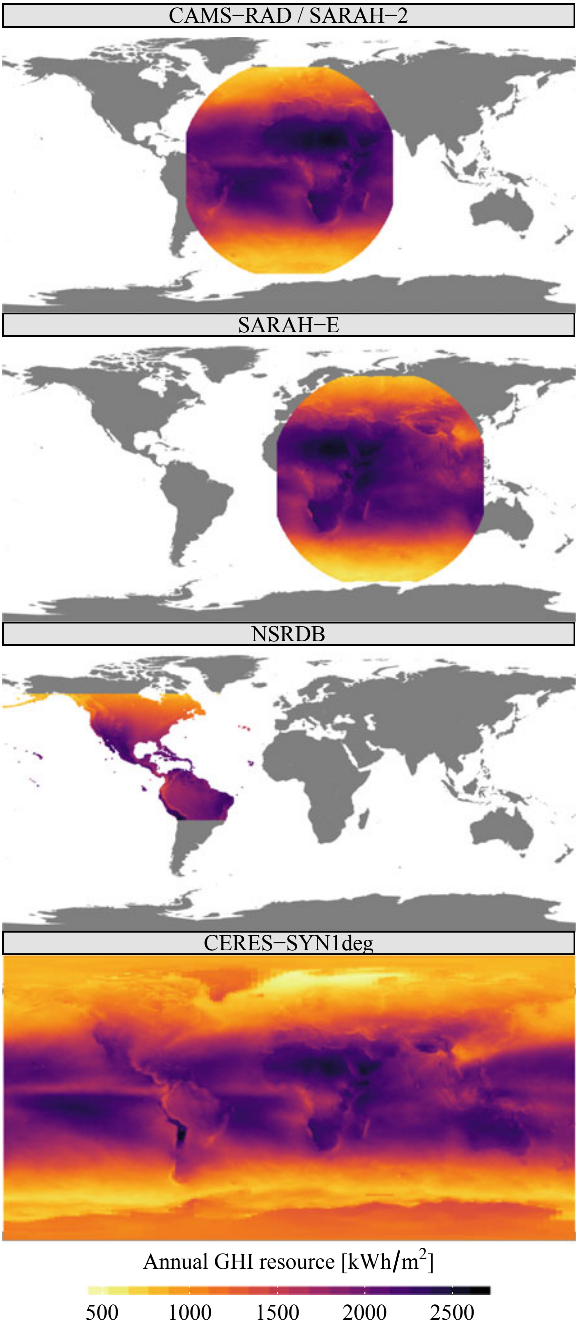
so-called "satellite-to-irradiance" models, these raw images are converted to GHI, BNI, and DHI. One of the earliest satellite-to-irradiance models was proposed in [19], in which a simple yet effective conversion methodology based on pixel-wise cloud index was put forward. Today, the satellite-to-irradiance models have become far more intricate than that used in [19]. In this regard, most of the datasets described below are produced using physically-based models, which take a wide range of atmospheric variables, such as aerosol optical depth, into consideration. Since the spatial-resolution of the satellite-derived irradiance products depends on the resolution of the raw images, these products are time series of lattice process. More specifically, the satellite-derived irradiance is often provided as time series, available on a regular grid—they are thus known as gridded products.

In this subsection, 5 latest freely available gridded products are reviewed, namely, (1) Copernicus Atmosphere Monitoring Service-RADiation service (CAMS-RAD), (2) National Solar Radiation Data Base (NSRDB), (3) SurfAce solar RAdiation data set-Heliosat, Edition 2 (SARAH-2), (4) SurfAce solar RAdiation data set-Heliosat, East (SARAH-E), and (5) Clouds and the Earth's Radiant Energy System (CERES). Their geographical coverage is depicted in Fig. 4.

4.2.1 CAMS-RAD

CAMS-RAD is part of the Copernicus Programme, an Earth observation programme coordinated and managed by the European Commission in partnership with the

Fig. 4 Geographical coverage of the 5 freely available gridded solar radiation products considered in this chapter. CAMS-RAD and SARAH-2 have the same coverage, over the Meridian; SARAH-E is above the Indian Ocean; NSRDB covers most of America (land only); and CERES-SYN1deg has global coverage. The colour bar shows the annual GHI resource, in kWh/m^2, for the year 2015



European Space Agency. It offers estimates on all three horizontal irradiance components, namely, GHI, BNI, and DHI. The main data method used for CAMS-RAD is Heliosat-4, which converts images acquired by the Meteosat Second Generation (MSG) satellites into snapshots of irradiance. As compared to the legacy methods Heliosat-1/-2/-3, Heliosat-4 uses a physical cloud retrieval process and a fast parameterisation of radiative transfer. The details for the CAMS-RAD satellite-to-irradiance modelling can be found in [20, 21]. The spatial coverage of CAMS-RAD is −66° to 66° in both latitude and longitude. Since CAMS-RAD uses raw data with different spatial resolutions, the final irradiance product is spatially interpolated to the point of interest. On the other hand, its temporal coverage is from 2004-02-01 up to 2 days ago, with the temporal resolution ranging from 1 min to 1 month.

All CAMS data can be accessed from the Copernicus portal.[7] However, for CAMS-RAD, the link in the CAMS data catalogue will direct the user to the SoDa website for downloading.[8] The detailed downloading procedure is as follows:

Data downloading procedure: CAMS-RAD

1. Register and login to http://www.soda-pro.com/web-services/radiation/cams-radiation-service
2. Enter the latitude, longitude, and altitude information, and select the time range and resolution for downloading.
3. Click the `Process` button.
4. Right click the `Result file` link, and save the processed files, in NetCDF format.

Besides the web-based downloading approach, CAMS-RAD could also be accessed through a programming means, namely, using the `camsRad` package in R [22]. There is, however, a daily download limit of 75 requests per day.

4.2.2 NSRDB

NSRDB is developed by the National Renewable Energy Laboratory (NREL). The first version of NSRDB was released in 1994, which contained only data at specific locations in the United States, based on ground-based observations made during 1961–1991. Through a few updates over the years, the latest NSRDB product offers half-hourly gridded data from 1998 to 2017, covering most of America (from −25° to −175° in longitude and from −20° to 60° in latitude). A good overview on NSRDB

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[7] https://atmosphere.copernicus.eu/data.

[8] http://www.soda-pro.com/.

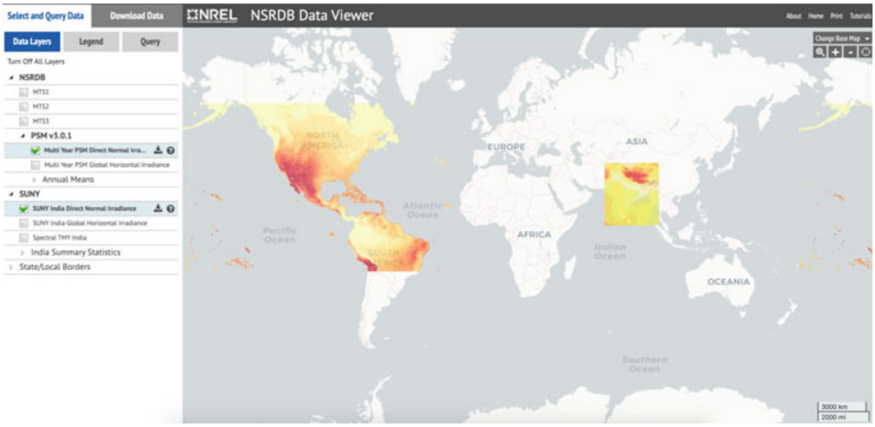

Fig. 5 Screenshot of the NREL NSRDB Viewer for NSRDB data downloading

can be found in [23]. Similar to CAMS-RAD, all three horizontal irradiance components are estimated and made available in NSRDB. The algorithm for satellite-to-irradiance conversion is called the Physical Solar Model (PSM), which leverages data from the NOAA's Geostationary Operational Environmental Satellite (GOES), NASA's Terra and Aqua satellites, among other sources. The reader is referred to [24] for the modelling details.

NSRDB can be downloaded with three approaches. First, the user could download the data, pixel by pixel, using the NSRDB Viewer,[9] which is a web tool offered by NREL. This approach is suitable only if data from a single site or a few sites are of interest. Figure 5 shows a screenshot of the NSRDB Viewer. Second, to download NSRDB over an area, a more systematic way is using the Python application programming interface (API).[10] An R package, `SolarData` [18, 25], is also available for R users to access the NSRDB API. Lastly, if downloading the entire, or a significant portion of, NSRDB is of interest, Globus can be used. Nonetheless, for local solar resource assessment purposes, using the Globus option seems unnecessary.

4.2.3 SARAH-2

SARAH-2 is a product family of the Satellite Application Facility on Climate Monitoring (CM SAF) [26], which is a centre established by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) around the year 2000. SARAH-2 data are modelled using observations from the Meteosat First Generation (MFG) and MSG satellites. In fact, both MFG and MSG are collective names for different satellites, e.g., MFG satellites include Meteosat-2 to -7. Owing to the

[9] https://maps.nrel.gov/nsrdb-viewer/.

[10] https://nsrdb.nrel.gov/data-sets/api-instructions.html.

large number of satellites and instruments used across the history of SARAH-2, it is produced using the Mesoscale Atmospheric Global Irradiance Code Solar (MAGICSOL) method, which is a combination of the well-established Heliosat method [27] with the SPECMAGIC clear-sky model [28], to ensure consistency over the 35-year period, namely, from 1983 to 2017. The geographical extent of SARAH-2 is almost identical to CAMS-RAD. However, it is only available at 30-min intervals. Nonetheless, this half-hourly resolution is sufficient for most resource assessment tasks.

SARAH-2 data is available at CM SAF. The user could access its data through the web user interface. The details are as follows.

Data downloading procedure: SARAH-2

1. Login to CM SAF Web User Interface (WUI) at https://wui.cmsaf.eu/safira/action/viewProduktSearch.
2. Search for `SARAH ed.2.1`, from the `Product search` tab on the left side of WUI.
3. A subset can be selected at the `PRODUCT ADAPTATIONS` section.
4. Define the area of interest by entering the boundaries in terms of latitudes and longitudes.
5. Upon selecting the time range from the next page, the order can be place via the `add to order cart` button.
6. The ordered data will be processed at the server side and sent via email once the preprocessing is completed.

4.2.4 SARAH-E

SARAH-E is similar to SARAH-2—it is another product family of CM SAF. Whereas the satellites used in SARAH-2 are situated over the Meridian, those used to produce SARAH-E are positioned over the Indian Ocean. SARAH-E covers a region from $-10°$ to $130°$ in longitude and $\pm 70°$ in latitude, from 1999 to 2016 [29]. The data production and downloading procedures for SARAH-E are almost identical to that for SARAH-2. However, SARAH-E is only available at an hourly resolution.

4.2.5 CERES-SYN1deg

CERES aims at providing Earth radiation budget data through satellite-based sensing [30]. It is a key component of NASA's Earth Observing System program. CERES provides various data products that can be categorised into 4 levels. The Synoptic Fluxes and Clouds (SYN1deg) is a level-3 product that contains data of spatially and temporally averaged fluxes and clouds. Unlike the other satellite-derived datasets herein discussed, CERES-SYN1deg is available for the entire globe. Its temporal coverage is from 2000-03-01 to 2019-05-31, whereas its spatial resolution is 1 degree in both latitude and longitude. CERES-SYN1deg leverages data from a large collection of satellites, including the previously mentioned GOES and MSG satellites, as well as the Multifunction Transport Satellite (MTSAT), and HIMAWARI-8. The radiation flux modelling sequence for CERES-SYN1deg is complex, see its online documentation[11] and the references therein listed. The downloading procedure for CERES-SYN1deg data is as follows.

Data downloading procedure: CERES-SYN1deg

1. Go to https://ceres.larc.nasa.gov/products.php?product=SYN1deg.
2. Click the `Browse & Subset` button corresponding to Edition4.1.
3. The GHI data is available under "Parameters" → "Adjusted TOA, Surface, and Profile Fluxes" → "Adjusted All-Sky Profile Fluxes" → "Shortwave Flux Down" → "Surface."
4. The other horizontal irradiance components are available under "Adjusted Surface SW Direct and Diffuse Fluxes."
5. Subset the data and select `Get Data`
6. Upon logging in, the system will process the data into NetCDF files that will be sent to the user via email when ready, together with download instructions.

4.3 Commercial Satellite-Derived Solar Data

Besides the freely available satellite-derived datasets, which are all produced by national centres and research institutes, there are also many commercial products in the market. Most notably, Solargis,[12] Solcast,[13] and SolarAnywhere,[14] are the popular ones. Whereas the first two products are available for worldwide locations, the third product is only available in North America, South America, and greater India.

It is generally unclear how the accuracies of commercial products compare to that of the publicly available ones. In most scientific studies, the information on these commercial products is limited to brief descriptions and a few overall accuracies. Moreover, validations of these commercial products are often done at a few chosen

[11] https://ceres.larc.nasa.gov/science_information.php?page=CeresComputeFlux.

[12] https://solargis.com/.

[13] https://solcast.com/.

[14] https://www.solaranywhere.com/.

locations, which might not be universal. Third-party validation works are rare. To that end, when budget allows, it is highly recommended to use all products available at the location of interest. The goal is to reduce data uncertainty by ensemble modelling. This point will be more discussed in Sect. 5.

4.4 Reanalysis Data

Similar to the case of satellite-derived irradiance data, there are quite a number of reanalysis databases that offer hourly irradiance estimations on regional and global scales. Reanalysis products have lower accuracies than the satellite-derived products. Nonetheless, they are still highly useful. While it is not the goal of this chapter to give a complete overview of the history of reanalysis, two latest reanalysis products are introduced, namely, (1) the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis, 5th generation (ERA5), and (2) the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2). The former is produced by ECMWF, whereas the latter is produced by NASA. Both ERA5 and MERRA-2 contain a large collection of weather variables, for all locations in the world, over 4 decades. For solar applications, only a small fraction of those variables are needed.

4.4.1 ERA5

ERA5 has a spatial resolution of $0.25° \times 0.25°$ in latitude and longitude. Its temporal resolution is 1 h, available from 1979 to a few days ago. Before the release of ERA5, ECMWF had several products, such as ERA-40 or ERA-Interim. Although these precursors are no longer being produced, the historical data are still available from the ECMWF data server.[15]

To download ERA5 data, some basic programming knowledge is required. More specifically, the data files need to be retrieved from the Climate Data Store[16] (CDS) using API. The ERA5 solar radiation data belong to the product group called "ERA5 hourly data on single levels from 1979 to present," which can be searched from CDS. Within that product group, the hourly GHI data is named "Surface thermal radiation downwards." An example Python script is given below, which downloads the ERA5 GHI data for the year 2004. For more information on this API, the reader is referred to official instruction.[17]

[15] https://www.ecmwf.int/en/forecasts/datasets/browse-reanalysis-datasets.

[16] https://cds.climate.copernicus.eu.

[17] https://cds.climate.copernicus.eu/api-how-to.

Python script to retrieve ERA5 GHI data

```
#!/usr/bin/env python
import cdsapi
import calendar

c = cdsapi.Client()

def retrieve_era5_reanalysis():
    yearStart = 2004
    yearEnd = 2004
    monthStart = 1
    monthEnd = 1
    for year in list(range(yearStart, yearEnd + 1)):
        for month in list(range(monthStart, monthEnd + 1)):
            numberOfDays = calendar.monthrange(year, month)[1]
            day = list(range(1, numberOfDays + 1))
            target = "era5_ssrd_1h_%04d%02d.nc" % (year, month)
            era5_request(target, day, month, year)

def era5_request(target, day, month, year):
    c.retrieve(
    'reanalysis-era5-single-levels',
    {
        'product_type':'reanalysis',
        'format':'netcdf',
        'variable':'surface_solar_radiation_downwards',
        'year':year,
        'month':month,
        'day':day,
        'time':[
            '00:00','01:00','02:00',
            '03:00','04:00','05:00',
            '06:00','07:00','08:00',
            '09:00','10:00','11:00',
            '12:00','13:00','14:00',
            '15:00','16:00','17:00',
            '18:00','19:00','20:00',
            '21:00','22:00','23:00'
        ],
        'area':[1, -2, -2, 1], # North, West, South, East.
        'grid':[0.25,  0.25], # Latitude, longitude.
        'format':'netcdf' # Supported format: grib and netcdf.
```

```
        },
        target)

if __name__ == '__main__':
    retrieve_era5_reanalysis()
```

4.4.2 MERRA-2

MERRA-2 is the first long-term global reanalysis that assimilates the space-observed aerosol information into the physical processes in the climate system [31]. It was introduced to replace the original MERRA dataset because of the recent advances made in the assimilation system. Its spatial resolution is slightly lower than that of ERA5, i.e., 0.5° × 0.625° in latitude and longitude. The temporal resolution MERRA-2 is 1 h, available from 1980 to 2 months ago.

MERRA-2 is available on NASA's Goddard Earth Sciences Data and Information Services Center (GES DISC).[18] The product group containing GHI data is called "MERRA-2 tavg1_2d_rad_Nx," and the variable corresponds to GHI is called "surface_incoming_shortwave_flux," not to be confused with other variables in the product group. A web tool is provided for data sub-selection and downloading. The detailed downloading instruction will appear after the user clicks on the "Subset / Get Data" tab, see Fig. 6.

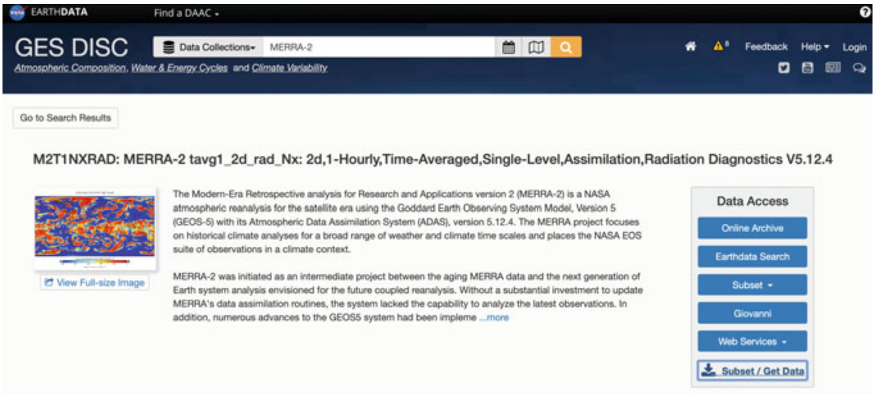

Fig. 6 Screenshot of the GES DISC web tool for MERRA-2 GHI data downloading

[18] https://disc.gsfc.nasa.gov/.

5 Handling Data Uncertainty

The best description of an irradiance estimate must contain an element of uncertainty. Instead of only saying the GHI estimate at location $\boldsymbol{s}$ and time t is x W/m^2, it is clearly more useful if the lower and upper bounds of that estimate (with a certain nominal probability) are given as well. The lower and upper bounds are jointly known as a prediction interval (PI). Suppose there are two PIs, and both are calibrated—the chance for the actual observations to fall within the bounds is high—one would certainly prefer the sharper (narrower) one than the wider one. This is called "minimising sharpness subject to calibration," which is a central concept in probabilistic prediction [32, 33]. In this section, methods to handle data uncertainties are discussed.

At this stage, the notation used in this section is clarified. Firstly, the truth at time t is denoted using x_t, the corresponding point estimate is denoted using $\hat{x}_t$, and a corresponding probabilistic estimate is denoted using $\hat{\xi}_t \sim f_t(\boldsymbol{\theta}_t)$, where f_t is the predictive distribution at time t, and $\boldsymbol{\theta}_t$ parameterises f_t. In solar resource assessment, ground-based measurements are often taken as truth, to gauge the quality and accuracy of the irradiance estimates from a gridded product. In that, $\hat{x}_t$ is simply a data point downloaded from the product website. On the other hand, $\hat{\xi}_t$ describes how uncertain the point estimate $\hat{x}_t$ is. For example, if one assumes a Gaussian f_t, the distribution is parameterised by mean and variance, i.e., $\boldsymbol{\theta}_t = (\mu_t, \sigma_t^2)$, where μ_t denotes the mean of f_t and σ_t^2 is the variance of f_t. Stated differently, $\mathbb{E}(\hat{\xi}_t) = \mu_t$ and $\mathbb{V}(\hat{\xi}_t) = \sigma_t^2$. It should be noted that $\boldsymbol{\theta}_t$, and thus $\hat{\xi}_t$, are always unknown, and need to be estimated from the data.

5.1 Mean Square Error and Site Adaptation

Suppose there is only one gridded product available at location $\boldsymbol{s}$, there is virtually nothing one can do to minimise its uncertainty. However, when a short period of ground-based measurements is available, a class of techniques called "site adaptation" can then be applied.

Considering the mean square error (MSE) of some x_t and $\hat{x}_t$, for $t = 1, 2, \ldots, n$, i.e.,

$$\text{MSE}\big(\hat{X}, X\big) = \frac{1}{n}\sum_{t=1}^{n}\big(\hat{x}_t - x_t\big)^2, \tag{6}$$

one can write it as:

$$\text{MSE}\big(\hat{X}, X\big) = \mathbb{V}\big(\hat{X} - X\big) + \mathbb{E}\big(\hat{X} - X\big). \tag{7}$$

Here, capital letters are used to denote random variables (RVs) that correspond to the small letters, which are particular realisations of the RVs. The first term on the right-hand-side of Eq. (7) is the variance of the prediction error, whereas the second term is the mean bias of the prediction. Equation (7) is known as the variance–bias decomposition of MSE. In order to reduce the MSE, one can either reduce $\mathbb{V}\big(\hat{X} - X\big)$, or reduce $\mathbb{E}\big(\hat{X} - X\big)$. Various existing site-adaptation techniques mostly reduces the latter.

The simplest way to reduce the bias is by fitting a linear least squares regression between X and $\hat{X}$. That is:

$$x_t = a\hat{x}_t + b, \tag{8}$$

where a and b are gradient and intercept, respectively. They need to be estimated from the data. Denoting the estimated regression coefficients by $\hat{a}$ and $\hat{b}$, when a new $\hat{x}_0$ materialises, the corresponding $\tilde{x}_0$ can be calculated through:

$$\tilde{x}_0 = \hat{a}\hat{x}_0 + \hat{b}, \tag{9}$$

where $\tilde{x}_0$ is the bias-corrected version of $\hat{x}_0$. For example, if one year of ground-based measurements and twenty years of gridded estimates are available at location $\boldsymbol{s}$, coefficients a and b can be estimated using the temporally aligned part of the data, and the remaining nineteen years of gridded estimates can be corrected using Eq. (9).

Besides least squares regression, another popular site-adaptation technique is called quantile mapping. Quantile mapping corrects bias in the gridded estimates by mapping quantiles at the same cumulative probability from the estimates data and the measurements. Mathematically, the concept is easier to understand:

$$\tilde{x}_0 = F_x^{-1}\left[F_{\hat{x}}\left(\hat{x}_0\right)\right], \tag{10}$$

where F_x and $F_{\hat{x}}$ are the empirical cumulative distribution functions (ECDFs) obtained from x_t and $\hat{x}_t$, $t = 1, 2, \ldots, n$. A graphical demonstration of quantile mapping is shown in Fig. 7. In this figure, one year (2012) of hourly GHI data, from a tropical site in Brazil, Brasilia (−15.601° S, −47.713° W), from BSRN and NSRDB is used. It shows how a data point, $\hat{x}_0 = 550$ W/m^2, from NSRDB is corrected by quantile mapping, which leads to a corrected value of $\tilde{x}_0 \approx 500$ W/m^2.

Based on the above discussion, it is immediately clear that there are other regression-based and quantile-based site-adaptation techniques. For instance, one can extend the linear regression to a quadratic fit, or include additional predictors and use a multiple regression. One can also extend quantile mapping to quantile delta mapping [34]. Nonetheless, the performance of these variations would not be significantly different from using the simple linear regression.

5.2 *Ignorance Score and Ensemble Model Output Statistics*

Suppose there are m gridded products available at location $\boldsymbol{s}$, as well as a short period of collocated ground-based measurements, a site-adaptation technical called

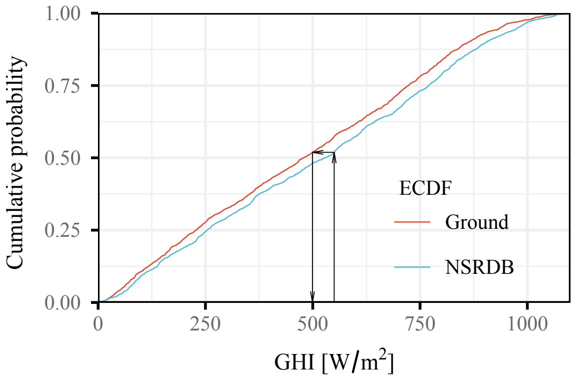

Fig. 7 A demonstration of quantile mapping. The two ECDFs, F_x and $F_{\hat{x}}$, are plotted using one year (2012) of hourly GHI data from Brasilia, Brazil (−15.601° S, −47.713° W). For $\hat{x}_0 = 550$ W/m^2, $F_{\hat{x}}\left(\hat{x}_0\right)$ first brings it to the blue curve, using the same probability (the horizontal shift), $F_x^{-1}\left[F_{\hat{x}}\left(\hat{x}_0\right)\right]$ then brings it down to the corrected value, $\tilde{x}_0$, which is approximately 500 W/m^2

the ensemble model output statistics (EMOS) can then be applied [35]. Denoting these m gridded products by $\hat{X}_1, \ldots, \hat{X}_m$, EMOS uses a multiple linear regression to model their relationship with the ground-based measurement. That is,

$$x_t = b_1\hat{x}_{1,t} + \cdots + b_m\hat{x}_{m,t} + \epsilon_t, \tag{11}$$

where $\hat{x}_{i,t}$ denotes the value of the ith gridded product at time t; $b_1, \ldots, b_m$ are the mixing weights (i.e., regression coefficients); and ϵ_t is an error term. On top of that, due to the different satellite-to-irradiance models used, the m gridded products will not give the exact same estimate. The variation among these m estimates can be described by their sample variance:

$$S_t^2 = \frac{1}{m-1}\left[\sum_{i=1}^{m}\hat{x}_{i,t}^2 - \frac{1}{m}\left(\sum_{i=1}^{m}\hat{x}_{i,t}\right)^2\right]. \tag{12}$$

Since this sample variance might be over- or under-dispersed, it is useful to use a scaling parameter, c. Consequently, one can write:

$$\mathbb{V}(\epsilon_t) = cS_t^2. \tag{13}$$

To that end, Eqs. (11)–(13) jointly describe the probabilistic estimate mentioned at the beginning of this section, namely, $\hat{\xi}_t \sim f_t(\boldsymbol{\theta}_t)$. In this case, f is simply the Gaussian probability density function (PDF), $\mu_t = x_t$, and $\sigma_t^2 = cS_t^2$.

$$\hat{\xi}_t \sim \mathcal{N}\left(b_1\hat{x}_{1,t} + \cdots + b_m\hat{x}_{m,t}, cS_t^2\right). \tag{14}$$

From the statistical model in (14), once the model parameters, $b_1, \ldots, b_m$ and c are estimated, a new set of gridded estimates, $\hat{x}_{1,0}, \ldots, \hat{x}_{m,0}$, can be corrected. More specifically,

$$\mathbb{E}(\hat{\xi}_0) = \hat{b}_1 \hat{x}_{1,0} + \cdots + \hat{b}_m \hat{x}_{m,0}, \tag{15}$$

$$\mathbb{V}(\hat{\xi}_0) = \hat{c} S_0^2, \tag{16}$$

where $\hat{b}_1, \ldots, \hat{b}_m$ and $\hat{c}$ are estimated parameters using the period which temporally aligned ground-based and gridded estimates are available.

The particular method to estimate $b_1, \ldots, b_m$ and c is through optimising a quantity called ignorance score (IGN). IGN for n samples is given by:

$$\text{IGN} = \frac{1}{2n} \sum_{t=1}^{n} \left[\ln(2\pi) + \ln\left(c S_t^2\right) + z_t^2 \right], \tag{17}$$

where

$$z_t = \frac{x_t - \left(b_1 \hat{x}_{1,t} + \cdots + b_m \hat{x}_{m,t}\right)}{\left(c S_i^2\right)^{\frac{1}{2}}} \tag{18}$$

is the standardised EMOS model error at time t. This is analogous to the least squares estimation: instead of minimising the sum of squared errors, EMOS minimises IGN, i.e.,

$$\arg\min_{b_1,\ldots,b_m,c} \frac{1}{2n} \sum_{t=1}^{n} \left\{ \ln(2\pi) + \ln\left(c S_t^2\right) + \frac{\left[x_t - \left(b_1 \hat{x}_{1,t} + \cdots + b_m \hat{x}_{m,t}\right)\right]^2}{c S_i^2} \right\}. \tag{19}$$

The optimisation problem in (19) is not straightforward to solve, and is sensitive to initial values. Nonetheless, most standard optimisation packages, such as the the `Rsolnp` package in R [36], are able to arrive at some local optimum, which is usually sufficient [37].

The clear advantage of EMOS, as compared to the single-product site adaptation, is that $\hat{\xi}_t$ not only describes the site-adapted point estimate, but also provides a quantification of the uncertainty involved in the satellite-based irradiance. In this case, the site-adapted point estimate is given by:

$$\tilde{x}_0 = \mathbb{E}(\hat{\xi}_0) = \hat{b}_1 \hat{x}_{1,0} + \cdots + \hat{b}_m \hat{x}_{m,0}. \tag{20}$$

5.3 *Uncertainty Mitigation Without Ground-Based Data*

The methods described in Sects. 5.1 and 5.2 require a short period of ground-based measurement to estimate the parameters during site adaptation. That said, such ground-based measurements are not everywhere available, for reasons given in Sect. 4.1. Hence, it is of interest to consider uncertainty mitigation without ground-based data.

Without ground-based measurements, the performance of various gridded products is generally unknown. Moreover, due to spatial inhomogeneity in most gridded products, a high-performing product at one location might have poor accuracies at other locations. On this point, the only logical action is to average the irradiance estimates from various gridded products, i.e.,

$$\tilde{x}_0 = \sum_{i=1}^{m} \hat{x}_{i,0}. \tag{21}$$

If $\hat{x}_{i,0}$ are biased towards different directions, then the arithmetic mean will often have a smaller MSE than the MSEs of the individual products [38].

Another notable technique is to use a trimmed average. In that, the highest and lowest members from the pool of m estimates are first removed before averaging. The motivation of trimmed averaging is analogous to the Olympic diving scoring system, where the top scores and the bottom scores are discarded, to minimise the bias in individual judgment [39].

5.4 Site Adaptation in Brasilia: A Case Study

A case study on the above-mentioned uncertainty mitigation strategies is presented next. A topical site, namely, Brasilia, Brazil (−15.601° S, −47.713° W), is used. The hourly ground-based data comes from the corresponding BSRN station, spanning from 2006 to 2015. A total of 6 gridded products are available at Brasilia, namely, CAMS-RAD, NSRDB, SARAH-2, CERES-SYN1deg, ERA5, and MERRA-2, among which the first 4 are satellite-derived datasets, whereas the last 2 are reanalyses. The data points after quality control are presented in Fig. 8. The total number of temporally aligned hourly data points over 2006–2015 is 19,974.

The data is split into a training set (2006–2007) and a test set (2008–2015). The training set contains 5096 hourly data points, whereas the test set contains 14,878 data points. This splitting mimics the fact that during actual site adaptation, solar engineers often have to work with only a short period of ground-based data. Subsequently, the two site-adaptation techniques introduced in Sect. 5.1, namely, linear regression and quantile mapping, are applied to each gridded product, separately. Two error metrics are used to compare the results: (1) RMSE and (2) mean bias error (MBE), as shown in Table 3. The errors are in percentage, which is calculated by normalising the RMSE and MBE by the mean irradiance during the test period.

It is clear from Table 3 that the accuracies of the 6 gridded products are quite different. In that, CERES-SYN1deg has the smallest RMSE of 21.83%, whereas MERRA-2 has the highest RMSE of 33.80%. Nonetheless, one should note that such performance ranking does not generalise—at other locations, the rankings may

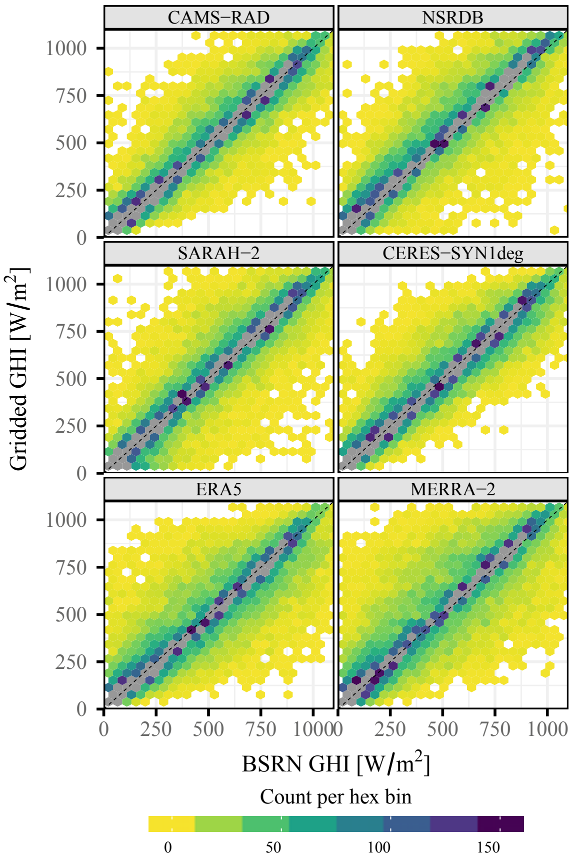

Fig. 8 Scatter plots of 6 gridded GHI products (CAMS-RAD, NSRDB, SARAH-2, CERES-SYN1deg, ERA5, and MERRA-2) versus the BSRN measurements at the Brasilia station, Brazil (−15.601° S, −47.713° W), over the years 2006–2015. Hexagon binning algorithm is used for visualisation, where number of data points per hexbin is indicated by the colour bar. The dashed line in each subplot shows the identity line

differ. Site adaptation using linear regression indicates an overall satisfactory result, where RMSE and MBE have decreased in almost every case, except for the MBE of ERA5. On the other hand, site adaptation using quantile mapping is controversial. In some cases, such as NSRDB or MERRA-2, quantile mapping is able to reduce both the RMSE and MBE. In other cases, such as CAMS-RAD or ERA5, it exaggerates the errors.

Next, the EMOS technique introduced in Sect. 5.2 is applied to the same training and test dataset. After fitting, the EMOS parameters, $b_1, \ldots, b_6$, are estimated to be 0.351, 0.123, 0.200, 0.292, 0.034, 0.000, respectively, for CAMS-RAD, NSRDB, SARAH-2, CERES, ERA5, and MERRA-2. From these mixing weights, one can conclude that the more accurate satellite-derived estimates have contributed more towards the final ensemble estimate, but the contribution from the reanalyses is limited. After performance evaluation, it is found that the RMSE and MBE for EMOS-corrected irradiance are 19.95% and 2.89%, respectively. In terms of RMSE, EMOS is more advantageous than linear regression and quantile mapping, suggesting using ensemble is better than using any single product.

Table 3 Root-mean-square errors (RMSEs) and mean bias errors (MBEs), in percentage, of 6 hourly gridded products at the Brasilia station, Brazil (−15.601° S, −47.713° W), over the years 2008–2015. Two site-adaptation techniques, namely, linear regression and quantile mapping (see Sect. 5.1), are used to correct the irradiance estimates from various products.

Technique	CAMS-RAD	NSRDB	SARAH-2	CERES	ERA5	MERRA-2
RMSE [%]						
Raw product	21.96	26.01	25.70	21.83	30.32	33.80
Linear regression	21.71	24.17	24.35	21.72	30.04	31.76
Quantile mapping	22.44	24.97	25.46	22.60	31.61	33.59
MBE [%]						
Raw product	2.33	7.26	2.56	2.22	0.74	7.42
Linear regression	2.32	1.97	1.24	1.94	1.82	0.12
Quantile mapping	2.44	2.25	1.55	2.16	2.05	0.22

Similarly, the simple averaging and trimming averaging techniques described in Sect. 5.3 are tested. Their RMSEs are 21.16 and 21.10%, with trimming averaging being slightly more accurate. It is also worth noting that both averaging techniques yield smaller RMSEs than those reported in Table 3. Hence, even if ground-based data is unavailable, one can still get a decent improvement from individual products by using ensemble. In that, the results support the claim—ensemble modelling should be used whenever possible in solar resource assessment.

6 Conclusion

In order to achieve continuous growth, the entire solar industry must be self sustainable, without being overly reliant on governmental stimulus packages, such as FIT programs, kick-start fundings, or tax incentives. This entails collaborative efforts from various stakeholders, such as the financial institutions, regulatory bodies, legal firms, or technical experts. It is essential to understand that realising a successful solar project requires proper risk identification, management, and mitigation, in both financial and technical aspects. While appropriate financing structure and contractual protections are the mitigants required for managing the financial risks, resource assessment with ensemble modelling is paramount for technical risk management.

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Understanding Social Impact and How to Measure It

Swee-Sum Lam and Xiang Ru Amy Tan

Abstract This chapter addresses the knowledge gap between bringing sustainable energy solutions to people and finding out whether the social changes observed (if any) among those people can be directly attributed to the solutions that were introduced. The importance of adequate impact evaluation cannot be overstated. For funders and implementers of development programmes, effective evaluation of both intended and unintended outcomes of an intervention is critical for managerial decision making, cost adjustments, business model pivoting and impact scaling. Similarly, technology developers would be eager to know if the solutions they bring to end users really create the impact intended. We highlight the need to understand social impact evaluation as more than a mid- or post-intervention assessment exercise; instead, impact evaluation should be incorporated alongside the initial outcomes planning and monitoring of an intervention. This ensures the robustness and validity of outcomes and impact evaluation later. This chapter will explain the key concepts of impact evaluation, and then discuss how evaluation can be done by providing overviews to commonly used evaluation methods.

Keywords Evaluation methods and designs · Impact evaluation · Impact measurement · Social impact · Social performance management · Theory of change

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1 Introduction: Show Me the Impact

Given that social impact assessment is a vast field of study in itself, it is not possible to cover all aspects of it in one chapter. Thus, we will focus on how social research methods can be applied to evaluating outcomes and impacts. We will begin by providing a basic understanding of what social impact means, and what an evaluation entails. Broad guidelines and key principles in terms of what should be considered, the methods that can be used and information to facilitate the practice of social impact evaluation will be discussed.

This chapter will only deal with the assessment of social impact at the project or programme level. To illustrate how outcome and impact evaluation can be done, we will use a project that engineered the electrification of a village in the remote tropics of Indonesia as our example case. The initiative was called Misi Kami Peduli (MKP), or Mission: We Care in English, in collaboration with an Indonesian solar energy company Alva Energi, and an Indonesian NGO Project Hope Sumba. MKP, consisting of students from the National University of Singapore (NUS), with the help of Alva Energi, designed and installed a solar photovoltaic (PV) and nanogrid system to supply electricity for lighting and phone charging in a remote village. In addition, the project also built toilets, sanitation facilities, a water filtration system, and a community hall that can be used for studying and other activities.

The project took place in May 2018 in Kampung Tanakandumbuka, Homba Karipit Village, Sumba Island in East Indonesia. Its broader aim is to provide basic infrastructures and education, as well as to provide electricity through renewable energy and technology. In so doing, the project hopes to improve the living conditions of underserved communities in Indonesia and empower them (see appendix 1 for project brief). Using this case, we will demonstrate how a theory of change can be constructed, and how an evaluation method can be developed, and indicators derived for outcomes and impact measurement. It should be noted that our conceptualisation of an evaluation design for MKP is a post-project exercise, primarily for academic purposes. We came to know of MKP only after the project activities had been completed.

2 What Is Social Impact Measurement?

Despite its importance, there is not a singular definition of "social impact" used by scholars. While development studies are conventionally most interested in impact evaluation, in the last two decades, social impact measurement has also received increased attention from other disciplines. The rise in hybrid organisations or what is generally known as the third sector has largely contributed to this trend [1–4]. Hybrid organisations are driven by a social mission or goal and are profit-making at the same time.

Related disciplines include business and management [5, 6], social accounting [2, 4, 7], social finance [8, 9], organisational development [1], social entrepreneurship [10, 11], evaluation studies [12–14], voluntary and non-profit [15–17], economics and econometrics [18].

Various jargons and frameworks are used by some of these disciplines to examine impact assessment as a subject matter. Nomenclatures can include: social performance management, performance measurement, social impact accounting, social impact measurement, impact evaluation and programme evaluation [19–21]. Different disciplines tend to use their own impact assessment terms and methodologies vis-à-vis their respective focuses. As a result, there is a lack of consilience in terms of what exactly is to be measured and the appropriate methods for measurement.

Scholars themselves agree that the increasingly diverse ways to define "social impact" are confusing and counter-productive [1, 22, 23]. In addition, having reviewed current impact reporting practices by impact investors in Asia, we have found that practitioners and funders frequently use output and operational metrics (not outcomes) as indicators of "impact" [24].

In light of these issues, it is important for us to clearly state our position. For us, *social impact* refers to "the portion of the total outcome that happened as a result of the activity of the venture, above and beyond what would have happened anyway" [25]. Borrowing Clark et al. [25]'s "impact value chain" below, we can clearly see that outputs are distinct from outcomes and impacts.

We favour Clark et al. [25]'s definition because it takes into consideration the counterfactual, meaning that it controls for social changes that would have taken place anyway, even if the intervention or project had never happened. Valid and robust measurements of social impact should aim to infer causality between the social changes observed and the intervention introduced. In so doing, changes in social behaviour and/or social attitudes can then be attributed to the project (and not any other reasons). Typically, causality can be established by way of examining the counterfactual using adequate comparison groups. These will be discussed in later sections.

In short, impact evaluations measure a project or programme's effectiveness typically by comparing outcomes of those (individuals, households or communities) who received the project's benefits against those who did not [27].

2.1 Understanding Inputs, Outputs, Outcomes and Impact

In reference to the impact value chain (see Fig. 9.1), *input* refers to all the resources—monetary, human, and otherwise—that are invested in the project or programme. *Activities* refer to what the project plans to carry out. In the case of MKP, some of the main activities carried out as part of the project are the installation of facilities and systems (such as the solar PV and nanogrid systems to provide electricity/light and water filtration), building of toilets and a community hall, knowledge sharing on good hygiene practices and financial literacy, etc.

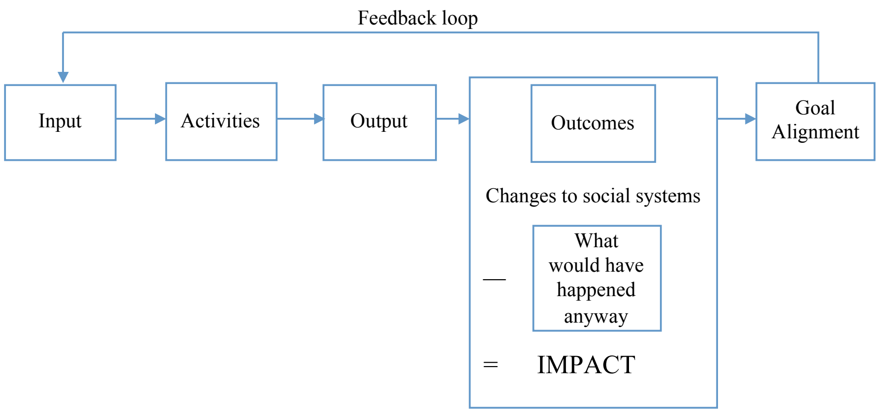


Fig. 9.1 Impact value chain—adapted from Clark, Rosenzweig [25], Maas and Liket [26]

Output refers to quantifiable end products or services that have been materialised as a result of the activities. For MKP, the outputs can be the number of toilets built, the number of water filters installed, the number of solar panels installed, the number of households with lighting points installed, or the number of knowledge and information sharing sessions held, etc.

Outcome refers to the desired social state set out for the target group, and outcomes would encompass changes in social behaviour and attitudes that can be measured by certain indicators. For example, if villagers start to practise better sanitation and hygiene, or if they begin to drink safe potable water from the filtration system installed by MKP (changed social behaviours), then these would constitute some of the outcomes of MKP's intervention.

Supposing values are assigned to measure each outcome indicator based on a standardised scale or index, then the results of all the outcome indicators of those who participated in a given project or programme can then be aggregated. The same outcome indicators have to be used on a control group (i.e. people who did not participate or did not receive the project's benefits) to obtain information or data on what would have happened anyway, i.e. if the project never took place. Likewise, the results of all the outcome indicators for the control group in the given project can then be aggregated. The difference between the two results can be inferred as the *impact* of the project.

Supposing values are not assigned on a standardised scale or index, then the aggregation of all outcome results will not be possible (which is usually the case). Then, comparisons between the participant group and the control group can be done on a per outcome indicator basis.

Finally, *goal alignment* and *feedback loop* complete the chain because the outcomes and impacts of a project need to cross-checked against the project's goal(s)—which is precisely the purpose of an evaluation. Unlike "research" in the general sense, "evaluation" is a type of study that is specific to a certain project or programme [28]. Because in any given programme, it is assumed that there is an inherent goal or purpose it should achieve. Evaluations assess the effectiveness of the activities and outputs in generating the desired outcomes and impacts. If the activities and outputs are not achieving the desired outcomes, then adjustments will need to be made to inform and/or refine subsequent inputs and activities.

In the next section, we discuss how to identify the end-goal(s) of a project or programme, and how to conceptualise the various pre-conditions that are needed to reach the goals. These will have to be determined at the start of the project, to set directions for monitoring of progress and evaluation of outcomes and impacts.

3 Theory of Change: Beginning with the End-Goal in Mind

A theory of change is a visual depiction of how an intervention is supposed to deliver the desired results. It is important to construct it at the beginning of a project or programme so that all stakeholders involved—including funders, project managers, field implementers, and partners on the ground, etc.—can have a common vision and understanding of what the intervention has set out to achieve. More importantly, a theory of change maps out the causal logic of how and why a particular project or programme will reach its intended outcomes. It is key to any impact evaluation, given the causality focus of the research. It also helps to specify and narrow down the relevant research questions [29].

It is crucial to engage the project's stakeholders to construct a theory of change so that the pre-conditions and assumptions make sense in the given context, and that can help to improve the entire project design. Likewise, needs assessment and formative research to understand the context and constraints of the field is absolutely crucial. This is particularly important for interventions that seek to influence or alter behaviour [29].

For discussion purposes, we have constructed a theory of change for MKP (see Fig. 9.2). Theories of change typically show the ultimate or long-term goals of the project, the intermediate outcomes that must happen before the ultimate goals can be achieved, the assumptions that are logically necessary for the outcomes to occur, and the different activities of the project or programme. It is a systematic and sequential exploring of all the pre-conditions that are necessary for change to take place, in the pathway towards the ultimate goals.

In the case of MKP, the ultimate goal (as inferred from the project brief), is to increase the quality of life of the villagers in Kampung Tanakandumbuka. In order for the villagers' quality of life to increase, they must have better physical health, improved economic and living conditions. These are, of course, only with relevance to what the project activities are offering. In order for villagers to have improved physical health, they need to consume safe potable water, and they will have to practise better sanitation and hygiene so they will not get sick as often.

The villagers also tend to use kerosene lamps for lighting because there was no electricity in the village prior to the project's intervention; as a result, kerosene lamps were frequently used as a light source at night. Given that kerosene lamps

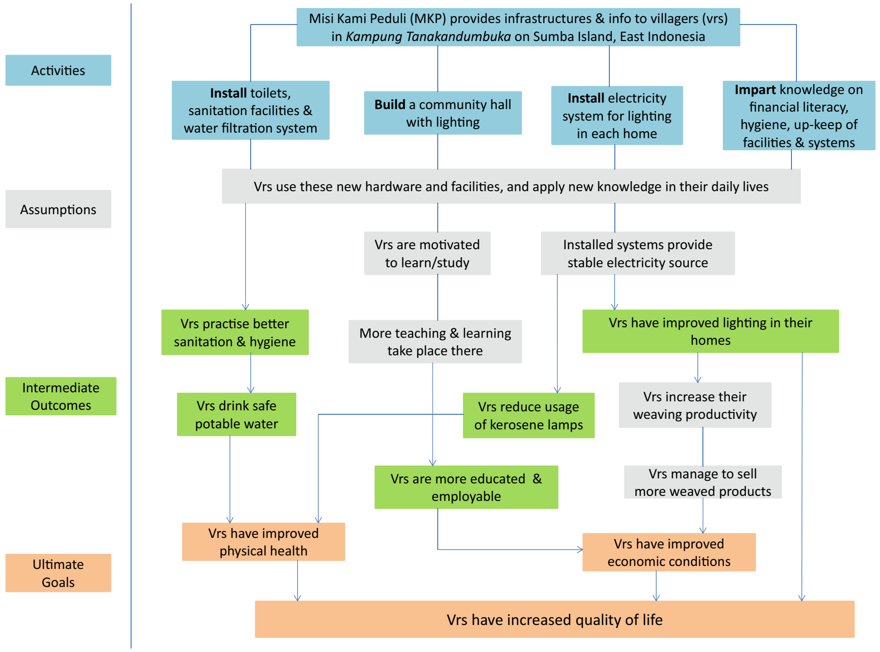


Fig. 9.2 Theory of change for Misi Kami Peduli (MKP), or Mission: We Care

are health and fire hazards, we can logically deduce that in order for the villagers to have improved physical health and have a better quality of life, they must reduce their usage of kerosene lamps. Further, in order for villagers to reduce their usage of kerosene lamps, there must be a stable and sustainable source of light/electricity that they would use as the alternative to kerosene lamps. Two conditions must be fulfilled here: the villagers must have access to this alternative light source, and they must consume it in lieu of kerosene lamps.

Similarly, in order for villagers to have improved economic conditions, a few conditions have to be fulfilled. We have learned that some villagers weave in their homes. Assuming that these villagers have improved lighting in their homes after the intervention, and as a result, they can weave more efficiently, their productivity would increase. But in order for them to have improved economic conditions (i.e. receive higher income), we have to set a pre-condition that these villagers must manage to sell more of their products to generate the higher income.

We have only set one assumption here, but there are definitely more assumptions that may have to be added, depending on the context. For instance, another assumption could be that the villagers must not be in debt, otherwise, even with higher income, their economic condition may not improve. So developing a theory of change is a dynamic exploratory process that depends greatly on one's knowledge of the intended beneficiaries for the theory to be as accurate and realistic as possible. With the outcomes and goals identified, we can then think about how to select outcome and impact indicators.

4 Choosing the Appropriate Indicators and Metrics

SMART is the acronym that is very commonly used guide that helps us to decide which indicators to use to measure outcomes [29].

- Specific: to measure the information required as closely as possible
- Measurable: to ensure that the information can be readily obtained
- Attributable: to ensure that each measure is linked to the project's efforts
- Realistic: to ensure that the data can be obtained in a timely fashion, with reasonable frequency, and at reasonable cost
- Targeted: to the objective population.

Returning to the example of MKP, assuming that a water filtration system has been successfully installed in the village and all the pre-conditions are fulfilled. That is to say, the villagers have access to the water filtration, and they use the system in their daily living. What would be a SMART indicator to measure the intended outcome (i.e. that the villagers drink safe potable water)? One could measure the quality of the water that the villagers drink to check for its potability.

Similarly, what would be an appropriate indicator to measure if villagers have improved physical health? The number of times one falls sick could be an indicator of good or poor health. This is a potentially SMART indicator if some amount of data is available or can be obtained regarding the number of times villagers had fallen sick before and/or after the intervention occurred. There is no right or wrong way to select outcome indicators; because there can always be more than one indicators. What would be more important is that the indicators chosen are relevant to the outcomes being evaluated.

5 Evaluation Methodologies

Once all the outcome indicators are chosen, the researcher conducting the evaluation must decide which evaluation method to use that is fitting for the nature of the project, and decide what would be the unit of analysis. The unit of analysis could be individuals, households, villages or communities. There are many evaluation methods at one's disposal (see Table 9.1), but it would be important to use one that is feasible and appropriate for the evaluation and the population that is being evaluated. In general, evaluation methods can be classified into three broad categories—experimental, quasi-experimental and non-experimental.

Experimental and quasi-experimental methods all have a comparison group, but the strength of the control can vary. The most ideal method, or what is commonly

Table 9.1 Overview of evaluation methodologies—adapted from J-PAL [27]

	Methodology	Description	Comparison group	Required assumptions	Required data
Quasi-experimental methods	Pre-post	Measure how programme participants improved (or changed) over time	Programme participants themselves—before programme	The programme was the only factor influencing any changes in the measured outcome over time	Before and after data for programme participants
	Single difference	Measure the difference between programme participants and non-participants after the programme is completed	Individuals who did not participate in the programme (for any reason), but for whom data were collected after the programme	Non-participants are identical to participants except for programme participation and were equally likely to enter programme before it started	After data for programme participants and non-participants
	Double difference	Measure improvement (change) over time of programme participants relative to the improvement (change) of non-participants	Individuals who did not participate in the programme (for any reason), but for whom data were collected both before and after the programme	If the programme did not exist, the two groups would have had identical trajectories over this period	Before and after data for both participants and non-participants
	Multivariate regression	Individuals who received treatment are compared with those who did not, and other factors that might explain differences in the outcomes are "controlled" for	Individuals who did not participate in the programme (for any reason), but for whom data were collected both before and after the programme. In this case, data is not comprised of just indicators of outcomes, but other "explanatory" variables as well	The factors that were excluded (because they are unobservable and/or have not been measured) do not bias results because they are either uncorrelated with the outcome or do not differ between participants and non-participants	Outcomes as well as "control variables" for both participants and non-participants

(continued)

Table 9.1 (continued)

	Methodology	Description	Comparison group	Required assumptions	Required data
	Statistical matching	Individuals in control groups are compared to similar individuals in participant group	Exact matching: for each participant, at least one non-participant who is identical on selected characteristics Propensity score matching: non-participants who have a mix of characteristics which predict that they would be as likely to participate as participants	The factors that were excluded (because they are unobservable and/or have not been measured) do not bias results because they are either uncorrelated with the outcome or do not differ between participants and non-participants	Outcomes as well as "variables for matching" for both participants and non-participants
	Regression discontinuity	Individuals are ranked based on specific, measurable criteria. There is some cut-off that determines whether an individual is eligible to participate. Participants are then compared to non-participants and the eligibility criterion is controlled for	Individuals who are close to the cut-off, but fall on the "wrong" side of that cut-off, and there do not get the programme	After controlling for the criteria (and other measures of choice), the remaining differences between individuals directly below and directly above the cut-off score are not statistically significant and will not bias the results. A necessary but sufficient requirement for this to hold is that the cut-off is strictly adhered to	Outcomes as well as measure on criteria (and any other controls)

(continued)

Table 9.1 (continued)

	Methodology	Description	Comparison group	Required assumptions	Required data
	Instrumental variables	These are the variables that influence participation in an almost random manner. They may be incidental factors (e.g. a political uprising that led to an isolated case of policy change) but they can only qualify as an instrumental variable of interest to one's evaluation if (1) it is uncorrelated with the outcome (2) it is correlated with project participation (and participation affects the outcome)	Individuals who, because of this almost random factor, are predicted not to participate and (possibly as a result) did not participate	If it were not for the instrumental variable's ability to predict participation, this "instrument" would otherwise have no effect on or be uncorrelated with the outcome	Outcomes, the "instrument", and other control variables
Experimental method	Randomised evaluation	Experimental method for measuring a causal relationship between two variables	People are randomly assigned to be in the participant group or control group	Randomisation "worked". That is, the two groups are statistically identical (on observed and unobserved factors)	Outcomes data for control and experimental groups. Control variables can help absorb variance and improve "power"

known as the “gold standard” for evaluation, is to conduct a randomised evaluation. This means that we randomly assign our unit of analysis to receive the treatment or to be the control. Given that a unit of analysis can be individuals or a household or a village, randomly assigning them would mean that if we are evaluating at the individual level, then with the roll of a die or by tossing a coin, we assign people to either be a participant or to become a non-participant. If we are using a coin, it could be the heads are participants and the tails are non-participants.

The benefit of random assignment is that it eliminates selection biases, and therefore the sample group that we create, be it a participant group or a control group, are fully representative of the population we wish to make conclusions on. But realistically, randomised controlled trials are not commonly conducted due to ethical, operational and/or funding concerns.

For quasi-experimental methods, assignment to comparison groups are not at random (therefore, there will be selective biases) so these methods would always aim to create a group as identical as possible to the group that receives the treatment, to make the comparison more valid. Non-experimental methods do not create any form of comparison groups at all.

In the case of MKP, we are looking at a post-intervention evaluation. Given that the number of households in the village is small (a total of 19 households), it is feasible to collect data from all 19. However, if no baseline surveys were done on the 19 households prior to the project, and it would mean that we do not have before-project data to make comparisons with. If the evaluators of this project decide that a comparison group is necessary (to ensure robustness and validity of evaluation), then the single difference method can be used to evaluate the project. In the same vein, for studies, where it may be difficult to set up a comparison group, baseline surveys should at least be done before the intervention is implemented so that there can be before-project data to compare with after-project data.

6 Collection of Data

After an evaluation method is selected, the evaluators can proceed to collect data vis-à-vis the outcome indicators that were previously established. For MKP, some of the outcome indicators whose data we would need to collect are shown in Table 9.2.

It is very unlikely that data of this nature can be sourced from a government or community level government database. In fact, it is not likely that data of such nature would be kept by a central body. Therefore, evaluators will have to go into the field to collect the data from the villagers themselves. In such cases, one may have to travel to the site or partner with a local agency to collect the data. A questionnaire will have to be compiled, to ask each household in the village, for instance, what is the frequency of their usage of the toilets in the last one week. Questions relevant to the collecting of information that would be relevant to all indicators will have to be asked, and the responses recorded for subsequent analysis and comparison.

Table 9.2 Examples of indicators that need to be measured to verify the intended outcomes for the case of MKP project

Indicators	Intended outcomes
Frequency of villagers using the toilets installed by project	Villagers practise better hygiene
Quality of water that villagers consume	Villagers drink safe potable water
Frequency of villagers falling sick	Villagers have improved physical health
Income of villagers	Villagers have improved economic conditions
Frequency of villagers using kerosene lamps	Villagers reduce the use of kerosene lamps

In addition to collecting quantitative data, it would also be ideal to supplement with some amount of qualitative data so that nuances that occurs in the field can be detected.

7 Conclusion

Many charitable projects, social enterprises and initiatives have noble aims to help uplift less privileged communities. Many of them claim to have positive impacts on the communities that they serve even when no impact evaluation takes place. This can be misleading, especially when the projects do not produce the intended impact (or even yield unintended impact instead). As such, this chapter has provided a basic understanding of social impact and how to conduct impact evaluation. Fundamental concepts of social impact evaluation, including methods to identify, measure and evaluate the social impact of a project have been outlined. While there are usually research ethnics concerns, time and budget constraints that may affect how an evaluation is designed and conducted, the basics of social impact evaluation introduced here are important knowledge that would enable project developers and practitioners to better verify whether their projects are producing the desired outcomes.

Appendix I - The Project Hope of Sumba

The following is the project report received by the authors of this chapter after the completion of the project. This project report serves as a rural electrification case study in the chapter. The formatting of the report has been modified to suit the format of this book.

THE PROJECT HOPE of SUMBA

Kampung Tanakandumbuka, Homba Karipit village

SUMBA

May 2018

Introduction

The disparity in socio-economic conditions between the West and East Indonesia has been around for a long time. While residents of Jakarta may enjoy the luxury of television and Internet at any time they wish, millions of people in East Nusa Tenggara still do not have any access to electricity. Our vision to empower communities in Indonesia through renewable energy and technology has, therefore, made us set our sight on to electrify communities in Eastern Indonesia—as a mean to accelerate their economic development—such as the one in this project in Sumba Island.

According to report by Indonesian Ministry of Energy and Mineral Resources, 94.91% of Indonesians have access to electricity at the end of 2017. This figure falls to a mere 60.74% for both East Nusa Tenggara and Papua provinces. Even then, many suggested that this number is inflated and the real number of people having access to electricity is even lower.

In Sumba Island, there are about 120,000 households. This means that approximately 50,000 households are not electrified yet, with a great number of them concentrated in Southwest Sumba. There, Kampung Tanakandumbuka, part of Homba Karipit village and home for roughly 200 residents, is located.

The *kampung* (a small village) suffers from inadequate infrastructure. While water piping system has already been established, the quality of water falls short of the acceptable drinking standard. Nevertheless, the villagers often drink from the pipe directly due to the lack of capital to boil the water to reach safe drinking standard. Furthermore, not all houses in the kampung have access to proper sanitation. The distant toilet and lack of lighting at night dissuade the villagers to use the toilet properly. Hence, they often choose to defecate in the bushes near their houses.

The difficult economic situation also results in high mortality rate. With one household having to feed around ten people, babies and mothers are in jeopardy as they do not get the right amount of nutrition. As a result, many babies who survive also suffer from disabilities.

Without any light source after the sun sets, most children in the kampung had to travel approximately an hour on foot to reach a local religious centre to study in the evening. For the slightly wealthier families, they rely on kerosene lamps for lighting after dark, which are extremely detrimental for the health, and do not provide nearly enough amount of lighting.

Realising the dire conditions, we are working closely with Indonesian students in National University of Singapore (NUS) under the Mission: We Care focusing on education, health and technology to empower the residents of Kampung Tanakandumbuka, in particular, we, Alva Energi, are responsible for the electrification aspect of the project, where we designed the solar PV and electrical distribution system (nanogrid), procure the components and construct the system.

The project was also carried out in partnership with the local religious leader and *Yayasan Harapan Sumba* (YHS), or Project Hope Sumba, a non-governmental organisation based on Southwest Sumba, who communicated with the villagers, made the local arrangements, and will help with the maintenance of infrastructures built.

At the end of the project, three main infrastructures were built. Firstly, a *Balai*, or community hall, serves as a multi-purpose hall and a learning hub. Secondly, toilets and sanitation facilities, together with the water filtration system, enable the villagers to have a better hygiene. Last but not least, the solar PV system provides the residents with lights and access to electricity, enabling activities in the evening and further economic development. Moreover, not only the building of infrastructures, but this project also imparted knowledge regarding financial literacy, nutrition and hygiene.

PV System Design

There are two main systems constructed to electrify the *kampung*, namely the solar PV system which produces electricity from the sun, and the nanogrid which distributes the electricity to the houses to be consumed by the residents.

The solar PV system is composed of nine solar panels—which convert sunlight into electricity—with a total installed capacity of 1.2 kWp. The solar panels are connected to four batteries (12 V, 150 Ah each) via a charge controller, which controls the charging and discharging of the batteries, and also ensures that the panels operate at maximum power point. The batteries make sure that the energy generated during the day can also be used at night. The batteries are then connected to an inverter to convert DC voltage into AC voltage, which is required for the electrical loads to operate (light bulbs and phone chargers). Although the charge controller and inverter include safety mechanisms, to enhance the overall reliability of the system, breakers have been installed at the output of the solar panels, batteries and inverter. A diagram of the design is presented in Fig. 9.3.

A nanogrid was also built to distribute energy generation to all the loads located at the different houses, toilets and *Balai* (community hall). Figure 9.4 shows a schematic of the installed nanogrid.

Implementation

The villagers were definitely an integral part of the project. Despite having no background in electrical installation, most of the villagers enthusiastically helped with the whole solar PV system and nanogrid installation process, from fixing the solar panels in place, making bamboo poles, pulling the cables through each house and installing the light bulbs (Fig. 9.5).

In total, the installation and commissioning process, including the preparations of an electrical box and two light bulbs for each house, took four full days. The works were mainly done by our engineering team, with various help from the villagers

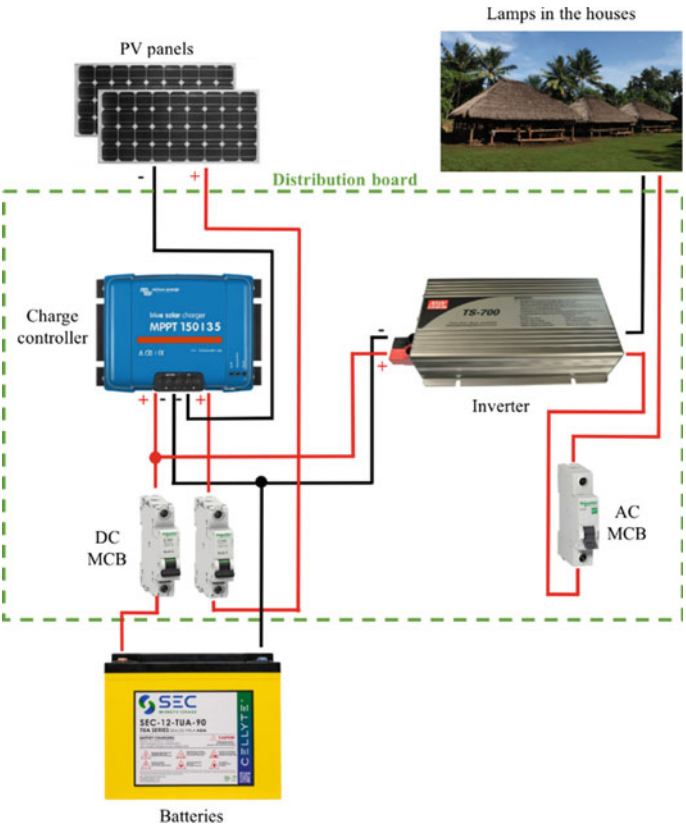


Fig. 9.3 PV system design

and other members of YHS and the MKP project. To make sure that the system and grid installed are sustainable, we took the time to explain the workings of the system to the different stakeholders, namely the person in charge of the village, YHS representative, two village representatives and a local electrician. Each of them was given a manual on how to operate and maintain the system, what to do in case of problems and emergencies, as well as whom to contact in those cases. The solar PV system was inaugurated by the *Bupati* (Regent) of Southwest Sumba.

Cleaning up and the checking of inventory handed over to the village were done on the final day. The inventory includes basic equipment and consumables that will allow the villagers to maintain the system and quickly replace faulty cables and bulbs (Fig. 9.6).

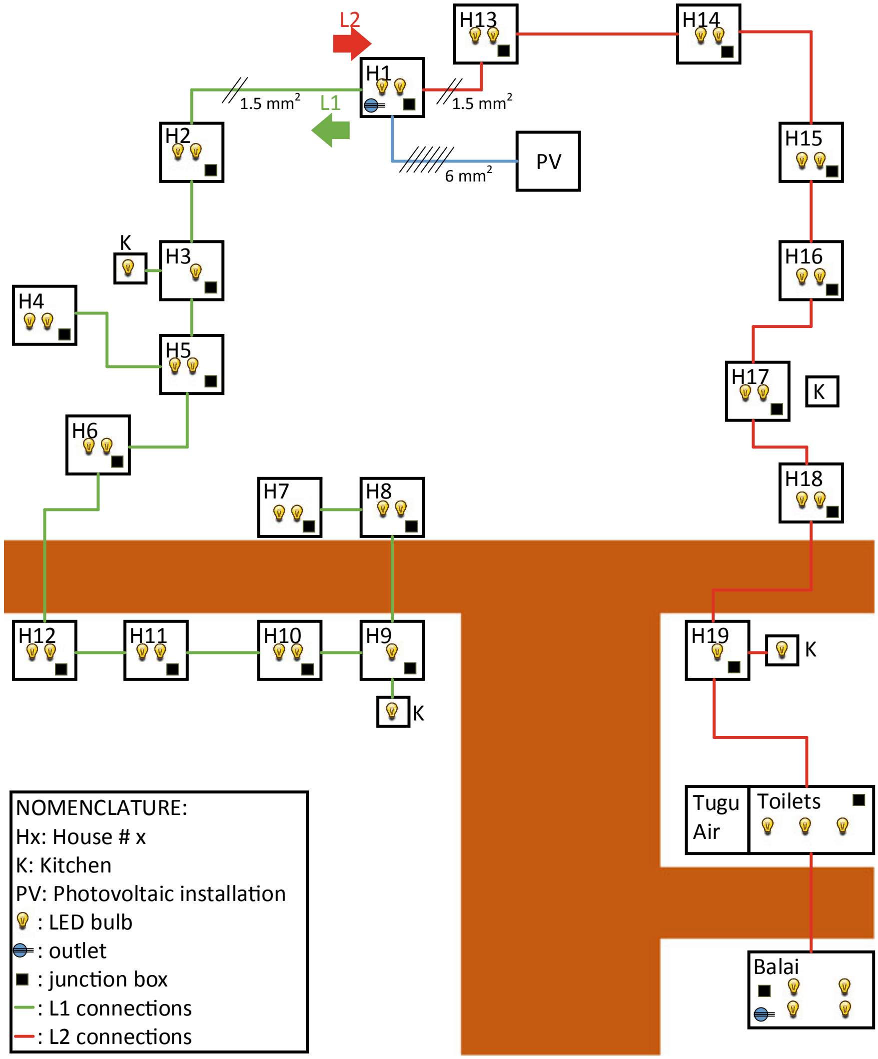


Fig. 9.4 Nanogrid design

Outcome

The installation of the solar PV system was a success and now the locals are able to enjoy electricity generated by the system, which hopefully will last for many years. This installation will improve their lifestyle in different ways:

Fig. 9.5 Villager pulling a cable to allow the house to receive electricity

Fig. 9.6 Demonstration by a village representative on how to maintain the solar PV system

- More activities in the village: Each house is equipped with two LED bulbs. Therefore, the families will be able to carry out their activities, e.g., cooking and weaving, more easily, not only during the night, but also during the day (the inside of the houses are quite dark when no artificial lighting is used). The lighting also allows the kids to play and do their homework after sunset;

- Health improvement: Previously, to light their houses, the villagers usually used kerosene lamps. However, the kerosene lamps are not very bright and are very hazardous, which may cause poisoning, fires and even explosions. This threat has been removed as the villagers can now count on LED bulbs for lighting;
- Charging stations: Besides the bulbs, sockets were also installed at key locations and are now used by the locals to charge their phones. Previously, there are times when the locals need to use their phones for emergencies but were not able to do so as the phones could not be charged readily. After this project, the locals will no longer face this problem; and
- Responsibility: As the locals understand the importance of this PV system, they have developed a sense of responsibility towards it and are taking care of it. They have even built a fence around the solar panels in an effort to protect them.

Although this PV installation has improved the locals' quality of life, there are still more aspects which can be improved. Consequently, we hope that the locals and other parties view this installation as the first step, and to continue working to improve the economic condition and livelihood of the people in Sumba (Figs. 9.7 and 9.8).

Fig. 9.7 Children now have a community hall with proper lighting within their *kampung* to learn together, even in the evening

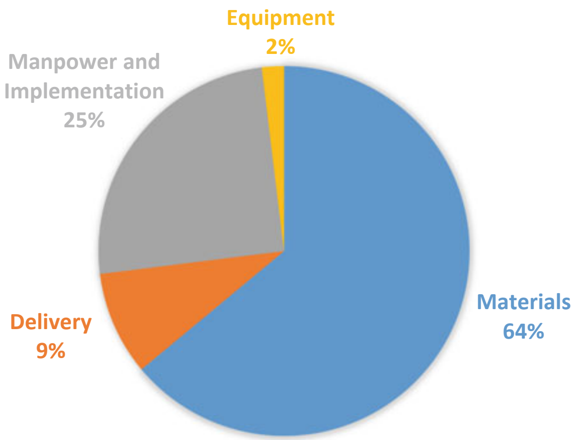
Fig. 9.8 Women in the *kampung* can weave more effectively with lights in each of the villagers' houses

Cost

The total cost of the solar PV system and the nanogrid are 90,887,450 IDR (approximately 6300 USD), which is made up by the following components (Fig. 9.9):

The system consists of 1.2kWp solar PV, 7.2kWh batteries, and 400 m of distribution line. It provides electricity to 19 households with 2 LED lights per household as well as 7 LED lights and 4 electrical sockets in shared spaces. The total cost also

Fig. 9.9 Project cost breakdown



includes inventory left for the villagers to maintain and expand the system, as well as to replace broken or faulty components for years to come.

This configuration only provides the basic necessity of a previously unelectrified community. Should more appliances are required (e.g. radio, fan, or television), then the size of the system and the cost will need to be increased.

Summary

At the end of the project, three main infrastructures were built. Firstly, a community hall serves as a multi-purpose hall and a learning hub. Secondly, toilets and sanitation facilities, together with the water filtration system, enable the villagers to have a better hygiene. Last but not least, the solar PV system provides the residents with lights and access to electricity, enabling activities in the evening and further economic development. Moreover, not only the building of infrastructures, but this project also imparted knowledge regarding financial literacy, nutrition and hygiene.

It is extremely heartening to see how excited the villagers are when the lights were turned on for the first time, and to see that the electricity has contributed to the livelihood of the villagers. In particular, one villager expressed that "the village is already like a city". As there are still many communities, in Sumba and across Indonesia, which have no or limited access to electricity, this project and its positive impacts can be replicated in many areas. Through our expertise in engineering design and installation, we are able to help institutions and organisations that are keen to carry out such a project. The design of the system will be customised depending on the characteristics of each village.

Future projects ideally will incorporate a more robust distribution grid that allows flexibility for houses to be relocated or added. Depending on the supporting infrastructures in the village, an electricity metre can also be installed to allow the collection of money from the villagers to maintain the system and replace broken components.

Appendix of the Project Report

See Figs. 9.10, 9.11, 9.12 and 9.13.

Fig. 9.10 Children studying with the help of LED lighting

Fig. 9.11 Our engineering team with the villagers

Fig. 9.12 MKP team installing the light bulbs and electrical box

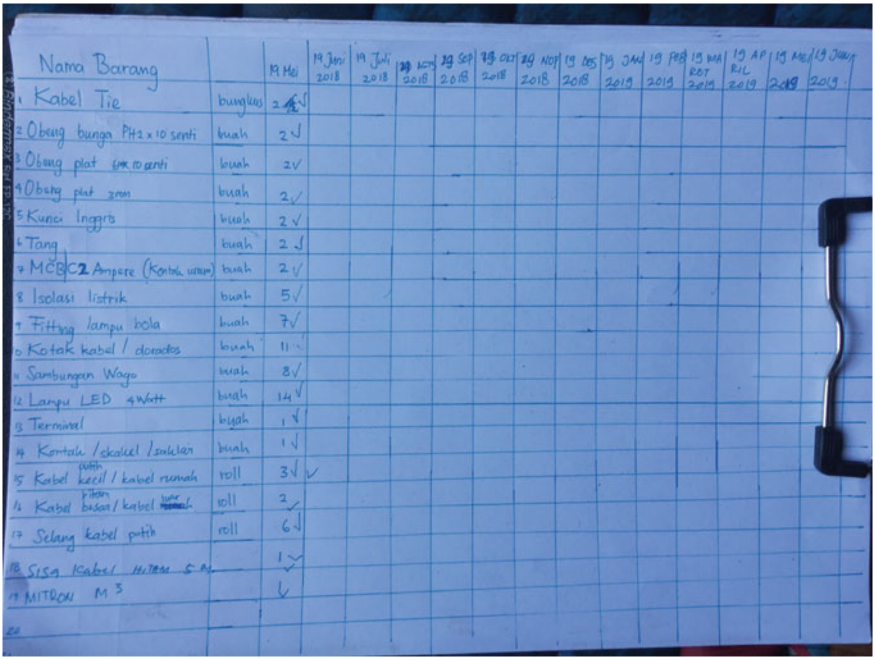


Fig. 9.13 Inventory handed over to the village

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The Grid of the Future

Walter Commerell

Abstract The electrification based on grid infrastructure in tropical areas today and in the future faces special challenging problems. Climate change, with increasing number of extreme phenomena such as cyclones, has a strong impact on the grid infrastructure; population growth and increasing demand of electricity will exacerbate the problem; and existing solutions in remote areas are not suitable for the future. Analysing the current situation shows that people in remote areas live without the grid or with a weak, unreliable grid. Meanwhile, the authorities and/or utilities might not extend the grid to the decreasing amount of people living in rural areas. State-of-the-art solutions for unelectrified areas are off-grid pico and solar home systems, as well as micro- and mini-grids. There is also an apparent trend towards a decentralised smart grid structure based on renewable energy sources. Decarbonisation, reliability and empowering consumers in a competitive market are the key words for the future. The Grid of the future in tropical remote areas will be based on self-contained smart grid cells supplied with 100% renewable energy sources. These independent smart grid cells are interconnected with other cells to exchange energy on demand or in emergency situations. Due to the self-sufficiency of the cells, the need for transmission of energy is limited. In an ideal situation, each cell is designed to supply its own demand. For each region, a clear master plan and a migration path from today to the future system will help all the stakeholders in planning their individual migration path. Several scenarios, technical applications and business models are discussed in this chapter.

Keywords Off-grid · Smart grid · Cellular grid structure · Smart grid cells · Energy router · Meshed grid · Any grid · Solar home system · Pico PV · Mini grid · Micro grid · Nano grid · Pico grid

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1 Electrification in Tropical Areas

The electrification in tropical areas today and in the future faces special challenging problems. The climate change has strong impact on the infrastructure; population growth and increasing demand of electricity will exacerbate the problem; and existing solutions in remote areas are not suitable for the future, as have been explored in the previous chapters. This chapter will look at the current situation and trends for the future.

1.1 Environmental Situation

The tropics are the area surrounding the equator with special climate conditions. They are spread over Central and South America, the Caribbean, Central, East and West Africa, southern India and Southeast Asia, as well as small islands in the tropical belt.

The special climate conditions highly impact the electrification and especially the grid infrastructure. The tropics are known for nearly constant climate with high temperature throughout the year and, in most parts, high humidity due to high precipitation.

The tropical regions are also heavily impacted by cyclones. There are several regional names for cyclones: “Tropical Cyclone” in the Indian Ocean, “Typhoons,” in the West Pacific and East Asia, and “Hurricane” in the Atlantic and East Pacific regions.

The lines in Fig. 1 indicate the strongest cyclones in the region of Western and Eastern North Pacific, North Indian, South Indian and South Pacific, Caribbean/Gulf of Mexico, and open North Atlantic. The colours indicate the strength of the cyclone (red means strong cyclones, while blue means less strong). It is remarkable that the strongest cyclones have occurred in the last few years.

Looking at the development of tropical cyclones from 1980 to 2016 in Fig. 2, we see that the frequency of heavy cyclones with wind speeds above 250 km/h has increased greatly. Due to global warming, it is expected that the tropics, in particular, will face a higher frequency and stronger cyclones in the future. The warming of the oceans will lead to an increase in tropical cyclones because the thermal energy of the ocean is the energy source of tropical cyclones.

The extreme tropical cyclone rainfall in tropical areas will increase greatly within the next decades. They will also affect regions between tropical and subtropical areas, e.g. the climate in southern Texas, by the Gulf of Mexico, is highly impacted by the Caribbean area. The Intergovernmental Panel on Climate Change (IPCC) estimated that the annual probability of 500 mm of rainfall in Texas will increase from 1% for the period 1981–2000 to 18% over the period 2081–2100 [2]. These heavy rainfalls lead to flooding and often the breakdown of the electrical infrastructure.

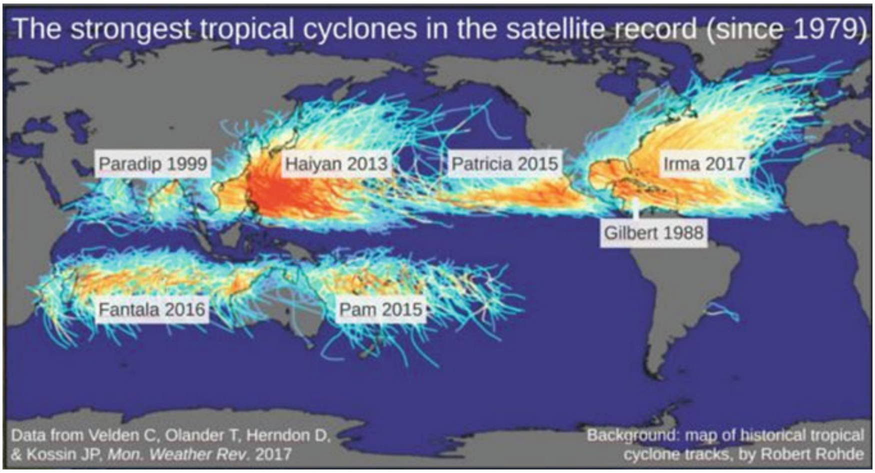

Fig. 1 Cyclones in seven tropical regions (Graph by Stefan Rahmstorf, background image from Robert Rohde, Cyclones Data by Velden et al., Creative Commons License CC BY-SA 3.0.) [1]

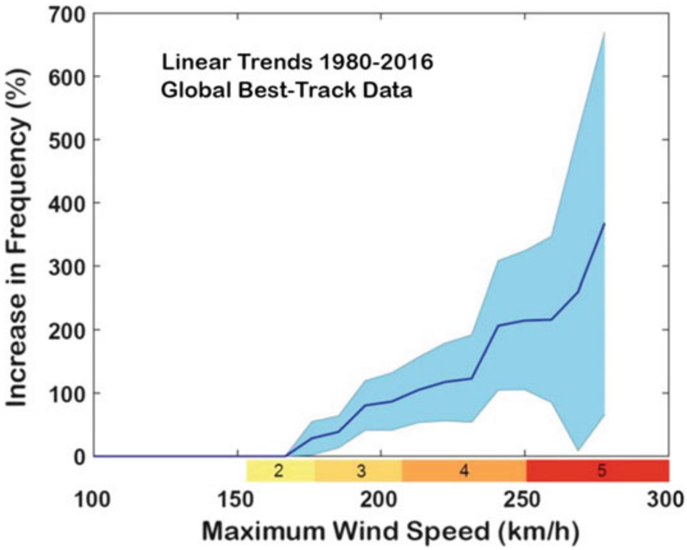

Fig. 2 Percentage increase in the number of tropical cyclones from 1980 to 2016 [1]

The grid system is especially impacted by cyclones. The high temperatures and the high precipitation also reduce the lifetime of components of the electrical system in the tropics.

1.2 Population

The population in the tropics is quickly growing. “By 2050, some 50% of the world’s population and close to 60% of the world’s children are expected to reside in the tropics” [3]. This increase in population goes along with a high urbanisation rate. For example, we can see in Fig. 3 the expected development of Brazil population in urban and rural areas; there is an extreme decline of population in rural areas.

Figure 4 shows where the current population is concentrated. We find hotspots at the seaside and very low population in the countryside. The low population in the countryside is partly due to less access to infrastructure, lower income and harsh environmental conditions like flooding. The data have a correlation to income and as well as education rate and electrification rate.

Looking at the grid system, one can identify that the grid is poorly developed in the countryside. In the case of Brazil, we can even find wide areas in the Amazon without any grid structure, as shown in Fig. 5.

Looking at other countries with smaller coastal areas, such as the Democratic Republic of Congo (DRC), we find that the situation is even worse. As shown in Fig. 6, we find that most of the country is without connection to the medium voltage grid, which is the basis of the low-voltage (LV) grid, to which the households are connected. LV grid lines can go for several kilometres from the medium voltage, and

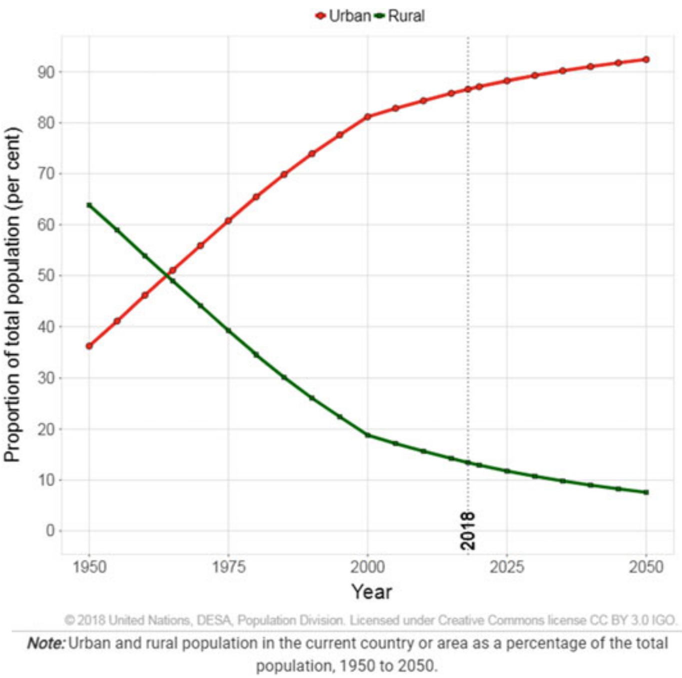

Fig. 3 Percentage of population in urban and rural areas in Brazil [4]

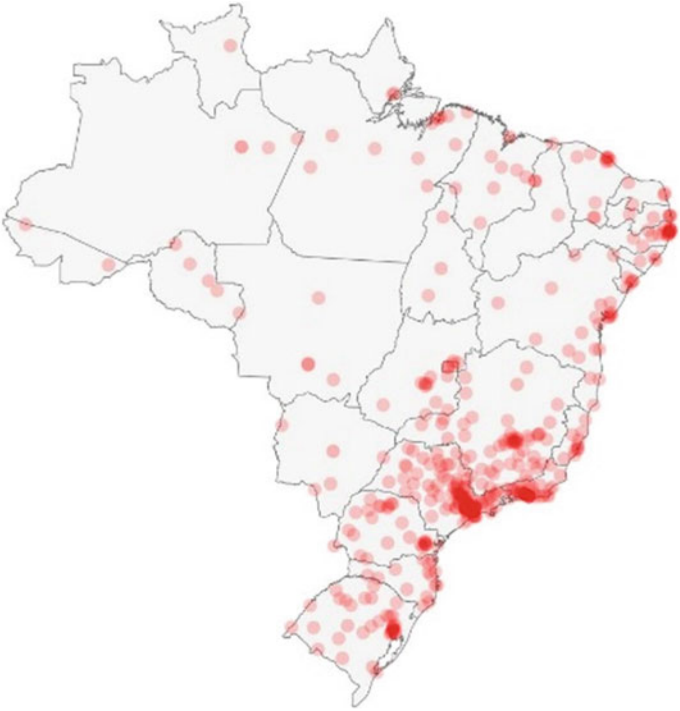

Fig. 4 Population density of Brazil [5]

this is often called "the last mile in electrical distribution". This means that in the DRC, we have wide areas of the country without grid infrastructure.

As shown in Fig. 7, the population distribution and grid systems do not correlate. This implies that in this country, there is a low electrification ratio—19.1% according to 2017 World Bank data [8].

1.3 Implications

The aforementioned main factors—rough climate situation, increasing population and urbanisation—will have a huge impact on the grid structure. The existing grid is often down due to tropical cyclones, and the reliability of the grid is weak. Due to vast areas with low population today and even lower population outlook, the grid extension may not go to each household in remote areas. Quoting the World Bank, "Some countries in Asia and Latin America are reaching the limits of grid extension. Further increases in coverage require intensive growth, which requires instruments designed for that purpose, or off-grid schemes, which need design improvements if they are to be financially sustainable" [9].

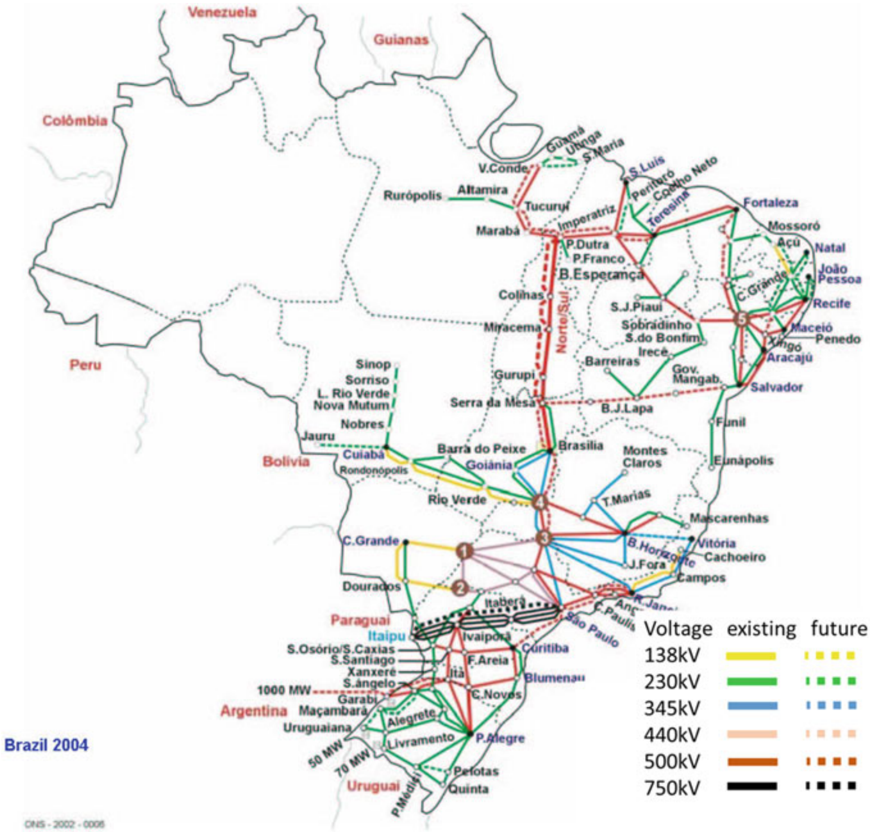

Fig. 5 Grid status of Brazil in 2004 [6]

Fig. 6 Medium voltage grid status in Democratic Republic of the Congo [7]

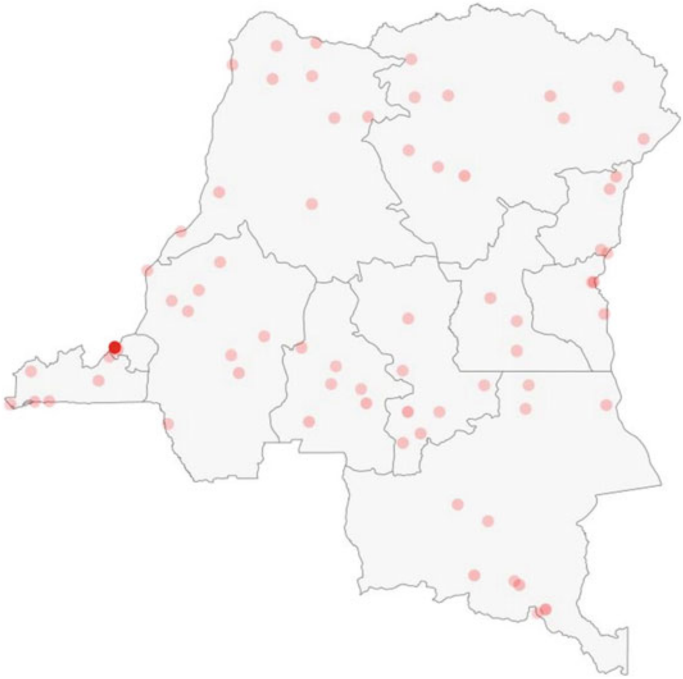

Fig. 7 Population density of Democratic Republic of the Congo [5]

Due to the low electrification rate in tropical areas as well as the low income and education rate, there will be an acceleration of the urbanisation rate in the tropical countries. The people who stay cannot expect to get access to the electricity grid in the future.

1.4 Grid Situation

In rural tropics, if it exists, the grid is often weak with outages, while grid development improves slowly.

Around the globe, approximately 30% of the people rely on the old grid, approximately 40% rely on an unreliable grid, and approximately 30% are without any grid. Unreliable grid leads to outages or power cuts.

Figure 8 shows the frequency and duration of power cuts for different countries. We can find several countries in tropical regions.

Nevertheless, the situation can improve should there be willingness from the government and the utility. In Asia, the number of people without any access to electricity has been shrinking rapidly in the past decades and will continue to do so. The International Energy Agency (IEA) states that “developing Asia sees the

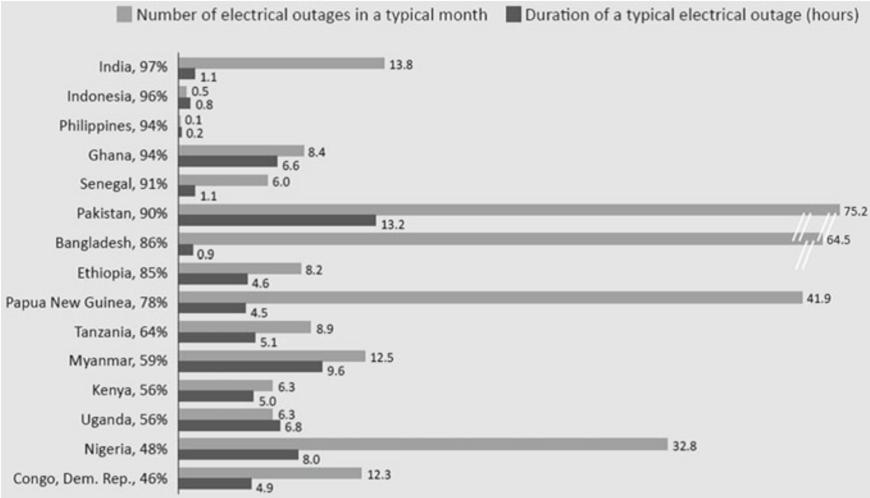

Fig. 8 Electrical outages of selected countries [10]

region reaching an electrification rate of 99% by 2030, with universal access by the mid-2020s in India and Indonesia" [10].

2 Technologies for Sustainable Energy Solutions

Business as usual will not solve the problems of the people in rural tropical areas. Supplying the people with reliable electrical energy requires new technical solutions.

2.1 State-of-the-Art Technologies

Especially in the remote tropics with small and poor population, the people rely on small renewable energy systems. In most cases, they use the so-called **pico Photovoltaic (PV) systems**—shown in Fig. 9—to replace candles or kerosene lamps with electrical lights. This kind of systems has integrated energy storage in the form of a battery, and it can be flexibly charged with different sources like from another battery, from a PV module of 1–20 W power, or from the grid. The pico PV system provides electrical light and energy to charge mobile devices such as mobile phones from a day's solar radiation.

A key feature of this system should be reliable since the users are generally not used to electric and electronic components at all. Therefore, it must be robust against water and shock, and intelligent enough to save power if the stored energy is getting low. For the pico PV system, there are several business models in place, such as direct

Fig. 9 Pico PV system [11]

purchase, where the user buys the system on his own, in some cases with financing support like micro-financing.

In pay-as-you-go (PAYG) business models, the owner lends the pico PV systems to many users. The user pays for the rent of the system for a weekly or monthly usage in advance. He can buy with cash or through mobile phone, whereby he receives a code, sends the code to the owner and gets a usage code back, which has to be put into the PV system.

Solar home systems (SHS)[1] are used if the power demand is higher, with several lights and more electrical loads like radios, televisions (TVs) or cooler/fridges, as shown in Fig. 10. The system consists of a PV module with 20–2000 W power, a solar charger, a bigger battery, and more electrical loads. The system works mainly on direct current (DC) voltage of 12, 24 or 48 V. For alternating current (AC) loads in bigger systems, DC/AC inverters are integrated into the system. This kind of system is able to provide power for several days or weeks without sunshine, depending on the size of the battery.

SHS, as shown in Fig. 11, is offered for easy and safe installation. The safety is reached by the integration of the battery and the charge controller within one unit, so the battery controller has full control over the battery and keeps it in a safe state. Due to the integration, the user is not able to bypass the battery controller and bring the system to an unsafe situation.

Mini-grids[2] are defined as pure off-grid systems with power sources, storages to supply a certain group of loads with a power up to 15 MW. In rural areas, the size of

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[1]Current and future role of SHS in electrifying the remote tropics is elaborated in Chapter "Swarm Electrification: From Solar Home Systems to the National Grid and Back Again?" of this book.

[2]PV mini-grids implementation, together with its challenges, is discussed further in Chapter "The Sustainability Dilemma of Solar Photovoltaic Mini-grids for Rural Electrification" of this book.

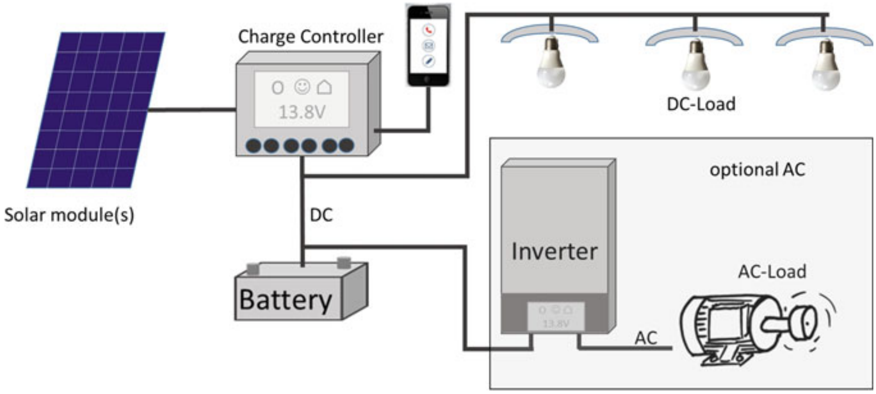

Fig. 10 Solar home system (SHS) diagram

Fig. 11 An example of Phocos SHS with three LED bulbs [11]

the systems is from several kilowatts to some hundred kilowatts. The load structure can be from several houses to villages.

Micro-grids are connected to the macro-grid and work inside of the macro-grid as a connected grid cell. Micro-grids can go off-grid in the so-called island mode.

Smaller off-grid units are also called **nano-grids** with some households connected in most cases over a low-voltage (LV) DC level. For much smaller systems, the term **pico-grids** is also used. Solar home system can also be called a pico-grid.

There is no clear definition when to use what term. As such, everybody should be sensitive when the namings are used.

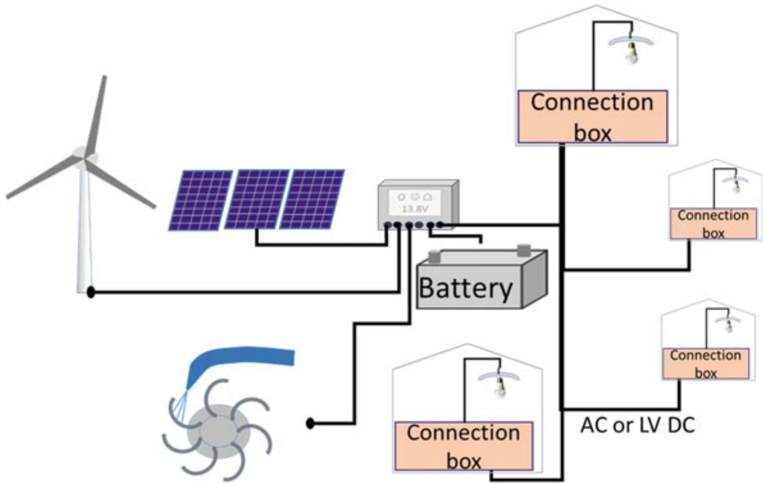

Fig. 12 Structure of a micro/mini grid system

Especially in remote areas, the name **micro-grids** is used as a generic term for nano- and mini-grids. They consist of interconnected loads supplied by one or more energy sources. In remote areas, the micro-grid works in the "island mode", without any connection to the grid, as shown in Fig. 12. They typically supply a village with electrical energy. Due to fluctuating energy sources, an electrical storage element is one of the main components of the system, to supply the loads for a certain period when the sources cannot deliver energy. Most mini-grids run on LV AC. Some attempts were made to develop DC mini-grids at several voltage levels to avoid conversion losses, and some have both DC and AC energy bus for loads. The connection box connects the house loads to the micro-grid. It can work as just an electrical connection, or it can be equipped with a smart metre.

As an example, Fig. 13 shows the presence of mini-grid systems in West Africa. As can be seen, the amount depends on the country. In some countries, mini-grids are supported by financial institutions and the government.

Mini-grids can use several energy sources such as PV, hydro, biomass, wind and non-renewable generator sets, which makes them hybrid systems. On the demand side, they generally supply households and small enterprises. They can have a supply strategy where public facilities such as medical centres and the police get premium access to energy in case of limited amount of stored energy.

Quite often, it is found that systems are set up and then break down within a short time, due to the lack of educated maintenance and the use of low-quality components. Getting to reliable sustainable energy supply requires education in the use of the energy system and proper maintenance.

Politically, electrification is often used to win elections. Some political leaders tend to promise grid access in remote areas. In such cases, people would wait before

Fig. 13 Mini-grids in West Africa [12]

investing into off-grid PV systems, because the grid might be coming soon. If the leaders did not fulfil their promise, the people might be waiting in vain.

2.2 Trends

Many solar PV systems, together with batteries, are connected at the low-voltage distribution grids. As more renewable energy sources are expected both in rural and urban grids, this would lead to more decentralised structures. A general Outlook 2018 study by IEA shows that the cost of PV will further go down [10] and the threat on fossil energy continues due to climate change issues. Quoting the report, "The electrical sector is experiencing its most dramatic transformation since its creation more than a century ago". [10]. Due to the volatile renewable energy sources and the need for storages, they will compete with gas-fired peak power sources.

Trends towards a smart grid system are described by the Institute of Electrical and Electronics Engineer (IEEE) Control Systems Society (CSS) group in their Vision for Smart Grid Controls: 2030 and Beyond in [13] where the main drivers for the change are:

- Decarbonisation and integration of renewables.
- Reliability in the face of growing demand. For example, in the USA, the demand is outpacing the infrastructure, and the infrastructure is not suitable for future situations like high loads at low energy input. Low storage capacity and grid management are sometimes prone to outages and cyberattacks.
- Electrification of transportation, where an increasing amount of electric vehicles without smart management lead to high peak loads.

- Empowered consumers, with their own power production (prosumers) and the ability to control the electricity demand and generation with real-time data, such as load and generation data.
- Market designs and regulatory paradigms with more and more competition between players and technologies.

As lessons learned in [13], it is stated that customer should own their detailed consumption data, they should have a direct metre and the demand management information should be connected over the existing infrastructure.

In [13], IEEE CSS showed several scenarios for the grid to evolve until 2040. The evolution of the grid will feature more integration of renewables, active endpoints, control and management features with "millions of individual institutional agents and new economic mechanisms and business models". The scenarios for interconnected micro-grids, where distributed renewable sources are integrated, were also explained.

In rural areas, it is possible to design off-grid structures based on the ideas and lessons from the grid system, and at the same time adjust the products and business models to the local situations.

2.3 Overview—Vision

Based on the special environmental and population problems in tropical rural areas, The Grid of the Future will be based on self-contained smart grid cells in similar sizes as today's mini-grid systems, a smart mini-grid, supplied by 100% renewable energy sources. This structure is one of our natures building blocks and we can find it if we look closely into the nature of plants, bones, bodies, ground structures, as shown in Fig. 14. These smart cells will consist of self-sufficient solar home system, which buy energy (consumer) and sell energy (producer) based on their situation. They will be the so-called prosumer.

Fig. 14 Natural cellular structure of the earth in Namib Desert in Namibia

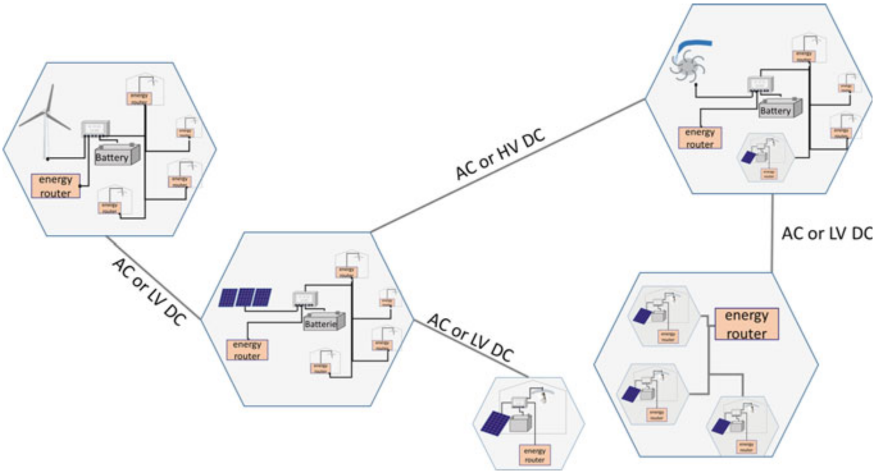

Fig. 15 Future grid with smart grid cells

If the geographical and financial situations allow them, these independent smart grid cells would be interconnected to exchange energy as sketched in Fig. 15. Due to the self-sufficiency of the cells, transmission of energy is limited to emergency situations. Therefore, the transmission lines and the infrastructure investment can be minimised. This kind of structure will be very reliable, because each cell, either the single household or the mini-grid, will be able to provide energy in normal situations for their loads and will be able to provide/obtain energy to/from the rest of the interconnected cells when necessary.

For example, a household with small business loads will be designed in a way that the households' own power supply is able to run the basic loads, such as lights and phone charging. Additional energy needs for the business, such as electrical motor, can be produced within the local small cell or can be bought from the next higher level, in this case the mini-grid.

A decision and measuring unit called the energy router, as shown in Fig. 15, controls the energy flowing in and out of the cells. The energy router can also transform the energy from DC to AC and vice versa.

In emergency situations, e.g. the transmission lines are cut due to natural disasters like tropical cyclone or flooding, the people can still be supplied with minimum energy for the critical loads. In the worst-case example above, this means that the household would still have power for lights, but not for running the loads of the business.

At a higher level, the single smart mini-grid can stay on even if the transmission lines to the next smart mini-grid are cut.

In emergency cases like in natural catastrophes, communication to remote areas is one of the essential needs to get a big picture of the situation. If each cell (home, village and area) can run on their own, the chances for cells to be alive are higher. This structure will help to keep the communication within a country functioning and to react in the right manner. At the same time, a basic medical infrastructure supplied by electricity can be kept after natural disasters.

If the smart mini-grid system is close to the grid, it works on "island mode" only partly, but if the system is far away from the grid it works mostly on island mode, and only partly on grid connection. The energy sources for this kind of grid must be carefully chosen based on the financial, geographical, disaster probability and growth situation. The system design should focus on reliability, expandability and flexibility.

This kind of Grid of the Future needs a smart management accompanied by new business models.

2.4 Future System Requirement

Migration to the Future

To move from today's situation into The Grid of the Future, more technical and economic investigations have to be made, as discussed in the previous chapters.

The systems can be designed in a way that they support the master plan. This means that from the current situation to the master plan, a migration path has to be drawn to show all the stakeholders where to go. For example, if it is clear that a specific region will not be connected to the grid, cellular structures which integrate already existing SHSs and take them as small cells should be developed, rather than ignoring existing systems and build up a new mini-grid. The basic aim of this migration path is for the users to get reliable access to renewable electrical energy. Aside from the technical migration path, new business models with regional difference have to be developed.

If the development in remote areas starts with a migration towards smart grid cells, the users have the benefit from immediate access to electricity, growing their demand as the system grows. If the region is connected to the grid in the far future, the smart grid cell can be used to stabilise the grid.

Whether the smart mini-grid would be running on DC or AC is still an open question. There is still a competition between AC and DC Grids. So the battle between DC and AC is re-enacted. In the late nineteenth century, the "War of the Currents" was won by AC because of easier generation in rotational generators like hydropower stations, and easier distribution and transformation from low voltage to high voltage and vice versa. Transforming electrical power into mechanical power was also easier using AC at the time. Nevertheless, as electrical conversion from AC to DC and vice versa is getting cheaper and more efficient today, and due to the increasing number of machines running with inverter, DC mini-grid is also an option.

Moreover, AC systems have some disadvantages. Transmission from point A to point B means the transmission of complex power consisting of active or real power. On the one hand, active power, also known as real power, is used for the lighting and machines. On the other hand, reactive power is needed for capacitive and inductive loads and is constantly flowing between sources and loads without doing useful work. This leads to higher current, and hence higher power losses in the transmission lines. Especially in off-grid systems, where electrical energy is generated with PV modules with DC generation and stored in batteries as DC storage, power losses must be compensated with bigger PV generation and higher battery capacity. Even in the grid system, long distance DC transmission is based on high-voltage DC (HVDC) lines, as shown in Fig. 15. The AC power is electronically transformed into HVDC, transmitted and transformed into AC again or into LVDC.

Nowadays, electrical loads like TV, radio, computer, etc. work internally on DC current. Electrical motors are in many cases controlled by an inverter, which works internally also on DC. Thus, from the load side, it makes little sense to supply them with AC. Transmission from LVDC to HVDC can be done with high efficiency.

Then, despite the many benefits, why is there no change of the electrical system to DC?

This is mainly because AC loads are much more available all over the world. There were up to now just a few specialised DC loads, often only available at higher prices. Now, some tendencies towards DC can be seen. Initiatives like DC at Home, European super-grid, super-smart grid with AC and DC grids, are going into this direction.

Companies, which have within their factory mainly DC loads, e.g. LED lights, or data processing centres, start with special DC installation within their facilities and produce most of the power on their own by using a PV system or transform the grid power to DC.

This means that for the future grid in remote areas, reliable and cheap transmission gateways must be developed. Research activities and blueprints are already in place to develop this kind of energy hub or energy router. The name energy router will be used to describe the power and data interface between cells. The current developments focus on the grid system. Therefore, these components also have to be designed for off-grid applications.

Grid Management

Managing the smart mini-grid structure based on self-sufficient cells for rural areas is new, and therefore, the necessary infrastructure and techniques have to be developed. Several ideas on how to manage single cells already exist in the traditional grids. In systems without storage, generation (including feed in from other cells) and load must be the same at all times. If not, the system controller has to manage the situation. If the values of frequency and/or voltage of AC systems go beyond the allowable range, some grid elements will become unstable and will switch off. This has resulted in headlines like “Millions across South America hit by massive power cut: Failure leaves people in Argentina and Uruguay without electricity” [14]. These big power cuts are usually caused by a single failure which leads to a cascade switching off, region by region. To prevent such problems from occurring, the use of swarm methods to form and optimise a grid out of single particles as in [15] has been investigated.

Load management is crucial for the future grid system, due to the fact that the grid is based on volatile energy sources and limited energy storages. If the available amount of energy from the sources and the storage is going down, low priority loads have to be switched off. Load management in mini-grid systems with one single power station already exist as shown in [16, 17].

These ideas and solutions have to be combined and tested. Remote area systems can profit from the investigations in the grid system.

The future grid in remote areas should have the goal to get to a robust, reliable and self-healing system. If the systems are well designed, they can even come up with a more reliable structure than in urban areas, where power cuts can happen due to the reliance on big single power units.

The future remote grid needs the capability of dynamic islanding, depending on the situation. Known methods, such as the droop method in AC systems, emulate behaviour of synchronous generator by controlling the voltage and frequency with output of real and reactive power. DC systems are easier to control via voltage droop methods.

Predictive or adaptive methods can be used to increase the reliability. Nonetheless, they make the control mechanism more complex.

The energy management system should rely on single cell controller without a central control in normal operation. For emergency situations, a wireless emergency communication channel must be installed, to tell the single unit to cut off non-emergency loads and supply the next higher level of the grid, i.e. the other grid cells, with power. This emergency procedure has to be designed very carefully, because it disrupts the concept of single operating cells. Known methods like master–slave, circular chain and others should be avoided because in these cases the single operation cell highly depends on others.

Cybersecurity in grid systems is currently an emerging topic in urban grid systems. For the new single cell control, cyberattacks will have low impact, because the local decision is done only based on physical values, without communication to a central station, except in the emergency mode where the single cells have to "help" the others by reducing the cell consumption and providing energy to the network. Therefore, the system is only prone to cyberattacks in certain situations, such as when the cell is continuously in an emergency mode. As such, it is recommended for the cell to allow the user to manually switch back into non-emergency (normal) operation, depending on other information like radio information.

The main challenge in managing such systems will be the handling of power quality. Especially when power is switched on or off, current pulses (transients) lead to disturbances with high frequencies, called harmonics. Since each cell has the need of a storage, the harmonic disturbances can be mitigated by the storage. This leads to decoupling of the cells and lowering of disturbances in the system. Upcoming active filtering techniques can also contribute towards a better power quality.

As the energy system in non-tropical countries becomes more decentralised with the use of renewables and technologies—such as HVDC transmission, upcoming DC installations in facilities with DC loads, and smart control—many new business models are being evaluated and integrated. Hence, the tropical areas can observe the results and take advantage of the findings.

2.5 Scenarios for Smart Grid Cells

In the transition towards the concept of smart grid cells, there are a few existing and future scenarios in the remote tropics that we need to understand.

Scenario I: DC smart grid with central power generation (DC mini-grid/micro-grid/nano-grid/pico-grid) as shown in Fig. 16 is a common concept if a house (left side of figure) or a village (right side of figure) is supplied with energy for the first time. In the smallest cell, it can be a pico PV or SHS system. A slightly bigger cell can be a micro-grid for a village. Moving towards the cellular structure and to the future scenario IV, the single cells have to be interconnected with the other cells. Each cell is connected via an energy router to the other cell. Each house without own energy source is connected via a connection box.

Scenario II: AC smart grid with central power generation (AC mini-grid/micro-grid).

Bigger systems, as shown in Fig. 17, with higher power demand are mostly based on AC grid due to AC power sources such as wind and hydropower stations, and higher transmission voltage. If the area is suitable for additional energy sources, e.g. wind, hydro or combined heat and power (CHP) sources can be integrated. Each household is connected via a connection box to the grid. Energy is transmitted only into the household. The connection of one cell (Fig. 17) to the next cell or upper structure is done by an energy router. It offers the possibility to get/supply energy from/to another cell.

Scenario III: AC/DC smart grid with prosumer and consumer.

If during the migration existing SHS system is integrated, then we would have both prosumers and conventional consumers within the system, as illustrated in Fig. 18. If the system is bigger, mostly AC is used on the grid lines and DC within the prosumers area. As it can be seen, the houses with own energy generation are connected via an energy router, the houses without are connected via a connection box.

Scenario IV: Interconnected smart cells.

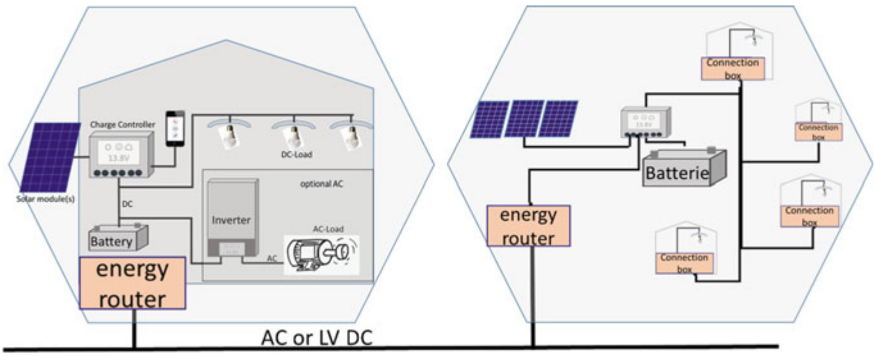

Fig. 16 DC smart grid with central power generation and storage per cell

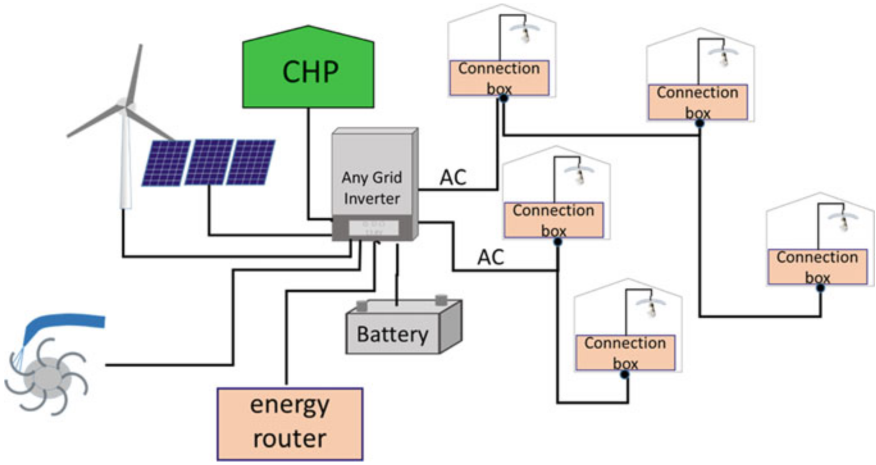

Fig. 17 AC smart grid with central power generation and storage solution

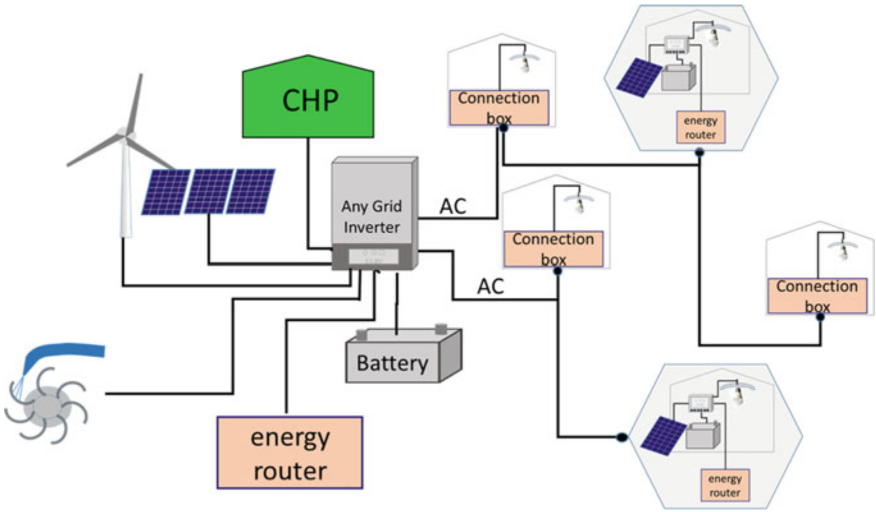

Fig. 18 AC smart grid with central power generation, storage and prosumers with DC systems

Interconnection of smart cells means that the inner cell is at minimum able to supply the emergency loads. Energy routers, as shown in Fig. 19, interconnect the cells and act as a power metre.

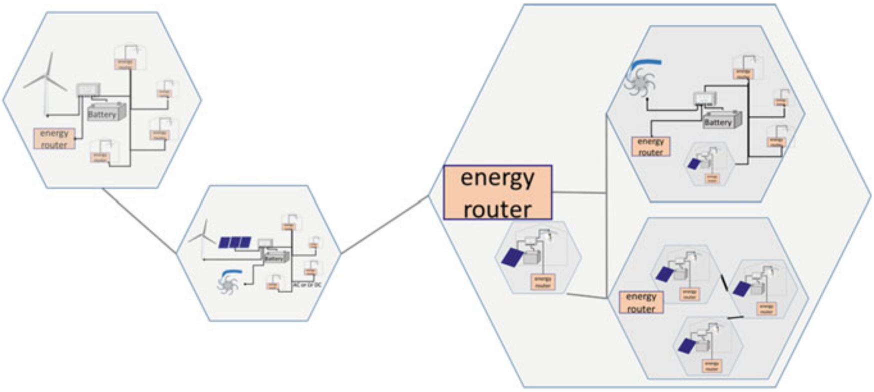

Fig. 19 Interconnected smart mini-grid cells

3 Applications of the Technologies

The four scenarios shown can be implemented as follows. The respective business models are discussed in more detail in the next section.

Scenario I (DC smart grid with central power generation (DC mini-grid/micro-grid/nano-grid/pico-grid)) is one of today's standards in terms of technology available on the market. In most cases, the system has a small size and runs on low voltage of 12/24/48 V to avoid safety issues. Some attempts to have higher DC voltages in rural areas have been made. Some industrial applications, especially for lighting and data centres, work with 380 V DC systems [18]. As there are nearly no loads available today—and possibly in the future—operating at this voltage, and because of safety issues, this will not be suitable for remote areas.

This kind of system is mostly owned by one person or a community with simple business models such as flat rate (Freemium without Upsell), because of the nearly equal loads (lighting and cell phone charging).

Pay per unit or other business models are suitable for bigger systems.

Scenario II (AC smart grid with central power generation (AC mini-grid/micro-grid) is a common standard for bigger off-grid systems. The benefit of AC lies in the ability to use conventional grid loads and installation materials commonly available for AC components.

Typical users are solely consumers: they do not produce energy themselves and may run small businesses. Due to the different load profiles for the users, such as household with fridge, household with small business, household with just lighting, business models like Freemium plus Upsell or pay per unit are in use.

Scenario III (AC/DC smart grid with prosumer and consumer) has to be accompanied by new technologies in energy flow, metering, and business models. First products for rural areas like the any-grid hybrid inverter charger are already on the market. The product, developed by Phocos, can be charged using DC (PV) and/or AC sources and can function as uninterruptible power supply (UPS) when no sources are available. PV can be set as the main source of energy to reduce the electricity cost [11]. Additional products are needed to transfer energy, if necessary, from AC to DC or vice versa, and to measure the energy flow for net metering.

Blueprints of energy routers to implement this scenario are already available, but they have to become cheaper and more robust for use in the rural tropics.

Scenario IV (interconnected smart cells) is based on Scenarios I to III and connects the smart cells to exchange energy among cells. Due to the fact that in an AC network each system runs on specific frequency and voltage, synchronisation may become a problem. Additionally, power losses due to the transmission of reactive power lower the transmission efficiency. Therefore, using HVDC lines for longer distances seems to be the future. Currently, many HVDC transmissions are set up all over the world [19]. This technology is well developed for high power transmission, but still has to be transformed into cheaper products with integrated measurement and communication for it to be viable.

Implementation

Scenarios II–IV offer the opportunity to integrate a biomass CHP station. In that case, it is possible to store energy in biomass form and produce electricity only when directly needed, instead of producing electrical energy and store it in batteries. The heat power output of the CHP can also be used directly or stored in a thermal storage.

Normally, implementing this structure needs the approval and/or assistance from several stakeholders:

- User of the electrical power (remote population)
- Government (local, regional, national)
- Utility
- Investors if financed
- Banks.

At first, it seems unrealistic to implement such a system with often contradictory stakeholder views. Due to the ability of this system to grow along the migration path from a single cell like an SHS to interconnected cells stabilising the utility grid, several stakeholders can be satisfied along the way.

If a weak grid structure is present and run by the utility, an agreement to run it partly in island mode may be necessary. Standards for islanding micro-grids are in place and defined in IEEE Standard 1547-2003. The IEEE standards coordinating committee [20] recommends “During transition to and operation of the planned island, one or more of the participating DR (author’s comment: distributed resources) may be allowed to operate according to a predefined set of requirements outside of IEEE Std 1547-2003”.

This standard focuses on conventional grid structures and islanding of regions within the grid. In remote areas, the focus is on the interconnected islands where the standard can also be used. These interconnected islanded cells are called meshed cells. This approach assumes that the existing islands already have enough power sources to supply their basic needs.

Metering is essential for successful business models in all scenarios. The energy flowing in and out of a unit (cell) has to be measured in both directions separately, because there can be business models where prices differ for power in (buying) versus power out (selling).

Different transformation paths are discussed in the following sections.

3.1 Installation

Installation of energy sources and local grid lines must be done in a robust way to avoid damages due to tropical cyclones and other possible disasters. Similarly, central power stations, like central housing of batteries or hydropower stations, should be designed in a way that they withstand natural disasters. If possible, grid lines should be put underground, although this will require higher cost. In general, each region has its own experience for this type of integration. It should be considered that the frequency and intensity of cyclones will get higher within the next decades, as discussed in Sect. 1.

3.2 Fault Protection

On top of the previously mentioned cybersecurity protection in Sect. 2.4, physical safety mechanisms (fault protection mechanisms) should also be of a high standard to avoid damages to persons and infrastructure. Therefore, existing standards and best practices should be followed.

In Fig. 20, a possible cellular structure is shown with a connecting unit at each connection point to the next upper structure, i.e. the upper/higher cell in a hierarchical structure. Fault protection devices, e.g. breaker and measurement unit can be placed at this point.

The system should behave in a way that if a single cell detects that "the outside" of the cell has a failure, the cell goes into island mode. The connection point then periodically checks if the outside area is back in service again. It will observe the situation and switch on to the connection to the larger grid when the grid is back online. In case of maintenance situations, the grid must be switched off to be safe during maintenance. Due to a missing central control, the grid can be switched off by fault injection, i.e. the maintenance persons produce a fault to trigger the switching off of the system. Then, all the single small cells will detect this situation and go into island mode.

If, for example, cell 1 detects a single fault (fault no. 1 in Fig. 20) outside of B1.01, it goes into island mode, and cell 1, 2 and 3 are still working together. If a single fault no. 2 is detected inside cell 2, breakers B2.01, B2.1 and B2.2 switch off. This means that cell 2.1 and cell 2.2 go into island mode and supply their loads with their available sources. Other loads inside cell 2 will not be supplied. If a single fault no.

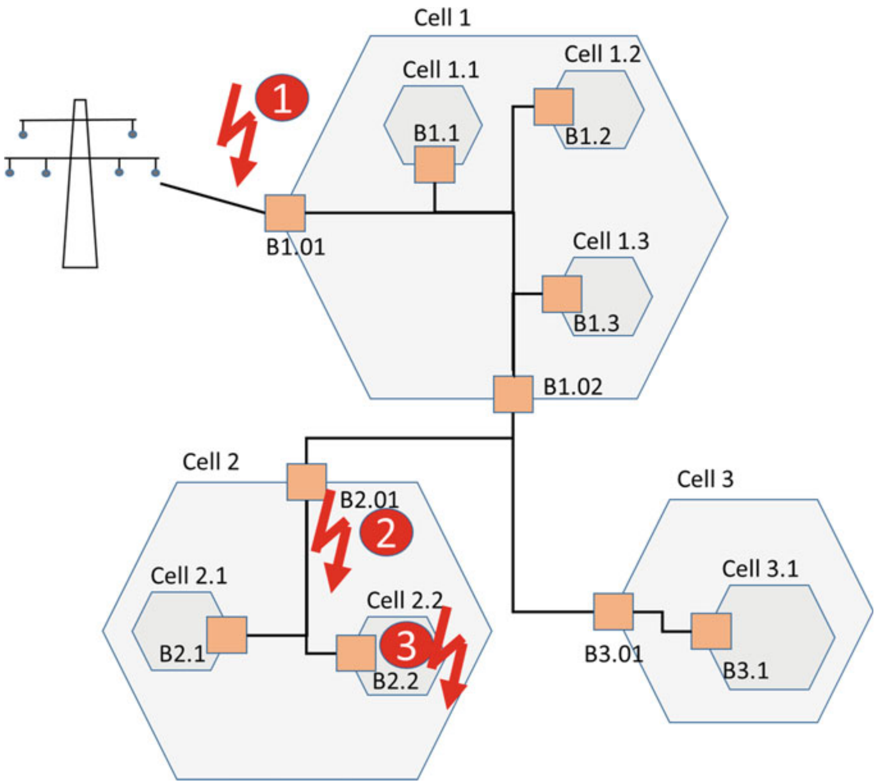

Fig. 20 Fault protection in a cellular structure with possible faults (Bx.x. means breaker x.x)

3 is detected inside cell 2.2, the breaker 2.2 opens and all other units except those in cell 2.2 will still be connected.

3.3 Structures

Different structures "inside" a cell or in the interconnection of cells can be realised. In the following, typical structures are adjusted to the future grid in tropical areas. A grid achieves a low probability of failure if each node can be supplied from two directions. This is called the $(n - 1)$ rule: A number of n power sources supply all the loads in the grid. If one source fails, the loads can be supplied by $(n - 1)$ power sources and grid lines. This means for the grid that if one supply line is cut or under maintenance the load/cell can be supplied by the other lines. This structure is costly because each node is supplied by a minimum of 2 lines where each of them is able to carry the full load of the supplied node. It means that this structure is highly oversized, but leads to low probabilities of failure, i.e. high reliability. This structure fits grids with centralised power generation.

In rural areas, this kind of structure leads to high costs and will not be implementable. The future grid in remote areas can have high reliability by using decentralised energy generation and decentralised storages with the smart islanding concept.

The different possible grid structures are shown in Fig. 21. In an ideal structure, every node (e.g. a single house) is connected with every other node (fully meshed structure), which will lead to a very high reliability, because each node can be supplied by all the other nodes.

Structures like the tree, star, ring and line structures or their combinations are common. In most cases, the most economical structure is realised. In remote areas, the structure should be designed along the path from the existing structure to the master plan solution.

In a line structure, the reliability is based on the reliability of each of the elements on the way to the feeding point. This structure is the weakest. A bus structure offers better reliability because the power is not fed through the nodes. A ring structure gives more reliability because every node is connected by two lines, but is more expensive.

Improvements are made by a tree structure where the reliability is based on the reliability on the way to the feeding point. Compared to the line structure, fewer nodes and lines are on the way to the feeder.

Star and tree structures are common within existing micro-grids with centralised power generation and storage.

Due to the self-sufficient cellular structure with more decentralised power generation and storage, the importance of the grid to the reliability of the system decreases, because each cell will have its own power supply and no longer solely rely on the grid.

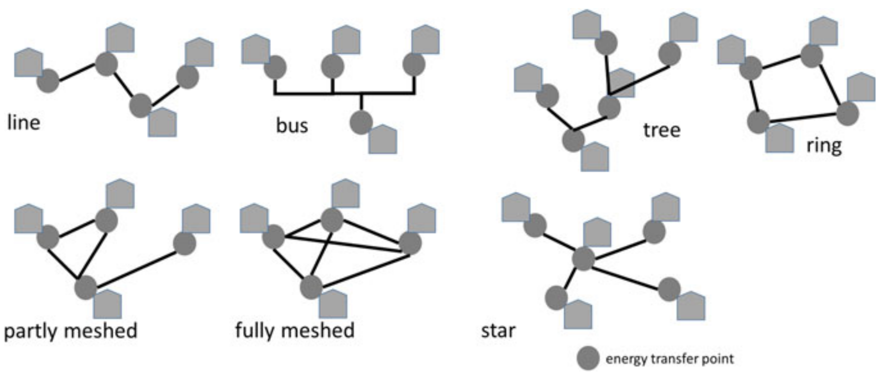

Fig. 21 Examples of different grid structures

3.4 Moving from off-grid to Meshed Micro-grids

The near-future demand for rural areas, where people do not have access to electricity, is in "pico, plug-and-play SHS, and component-based systems" [21]. If the demand grows and people want to run business with additional light, cooling or machinery, these systems will not be able to support them. Thus, systems bigger than SHS have to be designed.

The idea of the future grid in remote areas is to design today's system to move towards or to be integrated into the smart cell structure. Therefore, the pico PV, SHS kits, or SHS built by separate components must be integrated into a micro-grid cell. Consequently, a bidirectional energy router with measurement capabilities must be added to the system. The new small cell with its own power generation and storage can become an island if necessary, and can provide excess energy to the next higher cell for productive activities, such as irrigation, if its own storage is already full. The system can buy energy from the grid if the needed amount exceeds its own production.

3.5 Moving from Non-reliable Grid to Meshed Micro-grid

In tropical and other areas, non-reliable grids can be found. People and businesses are suffering from power outages in their daily lives and operations. In most cases, they use backup diesel generators to run their business during power outages. These areas face adverse environmental impacts with diesel and oil contamination of earth, rivers, and ground water, as well as air and noise pollution.

The future smart cellular mini-grid structure will help them to sell energy or buy energy in case of peak loads. Even today, sustainably powered electrical energy generation is already cheaper than diesel generators. The ability to island a house or village or region will help to make the grid more stable. Each cell can decide how much energy they produce and store themselves and how much they buy for additional loads.

Due to the fact that the existing grid in these areas is based on AC, the integration of a cellular structure will use the existing AC grid lines. Within the smaller cells, DC-based systems can be built.

4 Business Models

The previously discussed problems and technical solutions make it necessary to design and implement new business models.

4.1 Local Differences for Future Business Models

Using the right business models will be a key issue for the Grid of the Future in the remote areas in the tropics. There will not be only one business model which fits all regions and needs.

For each situation, the business model strongly relies on the social structure in the region and what is already known by the owner, user, buyer and seller. In general, the willingness and the ability to pay for energy are crucial. People in rural areas usually have lower and more volatile income, because in most cases, their earnings come from farming or fishing with strong seasonal and environmental variability. So, the purchasing power is low at the first touch with electricity.

The willingness to pay is high, because the alternatives to no electricity are, in most cases, more expensive than the cost of electricity. One driver that increases the willingness to pay is the access to energy for communication. To overcome the cost situation, micro-financing is one possibility. Therefore, the availability and familiarity with credits must be integrated in the community or set up carefully. The social role of the borrower plays a further role. In some communities, it turned out that the women have a higher repayment rate.

4.2 Different Business Models

New business models have to be designed such that the business model evolves with the system. It is worth noting that business models cannot change as easily as technical features, because they are related to contracts and customer relationships. Thus, the models have to be compatible with the technology and show a transformation path, just as in the technical area.

In the **Pay-as-you-go (PAYG)** business model, the user buys a certain amount of energy to use in advance via cash or cell phone. As the user uses the energy, the remaining energy available is decreasing. In some models, there is a time limit; if the user has not used the energy by then, the remaining available cash expires. The attractiveness of this market is analysed in [22].

In **Pay-as-you-earn (PAYE)** business models, energy is used to run businesses. In general, no liquidity is needed if the profit of the business is greater than the energy payments. This model is designed mostly for continuous businesses but can also be adjusted for seasonal businesses.

In a **Pay per unit** business model, a fixed price covers the maintenance to the infrastructure and cost per energy in a post-paid or pre-paid model.

Base and overage charges as known in car rental, where the user pays a base per time unit (base per month) and an incremental price per energy unit (kWh). It can be beneficial since the user can see his energy consumption in relation to the base unit.

Freemium + upsell where a minimum of energy is free to the user. If the user likes to have more energy, he will have to sign up and pay for more. The owner of the energy network will need to estimate how many users would sign up to determine how much energy is offered for free and the price being charged. This business model works with great success in the IT market, where services are offered via the Internet.

The **multiple tiers** price model can be used to charge users based on their maximum load requirement. If, for example, a household just uses some lighting loads, they can be charged for their consumption on a "basic load" with a low rate per energy. If the load demand exceeds the basic load, they have the option between load reduction and ordering the next tier, e.g. "extended load" or "business load". These models offer cheap access with the ability to grow.

In cases where the ownership is by the user, **bundling** of components for different usage will be an option to increase sales. There can be a bundle "starter" with basic components for energy generation such as a PV module, a battery and some lighting; or "micro-enterprise" bundles where machinery is included. Bundling of components offers the possibility to get lower prices through volume and to simplify maintenance.

Price segmentation can be done **by location**, where the prices can be higher if the region is more difficult to supply or long transmission lines are necessary. It can also be based on situation, such as when special needs, e.g. to have lower price in low season than in high season, are requested in a Fisherman's village. Price segmentation **by customer** is not recommended, because then the features or values of each system—even in the same village—have to be different. This makes the system more complex and may trigger tampering of the system by users, hence lowering the quality of the system.

Price segmentation **by demand** is a possible model, where prices rise if the demand is bigger than the offered energy. This is like the Uber surge-pricing model [23]. This model can be easily implemented in AC systems by inverse coupling of costs to frequency. This means that, due to the property of the AC grid frequency, if the energy supply is bigger than the demand, the frequency in the grid goes up and the price can go down and vice versa.

4.3 Future Business Models

In the future, PAYG business models will most likely work especially for the smart cellular mini-grid structure, where users get in touch with electricity for the first time. This model will also be in place if people are not used to loans and other business models with payback and refund.

If the cells are able to exchange energy with the other cells, metering needs to be in place to measure the energy flow in both directions. Then, one or more of the mentioned price models or their combinations would be possible. It is noted that most of the models need an independent service operator.

Regardless of the business model, the operator needs to communicate the models to the users, otherwise the users may be disadvantaged. For example, the following account was reported in [24]:

> In Tambo, South Africa, consumers had a choice between a connection fee of 200 rand (R) and a metered charge per kilowatt hour, or a lower connection fee of R10 and a fixed monthly charge of R15. Given actual consumption levels, most households would have been better off taking the first option, but most opted for the second because they could not afford the R200 connection charge and were not sure how much energy they would use. To make matters worse, many low-income consumers cannot always afford the R15 a month and so are disconnected and have to pay the R10 again to be reconnected.

Most of the poor customers have a power consumption much less than the base flat rate. This means that in a model with base and overage, the base flat rate power consumption should be set to the needs of the customers and in a way that motivates power saving.

For businesses, models like base and overage or freemium + upsell may be suitable. If the user sees the benefits, he will start paying for the additional energy he needs. These models should be adjusted to the customers' needs and should motivate power saving. Several examples in other areas showed that an unlimited access for free should be avoided. This model may lead to a lot of votes in an election, but not to a sustainable use of energy.

5 Impact

Access to a reliable grid structure in remote areas based on renewable energies has several positive aspects.

5.1 Social Impact

The quality of life of the rural communities will be increased from access to electricity because:

- Safety will be increased due to the avoidance of kerosene or candle lights in houses.
- Health will be improved due to the avoidance of kerosene and candle exhaust in the house and due to sufficient light for work after sunset.
- Quality of light significantly increases (candlelight has approx. 12 lm (lm) while LED light at 7 W provides 500 lm), which then enable children to study and family members to continue productive activities
- Communication via Internet, cell phone, radio and TV will increase. The people can have access to the information they want.
- People can increase their income by running other businesses based on electricity.

With higher quality of life, the rural communities may be more likely to remain in the countryside instead of moving to the growing mega cities.

The Independent Evaluation Group of the World Bank [24] showed that the costs for SHS/mini-grid are already lower than the grid and kerosene in countries like Indonesia, Mozambique and Nicaragua: the grid, mini-grid and kerosene have levelised cost of electricity (LCOE) of 0.04 $/kWh, 0.035 $/kWh, and 0.33 $/kWh, respectively. The costs of off-grid systems have gone down within the last few years and are projected to decrease further, while the costs for diesel and kerosene will go up. This means that the standard of living can be increased as less money would be spent on electricity, and more money can then be allocated to other needs.

Moreover, several studies [25–27] have shown that access to electricity reduces the absenteeism of workers in health facilities and teachers in schools. Teachers and health workers are educated mostly in cities and often do not like to go into rural areas due to lower living standards. The increasing living standard, due to electrification, makes it more attractive for people to move and stay in rural areas.

The impact on health increases greatly due to reliable electrification. Health facilities can offer a higher-quality care due to higher-quality light, reliable and longer opening hours, and offer better controls for temperature-sensitive medications e.g. vaccines. The access to communication channels, such as TV, has an indirect impact by providing health education and information access in rural areas.

Overall, it can be stated that future smart cellular mini-grid structure increases the reliability of electrical energy access, and therefore the living conditions in rural areas. This would eventually lead to an increasing willingness to pay for reliable electrical energy.

Politically, if people living in remote areas see that the country and local government take care of them by developing a future master plan in electrification, the governments will receive more support from the rural communities, who may previously see themselves only as a source of food or natural resources for the country.

5.2 Environmental Impact

Many grids in rural areas are still running on diesel with a high negative impact on the environment. The exhaust is a severe air pollution source and, in most cases, around the diesel generator one can find ground pollution through oil and diesel leaks. With the growing population in tropical areas, this problem is getting even worse. The power generation should be transformed to renewable energy sources like solar, wind and hydropower. Research has shown that hybridisation of diesel generators (which can be a first step before their complete replacement) with PV and batteries can decrease the lifetime equivalent CO_2 emission by 35% and at the same time reduce the LCOE of the system by approximately 30% [28].

6 Future and More Sustainable Solutions

Future grid structures in remote tropical areas should be built around renewable energy sources. Due to daily and seasonally volatile sources, the energy supply should, if locally possible, be able to accommodate an energy mix with different sources. Due to the higher frequency of natural disasters, the sources should be planned to withstand tropical cyclones and other phenomena. The proposed smart cellular mini-grid structure with decentralised power generation based on renewables minimises losses and environmental pollution, as well as improves the reliability of the grid infrastructure.

Sustainability does not only mean to use renewable energy sources. It means also to use the system over a long lifetime. Therefore, the design must be robust and reliable. This means the system must work with a high system availability and system utilisation over its lifetime. To achieve this, new skills and technical capacities should be generated. It is recommended that people are trained in energy system technology and energy economics to develop and adjust business models. The system should be able to measure its availability.

System misuse can be avoided through a better technical infrastructure, clear responsibilities and regular inspections.

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