This is a repository copy of *Finding the niche: A review of market assessment methodologies for rural electrification with small scale wind power*.

White Rose Research Online URL for this paper:
http://eprints.whiterose.ac.uk/165609/

Version: Published Version

Article:

Leary, J., Czyrnek-Delêtre, M., Alsop, A. et al. (12 more authors) (2020) Finding the niche: A review of market assessment methodologies for rural electrification with small scale wind power. Renewable and Sustainable Energy Reviews, 133. 110240. ISSN 1364-0321

https://doi.org/10.1016/j.rser.2020.110240

Reuse

This article is distributed under the terms of the Creative Commons Attribution (CC BY) licence. This licence allows you to distribute, remix, tweak, and build upon the work, even commercially, as long as you credit the authors for the original work. More information and the full terms of the licence here: https://creativecommons.org/licenses/

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk/

Renewable and Sustainable Energy Reviews 133 (2020) 110240

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: http://www.elsevier.com/locate/rser

Finding the niche: A review of market assessment methodologies for rural electrification with small scale wind power

J. Leary [a,e,h,*], M. Czyrnek-Delêtre [b], A. Alsop [c,e], A. Eales [c,e], L. Marandin [d], M. Org [e], M. Craig [e,f], W. Ortiz [g], C. Casillas [j], J. Persson [e], C. Dienst [g], E. Brown [a], A. While [h], J. Cloke [a], K. Latoufis [i]

[a] Loughborough University, UK
[b] MaREI Centre, Environmental Research Institute, University College Cork (UCC), Ireland
[c] University of Strathclyde, UK
[d] Pelican, Nicaragua
[e] Wind Empowerment, UK
[f] BlueEnergy, Nicaragua
[g] Wuppertal Institute for Climate, Environment and Energy gGmbH, Germany
[h] The University of Sheffield, UK
[i] National Technical University of Athens, Greece
[j] Independent Researcher, USA

ARTICLE INFO

Keywords:
Market assessment
Transdisciplinary
Development studies
Wind empowerment
Small wind
Rural electrification

ABSTRACT

The mass roll out of solar PV across the Global South has enabled electricity access for millions of people. In the right context, Small Wind Turbines (SWTs) can be complementary, offering the potential to generate at times of low solar resource (night, monsoon season, winter, etc.) and increasing the proportion of the total energy system that can be manufactured locally. However, many contextual factors critically affect the viability of the technology, such as the extreme variability in the wind resource itself and the local availability of technical support. Therefore, performing a detailed market analysis in each new context is much more important. The Wind Empowerment Market Assessment Methodology (WEMAM) is a multi-scalar, transdisciplinary methodology for identifying the niche contexts where small wind can make a valuable contribution to rural electrification. This paper aims to inform the development of WEMAM with a critical review of existing market assessment methodologies. By breaking down WEMAM into its component parts, reflecting upon its practical applications to date and drawing upon insights from the literature, opportunities where it could continue to evolve are highlighted. Key opportunities include shifting the focus towards development outcomes; creating community archetypes; localised studies in high potential regions; scenario modelling and MCDA ranking of proposed interventions; participatory market mapping; and applying socio-technical transitions theory to understand how the small wind niche can break through into the mainstream.

1. Introduction

1.1. Small wind for rural development

Leary, To and Alsop [1] explored the role of small-scale wind in the power generation mix of windy and remote developing regions. They observed that in some niche contexts, such as Inner Mongolia, Small Wind Turbines (SWTs) had thrived and made a valuable contribution to the electrification of a remote area at a time when there really was no alternative [2,3]. In contrast, in many other contexts, such as the Caribbean coast of Nicaragua, similar initiatives had failed [4]. Leary, To and Alsop [1] concluded that given the rapid decline in global PV (photovoltaic) module prices, small wind can no longer compete with solar PV in most rural electrification contexts due to the high maintenance requirements and the extreme variability of the wind resource. However, in the right context it can still be a valuable complement, offering diversity in power generation sources and the potential for local manufacture. Clearly, there is a need to identify these niche contexts to enable support for small wind to be focussed there.

* Corresponding author. Loughborough University, UK.
E-mail address: j.leary@lboro.ac.uk (J. Leary).

https://doi.org/10.1016/j.rser.2020.110240
Received 29 March 2020; Received in revised form 12 July 2020; Accepted 7 August 2020
Available online 3 September 2020
1364-0321/© 2020 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

List of abbreviations including units and nomenclature

IRENA	International Renewable Energy Agency
GIS	Geographic Information System
GoM	Government of Malawi
kW	kilo Watts
KAPEG	Kathmandu Alternative Power and Energy Group
MA	Market Assessment
MAWG	Market Assessment Working Group
MCDA	Multi-Criteria Decision Analysis
MLP	Multi-Level Perspective
O&M	Operation and Maintenance
PV	Photovoltaic
RE	Renewable Energy
SNM	Strategic Niche Management
STS	Socio-Technical Systems
SWT	Small Wind Turbine
USAID	United States Agency for International Development
WEMAM	Wind Empowerment Market Assessment Methodology

1.2. Market research

Market research is an essential component of business strategy [5,6]. Traditional market research is based around the analysis of three key aspects: the potential customers; the product/service; and the competition. It aims to identify a specific problem faced by a broad group of people ('*the customers*') and to match this with a potential solution ('*the product/service*'). Market research should identify, quantify and characterise '*the customers*' and compare the ability of '*the product/service*' to match their needs and aspirations with alternatives ('*the competition*') [6]. This paper positions rural people without access to electricity as '*the customers*', small scale wind power and the energy services it enables as '*the product/service*' and alternative power generation technologies, such as solar PV, hydro, diesel or the national grid, as '*the competition*'. Of course, these technologies can also be complementary to small wind in the form of hybrid or grid-tie systems.

Data collection for market research can be categorised into two types [7,8]:

1. Primary: collecting data directly from '*the customers*' and other relevant stakeholders, e.g. surveys, interviews, focus groups, observation and field trials [9]; or
2. Secondary: data collected by others, e.g. statistics, reports, related studies.

The analysis of this data should be undertaken with the end goal of constructing a reasoned argument for the recommendation of a particular solution/s [5,8,10] – in this case, whether small wind is a good fit for that particular context or not.

1.3. The development of the Wind Empowerment Market Assessment Methodology (WEMAM)

Locating, characterising and assessing the impact of the multitude of interrelated contextual factors that influence the viability of SWTs in any particular context requires a transdisciplinary methodology that connects across scales. For example, it must be able to bring together detailed case study findings from individual projects with broad spatial analyses of the most influential factors across the entire country to pinpoint the most viable locations. It must also be firmly connected to the reality on the ground, rather than abstract academic theory.

In 2012, WISIONS and Green Empowerment commissioned a SWT Market Assessment (MA) to guide their future interventions in Nicaragua [11]. An initial literature review showed that whilst a significant body of relevant literature existed [12–19], no one methodology was able to combine both the breadth and depth required to answer the core research questions of:

- What role (if any) can SWTs play in the electrification of rural areas?
  - How and where should they be employed?
  - How could their dissemination be supported by targeted interventions?

In this context, breadth refers to both geographical scale and transdisciplinarity; whilst depth refers to the ability to fully explore the factors that are most critical to small wind in particular.

As a result, the Wind Empowerment Market Assessment Methodology (WEMAM) was developed and operationalised to identify where and how SWTs could play the biggest role in bringing sustainable energy services to remote off-grid regions. Wind Empowerment is an international association for the development of locally manufactured small wind turbines for sustainable rural electrification. WEMAM's first application was in Nicaragua, however, in 2014, USAID and Mercy Corps funded a SWT MA in Ethiopia, in parallel with a series of practical wind turbine construction courses [20]. Subsequently, in 2016, the Scottish Government and the University of Strathclyde supported a PV-wind hybrid system MA with a capacity building component implemented in partnership with Community Energy Malawi (CEM) [21].

WEMAM has evolved organically with each application, drawing in the skills and experience of the members of the Wind Empowerment association's Market Assessment Working Group (MAWG). The application and evolution of WEMAM in these first three national contexts is explored in this paper, however two further applications of the methodology have since been carried out, which will be explored in future publications. In 2017, WISIONS funded a global MA, which used MCDA (Multi-Criteria Decision Analysis) techniques to identify and rank nations with regions where scalable small wind electrification programmes could be developed ([22]. In 2018, WISIONS supported a PV-wind hybrid system MA in Nepal implemented in partnership with the Kathmandu Alternative Power and Energy Group (KAPEG).

1.4. Aims and objectives

This paper aims to inform the development of a multi-scalar, transdisciplinary methodology for identifying the niche contexts where small wind can make a valuable contribution to rural electrification. The objectives are:

- to carry out a critical review of existing market assessment methodologies;
- to break down WEMAM into its component parts;
- to reflect upon its practical applications to date; and
- to highlight opportunities where the methodology could continue to evolve.

2. Literature review

This section presents a review and analysis of the literature relating to market assessments for renewable energy technologies in a development context. The lack of common terminology proved to be one of the major challenges in selecting and comparing methodologies, since only a few of the studies explicitly referred to a "market assessment" to describe the applied methodology. As a result, a broad literature search

Table 1
Overview of 24 selected papers on market assessment for renewable energy technologies in the Global South.

References	Audience	Technological focus	Geographical scale	Disciplinary focus	Research design
[12]	Domestic policy makers & RE promotors	• CSP[a]	Regional (North Africa)	Technical potential, geo-spatial	STEPS - an evaluation tool for solar power plants 1. GIS mapping of topographical & meteorological conditions 2. Suitable sites identified using cost of energy
[23]	Policy makers	• Wind • PV • CSP • Hydro • Geothermal	Global (country level)	Technical potential, geo-spatial	1. GIS to identify available areas 2. Potential per area (resource intensity) calculated
[24]	Domestic policy makers, national planners	• Grid extension • Mini-grids • SHS/PV • Hydro	National (Malawi)	Management, geo-spatial	1. Literature Review 2. RESVA (Rapid Energy Scenario Visualization Appraisal). Scenarios are defined based on potential regulatory/market force impacts and outcomes mapped in GIS and evaluated.
[25]	Policy makers, aid agencies, domestic decision makers, researcher	• Mini-grids • PV Lanterns • ICS[b] • LPG[c]	Africa	Social	1. Energy market systems mapping (market chain, inputs, services & finance, and enabling environment) 2. Identification & analysis of barriers & potential supporting interventions
[26]	Aid agencies, NGOs, domestic decision makers	• Any goods/services	National (regional variations within South Sudan)	Social	Market assessment manual; replicable in other African countries 1. Consumer Demand Survey 2. Market Opportunity Survey (businesses) 3. Youth Skills Survey (receptivity to training and support)
[13]	Policy makers	• PV • CSP • Wind	Regional (EU, US, Japan, China, India)	Techno-economic	1. Techno-economic analysis 2. Market demand and supply factors (interviews)
[27]	Policy makers, researchers	• PV • Wind • MHP • Biogas • Diesel • Grid extension	National (Nigeria)	Techno-economic, geo-spatial	1. Splits country into regions best electrified by grid-connection or off-grid solutions based on existing infrastructure and population distribution 2. Investigates potential off-grid solutions based on LCOE
[28]	Aid agencies	• Food market	Global	Social	EMMA toolkit (market mapping): 1. Gap analysis 2. Market analysis 3. Response analysis (recommendations) Based on interviews and case specific information
[14]	Donors, government, aid agencies	• LPG & traditional biomass	Country (rural India)	Socio-economic	1. Energy-economic model 2. Women's opportunity cost (of collecting fuelwood)
[15]	Policy makers, aid agencies	• Renewable energy	Global	Social	Barriers framework and market potential 1. Literature survey 2. Site visits 3. Stakeholder interviews
[19, 29–34]	Aid agencies, domestic decision makers	• Any energy access context	Country (generic framework)	Social	1. Pilot studies; national statistics, consultations with key stakeholders 2. Indicators for a healthy energy access ecosystem index scored in three groups: finance, policy & capacity.
[16]	Domestic policy makers, system planners	• Grid Extension • Mini-grids • SHS	Sub-national (Northern Transkei region of South Africa)	Techno-economic, geo-spatial	Automated tool determines a weighted benefit index of providing electrification to a given community, evaluates whether the benefit score justifies grid extension. If not, assesses whether mini-grid or SHS implementation is most suitable.
[35]	RE project developers, government	• Off-grid hybrid wind-PV system	Community (Sonzapote, Nicaragua)	Techno/Socio-economic, geo-spatial	Resource assessment & matching with demand points using micro-scale optimisation model
[17]	Policy makers	• Solar thermal • Wind	State (Maharashtra, India)	Social	1. Stakeholder level survey 2. Identification & ranking of barriers
[36]	Policy makers	• Biomass (wood & crops) for heat & electricity	Community (Sherborne, Drax & Barnsley, UK)	Social	Participatory sustainability assessment framework 1. Barriers, drivers & issues of concern identified through focus groups & workshops 2. Multiple Criteria Decision Analysis
[37]	Donors, policy makers, aid agencies	• Off-grid PV • Off-grid diesel • Grid extension	Africa	Techno-economic, geo-spatial	1. Spatial electricity cost model 2. GIS mapping
[18]	Policy makers, national planners	• PV • Wind • Diesel • Grid extension	National (Vietnam)	Technical potential, geo-spatial	Exclusion zones established where implementation unsuitable, estimates total theoretical potential
[38]	International aid groups	• Rural electrification	Global	Management, political, financial	Identifies indicators characterising the enabling environment for rural electrification interventions, assign relative weights and ranks each country based on the weighted sum of indicators scores.

(*continued on next page*)

Table 1 (*continued*)

References	Audience	Technological focus	Geographical scale	Disciplinary focus	Research design
[39]	RE Project developers	• Solar Microgrids • Social Enterprises	Community (generic framework)	Social, business modelling	1. Site-specific feasibility study 2. Assess market potential 3. Business scale-up scenario modelling
[40]	Urban planners, government	• Grid connection • SHS • Solar Lanterns	Informal Settlements (generic framework)	Social	1. Stakeholder interviews 2. Identification and weighted ranking of alternative solutions 3. Identification of barriers and opportunities
[41]	Investors, governments	• Renewable Energy	Global	Management, policy	Discussion and evaluation of market, regulatory and business factors enabling RE growth in developing countries. Ranking of countries based on these factors
[42]	Policy makers	• Small wind	National (Kenya)	Management	Strategic Niche Management (SNM) and Multi-Level Perspective (MLP)
[43]	Rural electrification programme designers	• Small wind	Regional (Argentina and Falkland Islands)	Social, technical, management, political, economic	Socio-Technical Systems (STS), SNM and MLP.
[44]	Rural electrification project developers	• Small wind • PV	Community (generic framework)	Social, technical, economic, geo-spatial	MILP optimisation: 1. Gather characteristics of target community. 2. Three stage process to select most appropriate system design. 3. Final solution cost optimised.

[a] Concentrated Solar Power.
[b] Improved Cook Stoves.
[c] Liquefied Petroleum Gas.

was carried out using both academic and general search engines[1] Table 1 summarises the 24 peer-reviewed journal articles and reports that were selected for in-depth analysis. Whilst the majority focussed on solar and/or wind, the review encompassed a variety of renewable energy technologies, as well as general market assessment methodologies that are relevant to a Global South context.

This review has shown that whilst a significant body of relevant literature exists, there is still no direct equivalent to WEMAM. In terms of scale, whilst many of the selected studies were conducted at broad scales (global/regional/country/state), only three focussed in on a specific community and none combined the two scales. Methodologies with broader geographical focus tended to take a top-down, supply-led[2] approach, with technical potential and techno-economic considerations taking precedent. Conversely, community level assessments tended to take a bottom-up, demand-led, social focus. The literature was found to incorporate technical, economic, financial social, political, management and geo-spatial perspectives, with many combining approaches, e.g. techno-economic or socio-economic. However, none encompassed all perspectives or spanned across geographical scales.

Table 2 shows that the many of the techniques identified during the literature review could enhance WEMAM. Of particular note is the GMG Market Assessment Methodology Report [45], which presents a detailed review and summary of many other existing methodologies and tools. Each paper was characterised by its target audience, geographical scale, disciplinary focus and research design to distil the individual techniques used in each. Table 2 categorises them into data collection, processing and analysis techniques to facilitate comparison with the existing components of WEMAM.

[1] Search engines included Web of Science, Scopus, Google Scholar and Google. Search terms included "market assessment", "technical potential", "renewable energy" and "developing countries" (plus analogous terms, e.g. "market mapping", "market analyses", "market potential", "market research" "technical feasibility", "wind", "solar", "hydro", "biomass" and "bioenergy", "Global South", "development", "developing").

[2] Supply-led indicates the driving focus of the study is led by which energy resources may be available, whereas demand-led studies are driven by which energy services are required. This characterisation broadly aligns with the top-down vs bottom-up dichotomy commonly referred to in electrification planning methodologies.

Table 2
Decomposition and categorisation of the techniques employed in the 24 studies selected for detailed analysis.

Data collection techniques	Data processing techniques	Data analysis frameworks

• Interviews/focus groups[a]
  • Workshops[a]
• Geographical, technological and meteorological measurements, (e.g. topographical data, power performance or wind resource measurements)[a]
• National/regional statistics[a]
• Literature review[a]
• Surveys[a]
• Site Visits[a]
	• Techno-economic modelling
	  • Micro-scale optimisation[a]
	  • Energy systems modelling[b]
	  • Opportunity cost[b]
	  • Economic forecasting[b]
	• Resource assessment[b]
	• Geo-spatial modelling
	  • Exclusion zones[a]
	  • Rural/urban split[a]
	  • Technical optimisation[a]
	• Identification of:
	  • barriers and drivers[a]
	  • supply and demand factors[a]
	• Scenario planning[b]
	• Business modelling[a]
	• Benefit point allocation[b]
	• Policy analysis[a]
		• Market mapping
		  • Participatory market mapping[b]
		  • Participatory sustainability assessment framework[b]
		  • Energy access ecosystems[a]
		• Technical potential[a]
		• Socio-technical transitions
		  • Socio-Technical Systems (STS)[a]
		  • Strategic Niche Management (SNM)[b]
		  • Multi-Level Perspective (MLP)[b]

[a] Techniques already included in WEMAM that could be developed further.
[b] Techniques not yet included in WEMAM.

3. Breaking down WEMAM and identifying evolutionary opportunities

In this section, WEMAM is broken down into its component parts and opportunities for further development are identified at the end of each stage.

3.1. Key components of WEMAM

Table 3 breaks down WEMAM into three key components: evaluating existing local small wind initiatives; quantifying the potential local market for SWTs; and mapping the local small wind ecosystem. In each context, the methodology was shaped by the outputs specified by the commissioners of the study, the skills and experience of the team members, the time and resources available to carry out the study and the availability of relevant data (see Table 4).

3.2. Stage I: learning from existing initiatives

Learning from past experiences through case study research can offer valuable insight into both the generic and contextual factors that contribute to the success or failure of the technology. Based upon detailed case study research in Peru, Nicaragua, Scotland, Argentina and the Falkland Islands [43,46] and the collective experience of the 50+ members of the Wind Empowerment association, spanning 25+ countries, WEMAM is guided by the following tools. Table 5 offers a list of critical factors to evaluate, whilst Fig. 1 can guide a preliminary evaluation of a new place[3]

3.2.1. Local small wind initiatives

Identifying and evaluating local small wind initiatives can provide valuable insight into place-specific critical success factors. Successful delivery models that have the potential to be scaled up [47], can create a blueprint for Stage II. Studying similar technologies, such as PV, can also provide additional insight. Pilot projects to test out the viability of new or improved delivery models for small wind can provide valuable learning experiences.

In Nicaragua:

- Literature review on the unsuccessful efforts of an NGO (blueEnergy) to electrify the Caribbean Coast of Nicaragua using locally manufactured SWTs [4].
- Field visit to evaluate a blueEnergy/AsoFenix pilot project in the central highlands to determine whether the challenges on the Caribbean Coast had been overcome [48].
- Expert interviews with Nicaraguan solar PV suppliers who had also supplied SWTs.

In Ethiopia:

- No previous SWT projects identified.
- Pilot project to locally manufacture and install a 1 kW SWT at a small commercial centre was carried out building upon Mercy Corps' experience electrifying rural commercial centres with solar PV and generators.

In Malawi:

- Students for Malawi (SfM) interviewed about 5 SWTs built in Southern Malawi and planned for 3 more.
- Field visit to evaluate the 6 PV-wind hybrid mini-grids installed by the Government of Malawi (GoM) under the Solar Villages programme.
- Prospective case study of a typical Malawian community in a region predicted to have good wind and solar resources (Fwasani CBO in Kamilaza, Mzimba).

[3] Of course, the many trade-offs amongst factors cannot be represented on a simple flow chart – e.g. the threshold for '*are buildings close enough to link via a micro-grid*' is lower, the stronger and more consistent the wind resource is.

3.2.2. Data collection techniques

For the evaluations of the blueEnergy/AsoFenix and GoM pilot projects, interviews were conducted with each NGO and the Department of Energy Affairs, respectively. Project design, installation and evaluation reports were reviewed, and field visits were made to each community, consisting of interviews with end-users, community leaders and community technicians; questionnaires for end-users; and a field diary to record observations and photographic evidence.

For the prospective projects in Ethiopia and Malawi, wind resource data was collected, and end-user surveys were carried out to identify the most desirable energy services. An anemometer and datalogger were installed on potential SWT sites (which in Ethiopia also measured the load profile after installation) and surveys focussed on the current availability of energy services and willingness to pay for new and improved services.

3.2.3. Data processing techniques

The interviews, field diaries and surveys produced both qualitative and quantitative data. Qualitative data was transcribed/written up and coded thematically using the factors listed in Table 5. Quantitative data on user preferences and experiences was processed with basic statistical techniques. Technical data recorded by the dataloggers was used to carry out a wind resource assessment and construct load profiles. A techno-economic energy systems model was constructed for each community visited using the software, HOMER, either retrospectively for those under evaluation or prospectively for the pilot project and feasibility study in Ethiopia and Malawi respectively (further details in Stage II).

3.2.4. Data analysis framework

The '*ethno-engineering*' approach is an extrapolation of Socio-Technical Systems (STS) theory [49] that fuses social science with engineering. It is a useful tool for understanding the root causes of the success or failure of a particular SWT project or for designing more culturally-informed pilot projects. Ethnographic techniques identify the key issues, whilst engineering analyses focus in and objectively explore the technical implications of each one. Sumanik-Leary et al. [46] offers the following examples:

- Comparing how much the system costs the community in terms of both time and money, with the time-saving and economic opportunities new energy services enable.
- Determining where spare parts come from, how long they take to obtain (if they can be obtained at all), who is responsible for this and applying engineering supply chain analysis techniques.
- Leveraging local knowledge on the availability of renewable resources. For example, women who hang washing in sunny/windy places can guide the location of engineering equipment (e.g. anemometer and datalogger) designed to make objective measurements.

3.2.5. Case study results

3.2.5.1. Nicaragua. Carvalho Neves et al. [4] highlight the multitude of challenges facing SWTs on the Caribbean Coast of Nicaragua. These resulted in high frequency of failures (due to lightning strikes and a highly corrosive hot, humid, saline environment) and long repair times (due to the remote locations of the communities in this region and the low level of technical capacity). Each challenge has a potential solution; however, each solution has an associated cost (both economic and social). In this context, the modularity, low maintenance requirements and rapidly falling price of solar PV made it a more appropriate solution.

However, the case study of the Cuajinicuil pilot project showed that most of the barriers faced on the Caribbean coast could be overcome in the more favourable context of the central highlands with a more

Table 3
Comparison of the three principal stages of the WEMAM methodology.

Stage	KEY RESEARCH QUESTIONS	Data collection techniques	Data processing techniques	Data analysis frameworks	KEY OutPUTS
Stage I: Learning from existing initiatives	What are the critical success factors? Which solutions could be scalable?	Global experience • Literature review Local case studies • Interviews • Questionnaires • Observation • Project report review • Wind resource, power performance & load profile measurements Pilot projects & feasibility studies	Transcription & thematic coding Techno-economic energy systems modelling Basic statistical analysis	'Ethno-engineering' Socio-technical systems	Identification of scalable delivery models & critical success factors
Stage II: Quantifying & locating the potential market	How scalable are these solutions?	System design parameters: • System configurations • Component costs • Load profiles National datasets: • National statistics • GIS layers	Techno-economic energy systems modelling Geographic Information System (GIS)	2 stage techno-economic geo-spatial filter	Size & location of target market segments for each scalable solution
Stage III: Mapping the local small wind ecosystem	What are the key barriers preventing these solutions from reaching scale? What can be done to overcome them?	Expert interviews Literature review	Transcription & thematic coding Network mappin g Basic statistical analysis Policy analysis Barriers & drivers	Energy access ecosystem framework Socio-technical systems	Recommendations for targeted interventions

Table 4
Comparison of the components of WEMAM employed in each of the three contexts assessed to date.

Stage	NICARAGUA	ETHIOPIA	MALAWI
Stage I: Learning from existing initiatives	• blueEnergy's experience on the Caribbean coast • Evaluation of Cuajinicuil pilot project • Interviews of Nicaraguan PV suppliers on experience with SWTs	• Experience from partner organisation, Mercy Corps' previous PV projects • Pilot project carried out in parallel with market assessment	• Feasibility study for pilot project in Kamilaza • Evaluation of GoM[a] PV-wind hybrid projects • Evaluation of Students for Malawi SWT projects
Stage II: Quantifying & locating the potential market	• 2 stage techno-economic geo-spatial filter: • Energy services: • Community micro-grid • Output: • Location of most viable regions for PV & SWT community micro-grids • Quantification of potential sites	• 2 stage techno-economic geo-spatial filter: • Energy services: • Small commercial centre • Output: • Location of most viable regions for PV-wind, PV-generator or PV-wind-generator hybrid systems & generators	• 2 stage techno-economic geo-spatial filter: • Energy services: • Maize milling, egg-incubation, workshop & community micro-grid • Output: • Location of most viable regions for PV-wind, PV-generator, PV-wind-generator hybrid systems & generators • Quantification of population in each region
Stage III: Mapping the local small wind ecosystem	• Interviews with Nicaraguan rural electrification experts	• N/a	• Interviews with Malawian rural electrification experts

[a] Government of Malawi.

comprehensive technician training programme. If productive applications can be established to cover O&M costs and a manufacturing base set up to produce higher volumes of SWTs in the central highlands, then this delivery model has the potential to succeed. As a result, the Cuajinicuil project (with these assumptions) was used as the blueprint for Stage II, which tested its scalability across Nicaragua.

3.2.5.2. Ethiopia. A SWT was manufactured and installed at a commercial centre in Hadew in the Somali region to enable lighting, mobile phone charging and refrigeration. Wind speed data was recorded at two educational institutions and the commercial centre, however annual mean wind speeds at all sites were below 3.5 m/s. The commercial system at Hadew was modelled in Stage II to establish whether other regions might have sufficient wind resources to justify adding a 1 kW SWT into the generation mix.

Based upon the experiences of the pilot project, it was estimated that a small business producing 10 turbines per year would create approximately 3 jobs[4] and would increase the proportion of the value chain within Ethiopia from 50% to over 70%.

3.2.5.3. Malawi. Wind resource monitoring at the GoM PV-wind hybrid site and potential pilot project site both revealed monthly mean wind speeds below 2.5 m/s. The 6 PV-wind hybrid mini-grids installed by the Government of Malawi (GoM) in 2007/8 under the Solar Villages programme were scheduled for decommissioning. Whilst the projects functioned successfully in the beginning [50], poor quality equipment, a lack of wind resource, poor system design, inadequate financial planning, a lack of operator training and a number of other issues all

[4] More if a rural service network is established.

Table 5
Ideal conditions for SWTs - the most critical factors are shown in bold/italic. Adapted from Ref. [46].

Domain		Factor	Data sources
Enabling environment	Environment	* High wind resource (>4 m/s monthly average throughout the year) in the regions where people lack access to electricity. * Lack of environmental hazards (low frequency of dangerously high winds and lightning strikes; and cool, inert environment to prevent corrosion, overheating or contamination with dust/sand). * Solar or hydro resources that peak in the opposite season to the wind resource and cannot provide sufficient power generation throughout the year. * Flat plains with no trees or other obstructions (to cause turbulence, reduce wind speeds and necessitate individual site assessment). • Wind resource that peaks in the same season as traditional productive activities, e.g. dry season for farmers in need of irrigation. • High air density (cold, low altitude) for maximum power extraction and cooling of the generator.	GIS layers (wind resource, population, topography, climate), evaluations of previous projects, seasonal profiles for renewable resources
	Finance	* If there is insufficient access to capital for upfront costs, the potential for establishing energy-based enterprises should be high and/or innovative financing models such as pay-as-you-go energy metering should be available. * Targeted subsidies for providing maintenance services or wind resource assessment can be effective.	Interviews, evaluations of previous projects
	Capacity	* High level of awareness of SWTs and understanding of the technical advantages and disadvantages. * Freely available high-quality wind maps (validated with anemometry in the areas where SWTs are most viable, of high resolution and relevant to low hub heights).	Interviews, evaluations of previous projects, ease of obtaining high quality data
	Policy	* A realistic evaluation of the national potential for SWTs and a plan for how to achieve this potential, which forms part of national rural electrification strategy. * In complex terrain, individual wind studies should be supported for each new location. * Strong and consistent institutional support to foster the development of a strong small wind ecosystem, in particular the social infrastructure required for maintenance. • Product quality standards that ensure consumer confidence, but don't unnecessarily hinder manufacturers. • Government endorsement to build trust in SWTs. • Tax exemptions for imported SWTs, wind pumps, power electronics and batteries. • Favourable feed-in tariff to encourage grid-tied SWTs.	Policy analysis, interviews, topographical data, evaluations of previous projects, interviews
Supporting services		* Good transportation infrastructure that facilitates easy access to installation sites. * Consumer and industry associations that share knowledge between SWT market actors, giving them a voice in the policy arena. • Universities that are willing to collaborate with SWT market actors on research projects and offer relevant training. • Utility-scale wind farm developers willing to support SWT market actors with funds and experience. • Grid electricity available in a nearby town/city (if manufacturing centrally).	Interviews, policy analysis, GIS layers (road network & electricity grid plus planned extensions)
Market actors		* A variety of training and demonstration centres that can raise awareness of SWTs and empower community technicians/end-users. * A network of service centres capable of bridging the gap between the supplier/manufacturer and the community by offering technical support for SWTs at a local level. • A variety of construction material suppliers offering products relevant to SWTs (if manufacturing locally). • A variety of SWT manufacturers offering a range of products that are well matched to local needs. • A variety of SWT suppliers with regional branches in all areas where SWTs are viable, offering support for site selection and system design, as well as installation.	Interviews, locations of key actors
Community		* High level of technical knowledge available at a local level. * Highly motivated individuals to take on the role of community technician. * End-users with sufficient capital to pay for O&M costs or a willingness to use the electricity to generate sufficient revenue. • End-users that are willing to adapt their behaviour around wind resource availability. • Effective community governance structures that can oversee the successful delivery of small wind initiatives.	Interviews, observation during field visits, evaluations of previous projects, national statistics

contributed to the demise of these systems [51]. Whilst the capacity building and ownership elements of SfM's projects had seen positive results, they were also discontinuing their small wind activities due to inadequate wind resources.

Stage II aimed to determine if sufficient wind resources might exist in other parts of the country to support the priority energy services identified by the feasibility study carried out in Kamilaza: a community micro-grid and 3 productive applications (maize milling, egg incubation and a workshop).

3.2.6. *Evolutionary opportunities for WEMAM*

Evaluating previous projects and carrying out feasibility/pilot studies offered rich learning opportunities; however, it would be beneficial to place greater focus on development outcomes as key metrics of

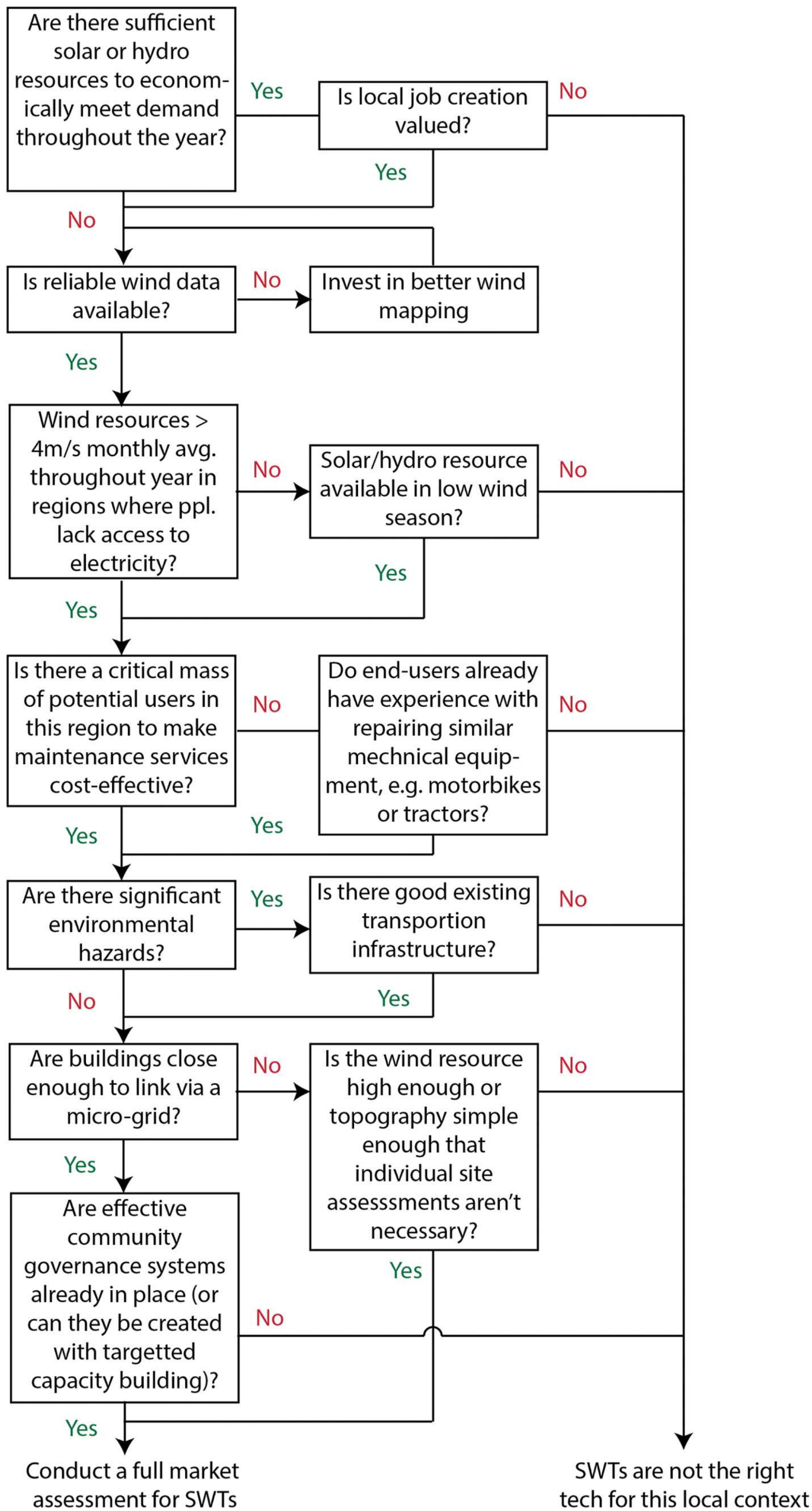

Fig. 1. Decision support tree for the identification of viable regions for SWTs [46].

success or failure. The broad range of multidisciplinary techniques employed yielded many measures to judge the success or failure of existing initiatives, however the majority were techno-economic, leaving scope for including a wider range of development outcomes [14,43,44,47]. For example, the Ethiopia and Malawi MAs explored the impact on livelihoods by estimating the number of jobs created through local manufacture/maintenance and focussed on productive uses of energy. However, this is still a top down approach to evaluating the social impact of small wind electrification programmes. Integrating participatory methodologies into Stage 1 of WEMAM could enable a bottom up evaluation of social impact that can empower rural people to evaluate the contribution that energy services delivered by small wind systems have made to their community. Promising examples of participatory methodologies include:

- Participatory Rural Appraisal [2], which enables rural people to examine their own challenges, set their own goals, and monitor their own progress towards them; and
- Participatory Sustainability Assessment Framework [36], which identifies barriers, drivers & issues of concern through focus groups & workshops.
- Eales' toolkits for evaluating the feasibility of social enterprise delivery models for solar mini-grids [39] and measuring social impact through a KPI framework [52].

Future MAs should carefully consider how to characterise each community within the area of interest to ensure that representative energy demand profiles are fed into the techno-economic optimisation. GIS based methodologies (e.g. 12, 23, 37) typically adopt a supply-led approach, focussing on identifying and quantifying what the economically optimal generation technology would be based on available resource and cost data. However, without an understanding of community-level demand profiles, there is a danger that important characteristics (such as resource-demand complementarity) could be ignored. The Malawi MA identified and assessed the viability of 4 popular energy services; however, it was assumed that they would all be equally attractive to all Malawian communities.

Effective community governance is another important consideration to ensure the longer-term sustainability of small wind initiatives, in particular for community micro-grids [39,40,53]. In particular, the experiences in Malawi highlight the need for strong leadership at both the community and programme management levels to be able to successfully navigate the challenges of implementing small wind projects in rural communities, such as lack of ownership and lack of capacity for financial planning. The most favourable contexts will already have well established community governance structures that small wind programmes be designed around, such as telecommunications and power cooperatives in Argentine Patagonia [43]. However, if they do not currently exist, they will need to be created. This could take the form of a village energy committee, which could oversee the work of local technicians and ensure the small wind system is delivering positive social outcomes for the community. In particular, blueEnergy's experience in the multi-ethnic communities of the Caribbean Coast of Nicaragua highlight the challenges of establishing effective governance structures in communities with low levels of cohesion. In contrast, blueEnergy's pilot project with AsoFenix in the central highlands took place in a much more cohesive community, which made the establishment of a village energy committee much easier.

The dichotomy of supply-versus demand-led approaches to electrification assessments arises primarily due to the availability of data at different scales. An MA matches a product/service (energy services enabled by small scale wind power) with a customer (rural unelectrified households), therefore a thorough understanding of the customers' demand is necessary. There is a huge amount of diversity within and between communities, which detailed methodologies such as [36,39,54] are designed to capture. They analyse specific communities with demand surveys, datalogging and other primary data collection techniques. However, to individually assess the demand of all communities in a particular country at this level of detail would far exceed the resources available for most national small wind market assessments.

Community archetypes (dispersed pastoral, clustered agricultural, etc.) could be developed and paired with appropriate small wind systems (water pumping, maize milling, community mini-grid, etc.) based upon detailed primary research in a community of each type. In Stage II, national statistics on population distribution and key livelihoods could then be used to identify similar communities across the area of interest, enabling the extrapolation of the anticipated demand for the communities visited to other similar settlements [43].

3.3. Stage II: quantifying and locating the potential market

This stage aims to assess the scalability of the promising delivery models identified during Stage I. In Nicaragua, this was the community mini-grid pilot in Cuajinicuil; in Ethiopia, the pilot at a commercial centre in Hadew; and in Malawi, the 3 productive applications and a community micro-grid from the feasibility study in Kamilaza.

In addition to the spatial variability of renewable resources, many other place-specific factors also affect the viability of SWTs. For example, the state of existing transportation infrastructure has a huge influence on installation and maintenance costs, whilst the off-grid population size is a major determinant of market size. To evaluate these spatially varying constraints, a Geographic Information System (GIS) model can be constructed. A techno-economic model of each energy system and a sensitivity analysis was carried out in HOMER on the key spatially varying parameters, which fed into a geo-spatial analysis to assess the viability of these systems across each country.

3.3.1. Data collection techniques

Table 6 compares the type of data collected in each country to evaluate each factor in Stage II of the analysis. The spatial resolution of GIS analyses is often limited by the spatial data source with the lowest resolution. In Nicaragua, much of the data was taken from the most recent population census, which was conducted at the municipal level. In Ethiopia, high resolution GIS layers were available, however, to simplify the analysis, the country was divided up by a 30 km grid. In Malawi, a variety of high resolution (<1 km) GIS layers were available and a much more detailed GIS analysis was carried out.

3.3.2. Data processing techniques

A techno-economic model of the blueprint energy systems was constructed in HOMER, based upon the quantitative data (energy resources, energy demand, component costs, etc.) obtained from project reports and field visits. The software calculates the power generated by each source and the power demand from the loads on an hourly basis, enabling the visualization of both the flow of energy through the system and the cash flow throughout the system lifetime. In Nicaragua, the Levelised Generating Cost (LGC) was used to directly compare between generation sources, whilst in Ethiopia and Malawi, the Net Present Cost (NPC) was chosen to identify the lowest cost system architecture capable of meeting a given load.

HOMER can compare a variety of technical, social and economic scenarios in sensitivity analyses. For example, Fig. 2 compares optimal system architectures across the range of wind and solar resources typically found in Nicaragua. Similar plots were produced to model the influence of other key issues, such as the falling price of solar PV and community technician training strategies[5] Comparable HOMER models were constructed to investigate the influence of scale (100 W, 1 kW and

[5] More training increases initial capital costs but leads to fewer visits by engineers out to the community and therefore lower O&M costs, especially for remote sites and unreliable technologies such as SWTs.

Table 6
Data collected to evaluate each factor in Stage II of the market analysis in each country. Full lists of data sources available in country reports [11,20,21].

Factor	Nicaragua	Data sources	Ethiopia	Data sources	Malawi	Data sources
	Data collected		Data collected		Data collected	
Component costs	• Cost breakdowns for SWT materials & manufacturing, energy system components, installation & O&M	• Actual costs from Cuajinicuil pilot project • Quotes from Nicaraguan & overseas RE suppliers	• Cost breakdowns for SWT materials & manufacturing, energy system components, installation & O&M	• Actual costs from Semera & Jijiga pilot projects • Quotes from Ethiopian RE suppliers	• Cost breakdowns for SWT materials, energy system components, installation & O&M	• Actual costs from project reports • Quotes from Malawian RE suppliers • Malawi Bureau of Land • Field visits • Expert interviews
Scale	• Modelling 100 W, 1 kW and 10 kW energy systems	• As above	• 1 kW scale only		• 1 kW scale only	
Place of manufacture	• Comparison of local manufactured SWTs with imported SWTs	• As above	• Only locally manufactured SWTs & imported PV		• Only locally manufactured SWTs & imported PV	
Existing transportation infrastructure	• Population density per municipality • Actual journey costs for remote/near sites • Locations of existing service centres	• National census • Interviews	• Population density map • Actual journey costs for remote/near sites	• IRENA Global RE Atlas • Interviews	• Petrol station locations • National fuel price • Land use, topography & road network GIS layers	• Field visits • Expert interviews • Publicly available GIS layers • Malawi Bureau of Land
Energy access	• Map of existing national grid and diesel mini-grid infrastructure • % with grid access per municipality	• ENEL (National Utility) • National census	• Map of existing national grid infrastructure	• IRENA Global RE Atlas	• GIS layer of existing national grid infrastructure	• National Roads Authority (high voltage) • Dept. Rural Affairs (Low voltage)
Protected areas	• N/A		• Protected areas map	• IRENA Global RE Atlas	• N/A	
Civil unrest	• N/A		• Overseas travel advisory	• FCO	• N/A	
Renewable resources	• Map of existing hydroelectric installations and sites with proven resource • Solar resource map • Wind resource maps • In situ wind resource measurements (secondary data)	• MEM • ENCO • UNEP/SWERA • UNI • UCA • blueEnergy	• Hydro resource map • Solar resource map • Wind resource maps • Land use map (obstructions for wind flow) • Altitude (air density) • In situ wind resource measurements at pilot sites (primary data)	• Various datasets from IRENA Global RE Atlas • Datalogging in Jijiga & Semera	• Land use, topography & solar/wind resource GIS layers. • Site specific wind resource measurements.	• Publicly available GIS layers • In situ wind resource measurements at pilot sites (primary data)
Energy demand	• Load profile	• Cuajinicuil micro-grid	• Load profile	• Commercial centre in Hadew	• 4 load profiles	• Kamilaza feasibility study
Ability & willingness to pay	• % living in extreme poverty per municipality • Baseline household expenditures on energy in Cuajinicuil	• National census • Cuajinicuil project reports	• Baseline household expenditures on energy at pilot sites	• Household surveys in Jijiga & Semera	• Poverty level GIS layer • Household/business questionnaires	• Publicly available GIS layers • Household & business surveys
Population	• Population per municipality	• National census	• Population per municipality	• IRENA Global RE Atlas	• Population distribution GIS layer	• Publicly available GIS layers

10 kW) in Nicaragua and, to investigate the four different energy services (mini-grid, egg-incubation, workshop and maize milling) in Malawi.

Geo-spatial modelling software, such as ArcGIS or QGIS, can extend the techno-economic analysis from HOMER across the whole country by taking into account the spatial variation of the variables tested during the sensitivity analysis. Table 7 and Table 8 show how a combination of HOMER, Excel and ArcGIS, linked together with Python, was used to evaluate the influence of each of the key factors in the latest application of WEMAM in Malawi.

3.3.3. *Data analysis framework*

Fig. 3 shows the data analysis framework for WEMAM, which enabled the location and quantification of the market for SWTs in Malawi. It is based upon the assumption that where available, grid connection would always be the preferred option. It doesn't yet specifically evaluate hydropower, as the resource assessment process is quite different to wind/solar. Similar frameworks were employed in Nicaragua and Ethiopia, with the former using LGC as the key comparative metric to directly locate and quantify the markets for wind and solar; and the latter extending this to hybrid systems and generators to locate, but not quantify the market.

3.3.4. *Case study results*

3.3.4.1. Nicaragua. Fig. 4 shows that in Nicaragua, the distribution of the wind resource (high in the central highlands and on the Southern Pacific coast) does not match well with the location of people without access to grid electricity (mainly in the Northern regions and on the Atlantic Coast). The potential market for 1 kW scale community micro-grids powered by SWTs in Nicaragua was estimated at 12,949 people, 2590 households, or 185 systems focussed in 11 municipalities in the Southwest and central highlands. The topography in the Southwest is generally flat and open, but most are already grid connected, whilst in the central highlands, grid access is lower, but the terrain is hilly and forested, greatly reducing the probability that communities will have access to a suitable site for an SWT. As a result, this is as a very optimistic estimation of the market size.

3.3.4.2. Ethiopia. In the Somali region in Southeast Ethiopia, both the

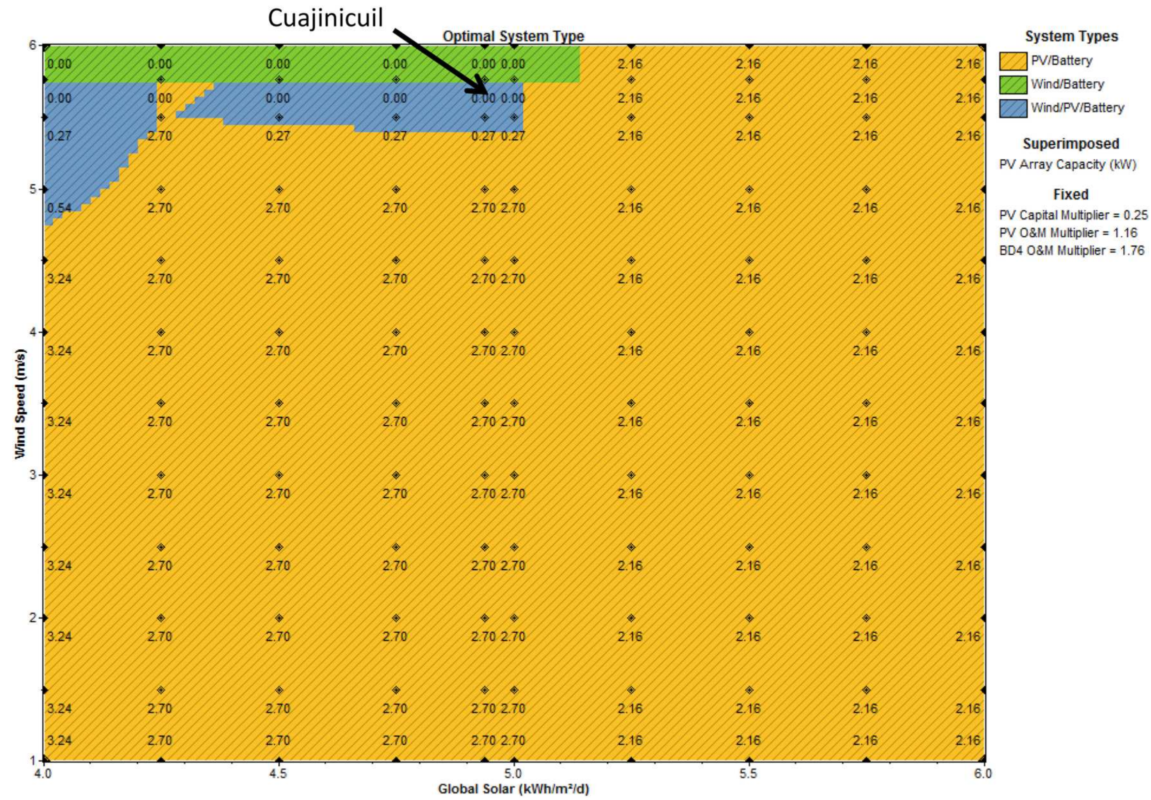

Fig. 2. Two dimensional plot of optimal system architectures for community micro-grids in Nicaragua based on the 'worst case scenario' for wind in all other parameters [11]. Locating Cuajinicuil on this diagram using the actual wind/solar resources available in the community show that a hybrid system with a 1 kW SWT and 0.27 kW PV is the least cost option. However, for most communities, PV only systems are cheaper, as indicated by the predominantly yellow colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

wind and solar resources are high (>4.5 m/s and >6 kWh/m^2/day respectively) and the topography is flat and open. Fig. 5 shows that across most of Ethiopia, PV systems with a generator backup are the most cost-effective option for off-grid electrification of 1 kW scale commercial centres. However, in the Somali region, which is predominantly open grassland with few obstacles to create shelter or turbulence, PV/wind/generator hybrids are optimal. After some preliminary on-site measurements have verified the wind resource, it may be possible to install further SWTs without subsequent in-situ wind resource measurements, greatly increasing the speed of implementation and reducing risk and upfront investment.

3.3.4.3. Malawi. In Malawi, four systems were modelled, however only the micro-grid showed any potential for PV-wind hybrid systems. Fig. 6 clearly illustrates that whilst the PV-generator system architecture is scalable across the whole country, the PV-wind-generator system architecture is only optimal in a few isolated pockets. However, Table 9 shows that just 7% of the population live within these pockets and even within these areas, it is a marginal result, indicated by the speckled green patches rather than larger areas of solid colour. This would mean introducing significant additional risk into off-grid electrification projects, as even if a costly and time consuming full wind resource assessment is properly carried out, then there is no guarantee that the on-site measurements will find sufficient wind resources to justify the installation of a PV-wind hybrid system. This is exemplified by the findings from the dataloggers installed during the Malawi MA, which despite being located in supposedly high wind regions, found monthly average wind speeds of <2 m/s at 10 m height.

3.3.5. Evolutionary opportunities for WEMAM

Whilst the techno-economic geo-spatial modelling conducted in each country has been able to locate (and for Nicaragua and Malawi, quantify) the local market for SWTs, significant assumptions were made, limiting the validity of the findings. Lack of data was a major issue, limiting not only the way in which each factor could be evaluated, but also completely eliminating certain factors from the analysis.

Market size estimations could be improved by classifying populations that are best suited to standalone systems, mini-grid systems or grid extension. Obtaining up-to-date national grid maps is often a challenge, especially for low voltage distribution lines and planned extensions. As a result, WEMAM currently assumes that anybody within a certain distance from known transmission infrastructure is electrified. This also does not reflect the reality of those who live '*under the grid*' [34]. To determine current electrification status, it is possible to use night time light pollution satellite data, combined with population distribution data to separate electrified and unelectrified populations [55]. Households that are close to currently electrified areas and (if data on planned grid extensions is available) areas soon to be connected, should be considered separately from households that are far from it to allow for analysis of future scenarios where grid extension may have connected them.

Further discussion and sensitivity analysis on the available wind data is needed, as the results of this analysis are highly dependent on quality of the wind map used as an input. Global wind speed maps are available at 1 km resolution [56], but at a community scale, micro-siting issues require much higher resolution data. Validation through ground measurements are necessary before any implementation projects, especially in complex topography, e.g. mountains.

WEMAM should focus on PV-wind hybrids and expand to other renewable resources. PV-wind hybrid systems were included in the Ethiopia and Malawi MAs and should be in all subsequent studies, as the continually falling price of PV modules has made it an valuable

Table 7
The techniques used to process the data for each factor taken into account by WEMAM in Malawi [21].

Factor		Software
Component costs & system architectures	System architectures from Kamizala feasibility study costed using previous project reports. Road network used to estimate transport costs for installation & maintenance.	Excel, HOMER
Diesel price	Local diesel price calculated by adding cost to transport fuel to remote communities.	HOMER, QGIS
Energy demand	Actual energy demand in Kamilaza (Fwasani CBO) estimated using questionnaires. Traditional productive activities matched with appropriate energy services. Population distribution used to calculate market size.	Excel, HOMER, QGIS, Kobo Toolbox
Electricity access	Population with access or soon to gain access to national grid excluded from market size for off-grid systems.	QGIS
Solar & wind resources	Spatial variation of solar & wind resources (18 m height) from mesoscale modelling fed into optimal system map using HOMER modelling results. Land use & topography used to assess difficulty of making local resource assessments. Surface roughness from land use used to convert wind resource different heights. Python scripts used to investigate complementarity on different timescales. Site specific data used to validate mesoscale modelling.	QGIS, HOMER, Python, Excel
Ability & willingness to pay	Questionnaires used to assess current energy expenditures, willingness to pay for energy services. Spatial analysis of poverty levels used as indicator of ability to pay.	QGIS, Kobo Toolbox

Table 8
Custom GIS layers created for the Malawi study and the key input data used to create them [21].

Filter	Custom GIS layer name	Key input data
Optimal system architecture filter	4x 'Optimal system architecture layers'	• Output file from HOMER simulations of 4 load profiles • Solar resource GIS layer • Wind resource GIS layer • Diesel price GIS layer
	'Diesel price layer'	• Petrol station location GIS layer • Road network GIS layer • Land cover GIS layer
Market size filter	'Grid proximity layer'	• PDFs of existing and planned power lines (converted to a GIS layer)
	4x 'Off-grid market size layers'	• Population distribution GIS layer • 'Grid proximity layer' • 4x 'Optimal system architecture layers'
	'Ability to pay layer'	• Poverty distribution GIS layer • Population distribution GIS layer • 'Grid proximity layer' • 4x 'Optimal system architecture layers'

compliment to an SWT on almost any site [1]. Competition or complementarity with other off-grid technologies, such as micro-hydro or biomass gasification, should also be considered in regions with appropriate resources.

Site accessibility should be considered in greater detail, to account for logistical costs during installation and maintenance. Specifically, 'benefit point allocation' would allow an evaluation of the benefit associated with installations at specific sites [16,57].

A broader range of energy services and scales of SWTs should be evaluated and matched to local community archetypes. Community micro-grids were the focus of the study in Nicaragua (which excluded small businesses), whilst small businesses were the focus in Ethiopia (which excluded community micro-grids) - only in Malawi were multiple delivery models studied. However only in Nicaragua were different scales of SWTs considered.

Whilst national studies can locate and quantify potential markets, they should be followed up by local studies in the regions of highest potential. In particular, further detail should be gathered on ability to pay and locally appropriate delivery models that can enable financially sustainable and replicable initiatives to be set up. In Nicaragua, the assumption that people living in extreme poverty were not able to pay for the high O&M costs of SWTs counteracted Wind Empowerment's aim of alleviating poverty. In Ethiopia and Malawi, the focus shifted to productive applications that enhance local livelihoods. However, it is important to also assess the availability of innovative financing mechanisms such as pay-as-you-go, the opportunity to displace expenditures on kerosene, batteries and other energy products and the viability of enhancing existing or creating new livelihoods. For community micro-grids, community governance and cultural differences within or between communities are particularly important issues. Environmental hazards, such as lightning (amplified on hilltop sites) and corrosion (vastly accelerated on coastal sites), must also be evaluated at a local level.

Finally, scenario modelling should be carried out to project the market size and distribution for a range of different future pathways that could be created by strategic interventions. This could be enhanced by breaking down the results by sub-national administrative regions, as in the Nicaragua MA, which would help focus interventions by local or national government entities.

3.4. Stage III: mapping the small wind ecosystem

Practical Action [30] described the interrelated network of organisations and contextual factors that enable or constrain the delivery of energy services in a particular place as an '*energy access ecosystem*'. In both natural and business ecosystems, "co-evolution and collaboration, as well as competition" are recognised as the drivers of healthy ecosystems [31,58]. By understanding the ecosystem in a particular place, the most effective "*pathways for action*" [29] can be identified.

The primary output of this stage is a series of recommendations for targeted interventions designed to strengthen the small-scale wind ecosystem. This is achieved by first developing an in depth understanding of the current state of the ecosystem, then by identifying the key barriers preventing further action. It is important to distinguish between insurmountable barriers (e.g. lack of wind resource) and those that could be overcome by targeted interventions (e.g. poor wind resource mapping). If Stage II has identified a sizeable potential market, then these targeted interventions can create a pathway to facilitate the development of the market.

3.4.1. Data collection techniques

Both primary and secondary data collection can offer insight into the roles of different actors: interviews, focus groups, surveys and questionnaires can be complimented by a literature review of secondary sources, such as local/national policies and practitioner reports. In all three countries, a series of semi-structured interviews were conducted

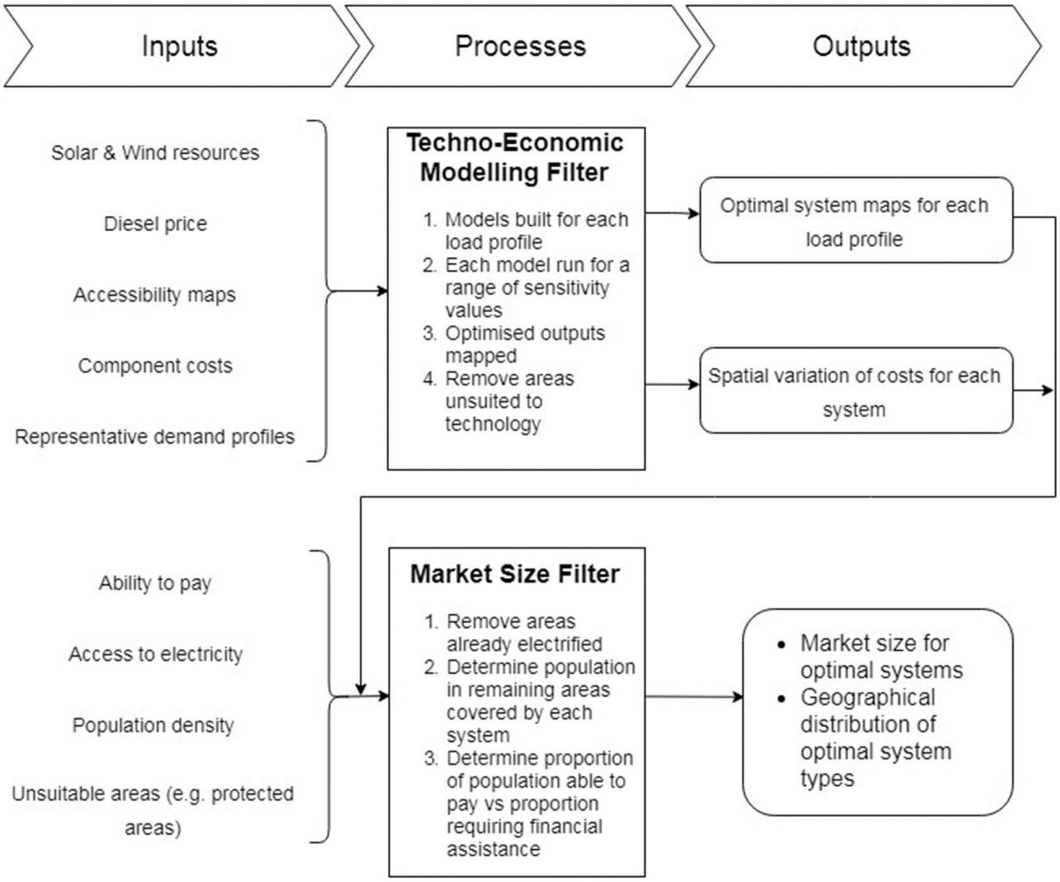

Fig. 3. The two-stage filtering process used to determine the size and location of the market for PV-wind hybrid systems.

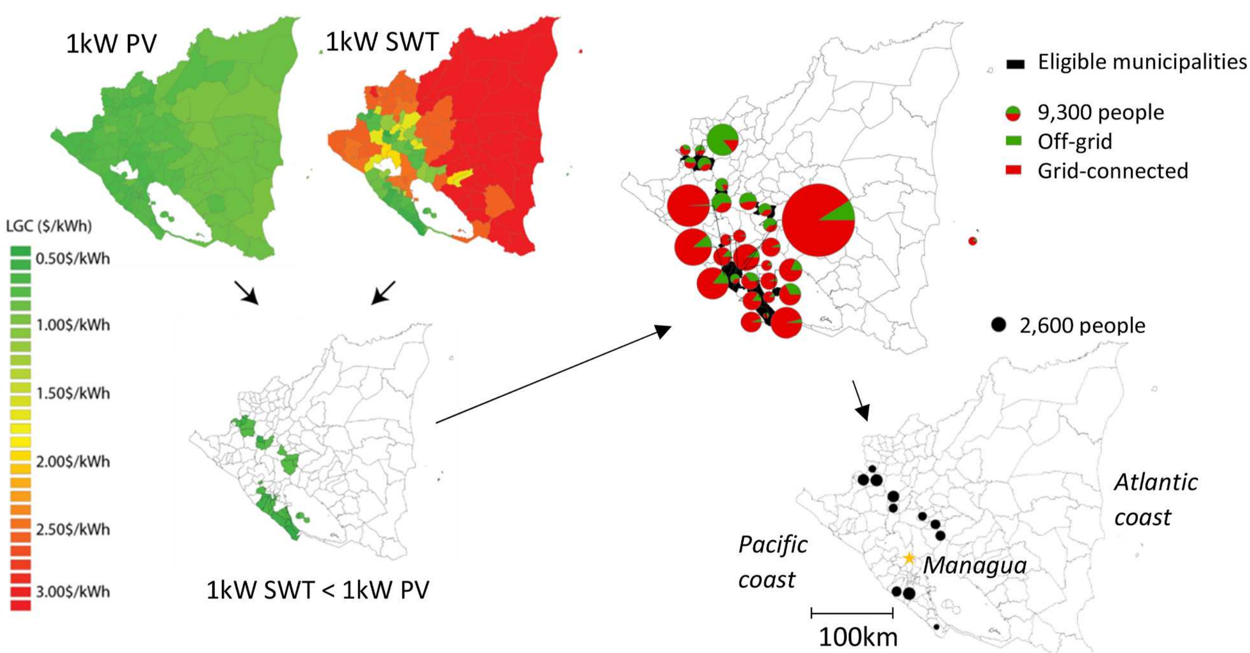

Fig. 4. GIS output plots of Nicaragua showing the WEMAM Stage II methodology. Firstly, typical LGCs (Levelised Generating Costs) of 1 kW scale wind and solar systems were calculated in each Nicaraguan municipality (top left), to identify the municipalities where wind has a lower LGC (bottom left). People with grid access are subtracted from the total population (top right), as are those with low ability to pay (represented by extreme poverty) to leave the total estimated market size in each municipality (bottom right). Adapted from Ref. [11].

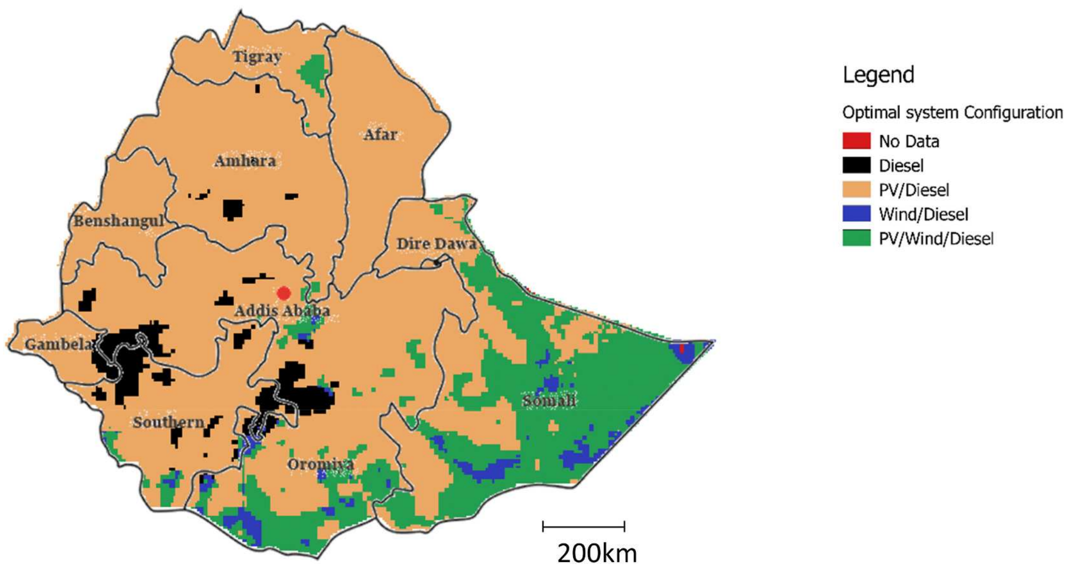

Fig. 5. Optimal off-grid small scale renewable energy system configurations in Ethiopia. Adapted from Ref. [20].

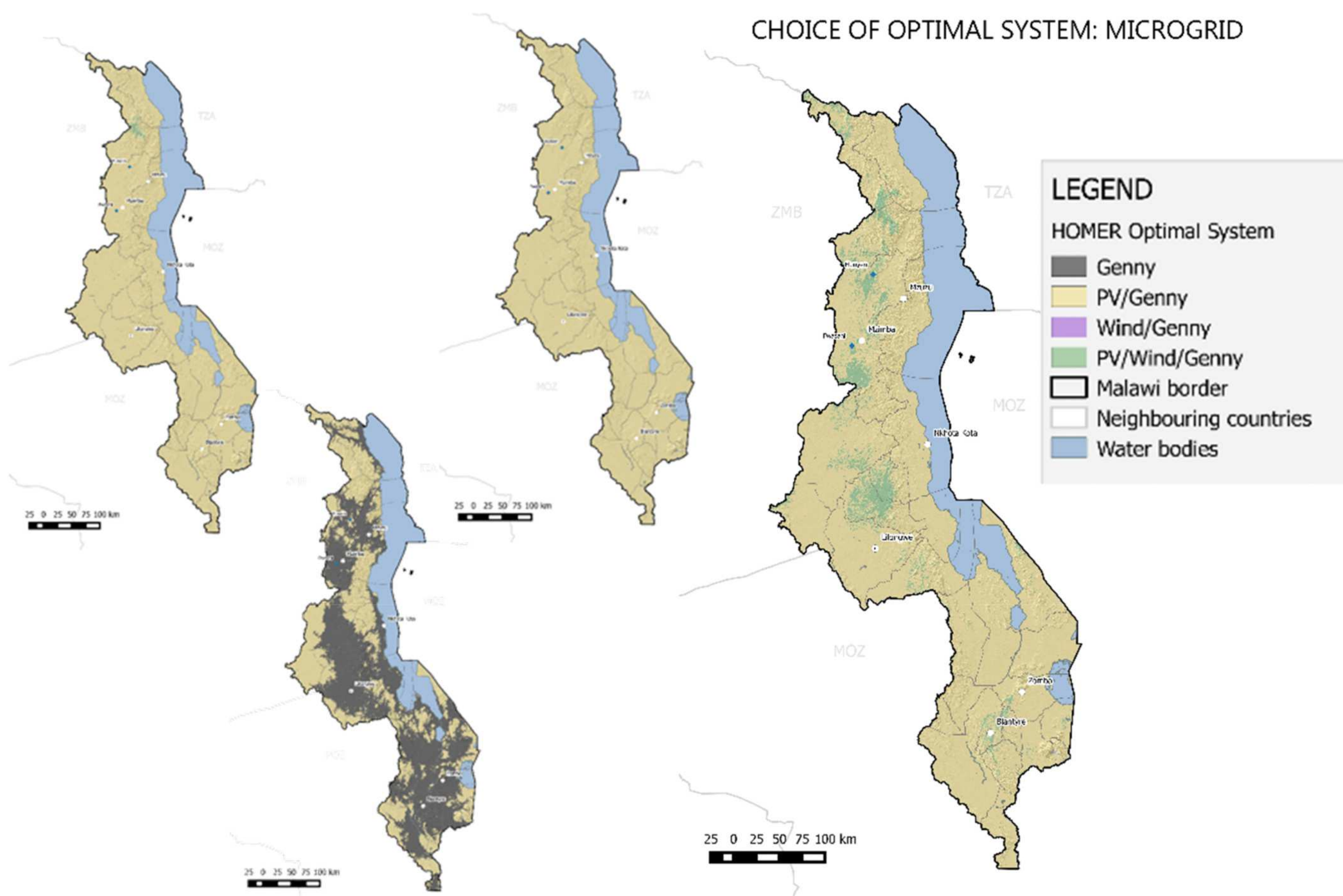

Fig. 6. Optimal system architecture maps for the four applications modelled in Malawi: micro-grid (right), workshop (top left), egg incubation (top middle) and maize milling (bottom left). Adapted from Ref. [21].

with local wind power experts from a variety of sectors, notably academia, NGOs, private sector and government (see Fig. 7). During the interviews, informants were first asked about their activities in the small wind sector, then to identify which areas of the country have highest potential, compare small wind to alternative options and identify the key barriers preventing its wider dissemination.

3.4.2. Data processing techniques

Transcription and thematic coding combined with network mapping can cut across and pull together the vast amounts of qualitative data

Table 9
Estimated market size in off-grid regions as a percentage of the total population of Malawi for each load profile category and each system architecture [21].

	MINI-GRID	WORKSHOP	MAIZE MILLING	EGG INCUBATION
GENERATOR	0%	0%	71%	0%
PV/GENERATOR	79%	86%	15%	86%
WIND/ GENERATOR	0%	0%	0%	0%
PV/WIND/ GENERATOR	7%	0%	0%	0%
GRID-PROXIMITY	14%	14%	14%	14%

obtained during this stage of the market assessment. Spatial mapping of the locations of each actor can support understanding of the market system, as long and unreliable supply chains are expected.

3.4.3. Data analysis framework

Fig. 7 Illustrates the most important elements and interactions in a small wind ecosystem. This framework can act as a guide for.

1. Identifying informants - key actors are in circles;
2. Thematic coding – interactions (black text), factors (square boxes) and their groupings (environment, capacity, policy, finance) can be key themes; and
3. Network mapping - Fig. 7 is a generic a template.

[46] Offers a full explanation of each of the elements within this framework, illustrated by case study work in Peru, Nicaragua and Scotland.

3.4.4. Case study results

3.4.4.1. Nicaragua. Using the ecosystem mapping to extend the findings from the previous stages suggests that the Atlantic coast is not the right context for SWTs, as it has the lowest wind resource, most severe environmental hazards (lightning, corrosion, hurricanes) and lowest accessibility (hindering access to maintenance services). The central highlands offer greater accessibility, superior wind resource and a more benign environment, suggesting that there could be a small localised market for hybridising community micro-grids if more comprehensive training for community technicians can be delivered.

However, the expert interviews suggested that there is a lack of technical capacity for SWTs in Nicaragua and a negative perception of the technology due to the lack of successful installations. SWTs have

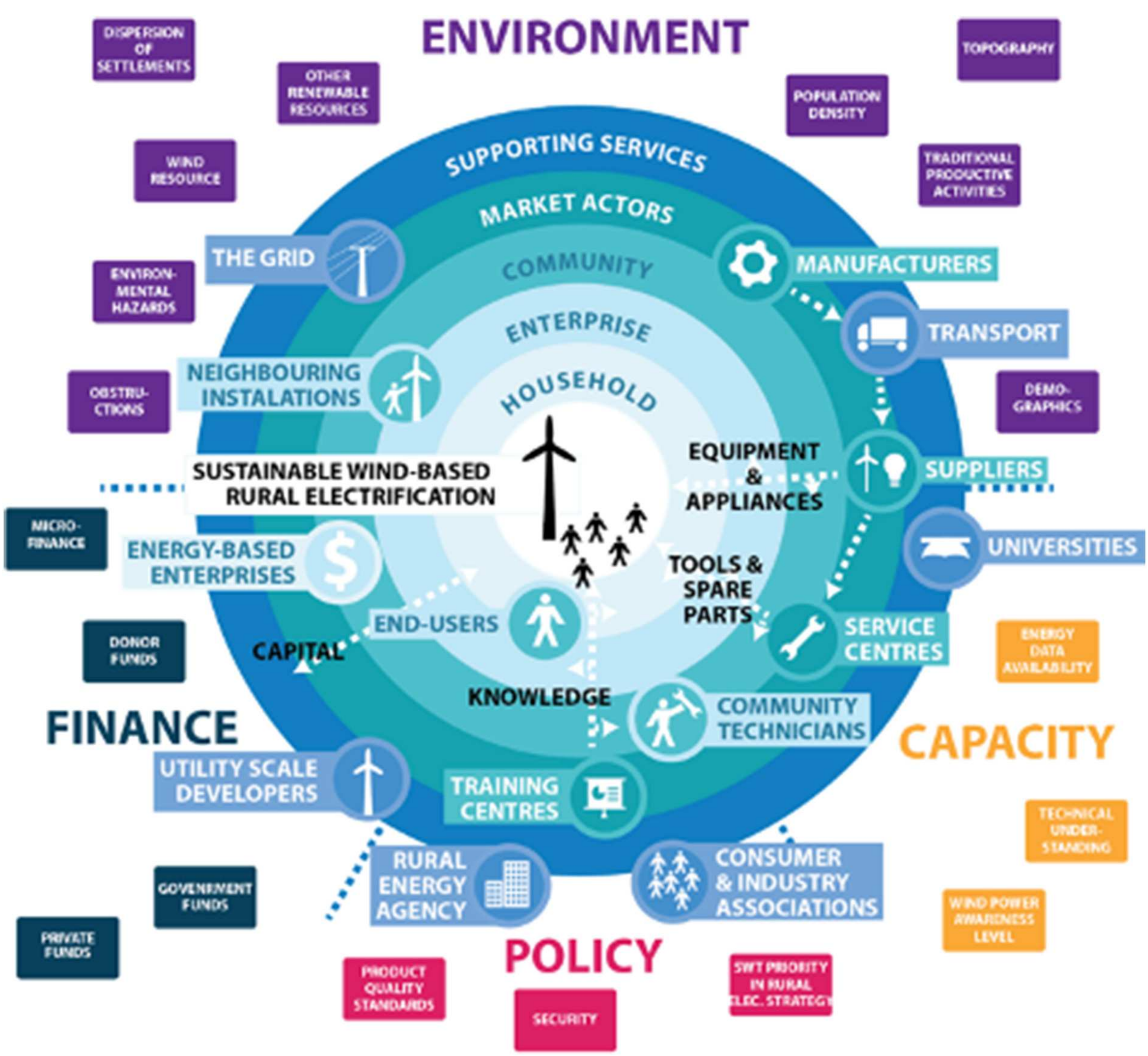

Fig. 7. Graphical representation of the elements that make up the small wind ecosystem and the interactions between them. Adapted from Ref. [30] by Ref. [46].

been able to 'piggy-back' on the development of the Nicaraguan solar industry, as many system components are the same. Unfortunately, as a result, the only actors offering maintenance services for SWTs are based in non-windy areas. The wind resource is more difficult to assess than solar, so SWTs have been installed on sites with little wind and left in a state of disrepair after their first failure. Key enabling interventions include improving the quality of wind maps; offering technical/financial support for individual site assessments; targeted awareness raising in windy areas with a critical mass of potential users; and technical training on wind resource assessment and SWT maintenance for local solar suppliers, specifically in their branches in these high potential regions.

3.4.4.2. Ethiopia. The most viable region for SWTs in Ethiopia, the Somali region, has high solar resource, low population density, no access to grid electricity, high levels of civil unrest and poor existing transportation infrastructure. These factors present both significant opportunities and challenges for the implementation of SWTs, in particular with regards to maintenance. Hybridising with PV and generators can mitigate this to some degree, however, sites selected for SWTs should be within one day's travel (round trip) from where maintenance services are available and on-site personnel should be trained to carry out regular preventative maintenance. In the longer term, a network of service centres could be established to extend the geographical reach of the initiative.

The main arguments to justify the implementation of this more challenging technology are the potential for local capacity building and economic development. The service centres would also create additional jobs and feed money back into the local economy in a remote area, where such benefits are likely to be highly valued.

3.4.4.3. Malawi. In Malawi it was found that the potential for job creation, capacity building and strengthening of the local economy are certainly strong drivers for small wind, however the fundamental lack of wind resource creates an insurmountable barrier. What is more, although many SWT components can be sourced locally, Malawian industrial capacity is relatively limited, so most are likely to have originated from an overseas supplier. The evidence showed that the wind resource in Malawi is much more variable than solar and the two resources show limited complementarity. The development of additional a small wind service network can only be justified where there is a significant local market, however the scattered nature of the wind resource in Malawi means that the few potential customers are spread all over the country.

However, the study highlighted that solar PV has an extremely high potential for meeting the energy needs of rural Malawians, yet to date, has had limited success in Malawi. Low ability to pay, market distortion by NGO handouts, lack of ownership, little existing technical capacity and maintenance issues relating to battery storage were found to be the principal barriers holding back further market expansion. Pay-as-you-go business models, community energy committees and energy kiosks in remote communities are promising potential solutions to some of these issues, however no truly sustainable model has yet been proven.

3.4.5. Evolutionary opportunities for WEMAM

The small wind ecosystem framework offered a structured approach to analyse the strengths and weaknesses of the network of actors present in each local context. However, it could be improved by incorporating a number of complementary approaches, notably participatory market mapping, Multi Criteria Decision Analysis (MCDA) and socio-technical transitions theory.

The participatory market mapping approach [25,36] starts and ends at the same points as the small wind ecosystem framework - both begin with understanding the market system and end with targeted interventions to address specific barriers. A preliminary market mapping exercise aims to characterise the market system at three levels [25]: market chain; inputs, services and financial instruments; and political, socio-cultural and economic factors. It identifies key barriers, drivers and issues of concern by taking a more participatory approach including focus groups/workshops with a diverse range of key stakeholders from across the supply chain, including suppliers, customers, policy makers and investors. This approach is likely to be more effective in developing 'pathways for action', as the stakeholders who will need to take these actions will be directly involved in developing them.

Once the specific interventions have been identified, it would be beneficial to carry out a prioritisation, or ranking, to identify those with greatest benefit-to-cost ratio. This could draw on the MCDA techniques applied by many of the reviewed studies [17,22,36,38,40,41].

Finally, socio-technical transitions perspectives have been designed to understand the processes that enable niche innovations to break through into the mainstream. Specifically [42,43], used Strategic Niche Management (SNM) and Multi-Level Perspective (MLP) to understand the small wind market systems in Kenya and Patagonia/the Falkland Islands (respectively).

3.5. Discussion

The combination of case study evidence (Stage I) with the quantitative and spatial estimates of market potential (Stage II) and the barriers identified during the expert interviews (Stage III) facilitated the triangulation of key research findings from multiple sources. For example, in Nicaragua, the identification of the central highlands as a potentially viable region for small wind was demonstrated by the success of the Cuajinicuil pilot project evaluated in Stage I, the identification of viable markets in some central highland municipalities by the techno-economic geo-spatial methodology in Stage II and the recommendation of this region by the wind power experts in Stage III. As a result, there is a high level of confidence in the overall conclusions of the study, i.e. that there is a small potential market in the central highlands, but on a national scale, the scalability of the technology is extremely limited.

Of the 3 MAs conducted to date, all identified significant barriers and only the Ethiopia study concluded that the time and effort required to overcome them could be justified, as there is potential for scalability.

1. In Nicaragua, the contribution that SWTs could make to rural development was extremely limited. The scalability of the technology was restricted most fundamentally by the scattered wind resource, which did not correlate well with off-grid areas. Significant time and effort would need to be invested to strengthen the small wind ecosystem through an extended programme of technical training, awareness raising, lobbying, further research and technology demonstration. In contrast, the decreasing cost and increasing availability of solar PV, coupled with its modularity, low maintenance requirements and the even distribution of the solar resource throughout the country now offers a much more attractive option.
2. In Ethiopia, small wind could potentially offer a scalable solution in the Somali region, which has a strong and evenly distributed wind resource. This is one of the most marginalised regions of one of the world's poorest countries and as a result, the value placed on local job creation is much higher. However, local technical capacity is also much lower and much less infrastructure exists. As a result, although the potential rewards are bigger, so too are the challenges.
3. In Malawi, whilst the potential for job creation, local capacity building and strengthening of the local economy are certainly strong drivers for small wind, the fundamental lack of wind resources in most of the country created an insurmountable barrier. The evidence showed that the wind resource in Malawi is also much more variable than solar and that the two resources have limited complementarity, again making solar PV the more attractive option.

WEMAM was implemented differently in each country. In Ethiopia, a much greater range of factors and sensitivities were included in Stage II, which was accompanied by a series of pilot projects. Whilst this gave much greater confidence in the outputs of this stage, the analysis in Nicaragua included a much broader range of techniques in Stage I and Stage III. This enabled a deeper understanding of the impact of previous projects and the state of the small wind ecosystem. However, as the pilot projects in Ethiopia were carried out in parallel with the market assessment, this enabled a more iterative process, with the preliminary findings from Stage I and Stage II informing each other, rather than the more linear path taken in Nicaragua where previous pilots were simply evaluated. In Malawi, a capacity building component was added, and all 3 stages were fully implemented, with Stage II expanded to model a range of load profiles for locally appropriate energy services.

Market assessments present a snapshot of a particular place at a particular moment in time, as markets are dynamic. Of particular note is the global downward price trend for PV. The simplicity and modularity of PV make it an ideal choice for remote off-grid applications, where capacity for maintenance is low, households are dispersed, and energy demand is low. Whilst the Nicaragua MA pitched solar against small wind, the Ethiopia and Malawi MAs embraced it as a complimentary technology. Future MAs should thus focus on PV-wind hybrid systems by exploring the value that small wind could add to PV or PV-diesel electrification programmes through diversification of power sources and local manufacture.

4. Conclusion

With each new application, WEMAM will continue to evolve. A study has recently been carried out in Nepal, which will see further development of the methodology (to be discussed in future publications). This paper has outlined several opportunities for WEMAM, most notably:

- Stage I: Shifting the focus away from techno-economic performance towards development outcomes and creating a range of community archetypes to feed into Stage II that match the similar types of communities with appropriately designed small wind systems.
- Stage II: More precise spatial differentiation of the off-grid population and wind speed data sensitivity analyses. Localised studies in high potential regions to match community archetypes from Stage I with a broader range of energy services, technologies for hybridisation and scales of SWT. Scenario modelling to show the impact of grid expansion and strategic interventions from Stage III.
- Stage III: Shifting the focus from expert interviews to participatory market mapping, MCDA ranking of potential interventions and applying socio-technical transitions theory to understand how the small wind niche can break through into the mainstream.

5. Acknowledgements

This methodology has been co-created by the members of Wind Empowerment's Market Assessment Working Group (MAWG) and those who commissioned and implemented its various iterations to date. Using the CRediT system, the specific contributions have been:

- Writing - Original Draft: Jon Leary, Magdalena Czyrnek-Delêtre, Alfie Alsop.
- Writing - Review & Editing: Jon Leary, Alfie Alsop, Aran Eales, Magdalena Czyrnek-Delêtre, Willington Ortiz, Jon Cloke.
- Methodology, Investigation and Formal Analysis: Jon Leary, Aran Eales, Lâl Marandin, Jon Persson, Madis Org, Mathias Craig, Christian Casillas, Kostas Latoufis.
- Conceptualisation: Jon Leary, Aran Eales, Carmen Dienst, Willington Ortiz, Lâl Marandin, Mathias Craig, Alfie Alsop.
- Funding acquisition: Carmen Dienst, Willington Ortiz, Aran Eales, Jon Leary, Alfie Alsop, Ed Brown, Magdalena Czyrnek-Delêtre.
- Supervision: Aidan While, Ed Brown, Mathias Craig.

The implementation of WEMAM in Nicaragua, Ethiopia and Malawi was funded by Green Empowerment and WISIONS; USAID and Mercy Corps; and the Scottish Government (respectively). The authors are particularly grateful to WISIONS, who commissioned the first MA and funded many of the Wind Empowerment association's activities, including the global market assessment [22] and WEMAM's latest implementation in Nepal.

This work was also supported by:

- the EIT Climate KIC's Pioneers into Practice programme via a placement for Magdalena Czyrnek-Delêtre at Loughborough University; and
- the UK Engineering and Physical Sciences Research Council (EPSRC) via:
- a PhD scholarship at the E-Futures DTC (EP/G037477/1) and a Doctoral Prize Fellowship (EP/L505055/1) for Jon Leary at the University of Sheffield;
- the LCEDN USES Programme Network at Loughborough University (EPSRC Project EP/L014858/1); and
- a PhD scholarship at the Wind Energy Systems DTC (EP/G037728/1) for Alfred Alsop at the University of Strathclyde.

Figs. 2, 3, 5–7 adapted from Ref. [11,20,21,46] with permission.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Leary J, To LS, Alsop A. Is there still a role for small wind in rural electrification programmes? LCEDN. Loughborough, UK: Low Carbon Energy for Development Network & Wind Empowerment; 2018.
[2] Batchelor S, Scott N, Daoqi L, Bagen. Evaluating the impact of wind generators in inner Mongolia - project technical report. Reading, UK: DfID, Gamos Ltd.; 1999.
[3] Lew DJ. Alternatives to coal and candles: wind power in China. Energy Pol 2000; 28:271–86.
[4] Carvalho Neves P, Gleditsch M, Bennet C, Craig M, Sumanik-Leary J. Assessment of locally manufactured small wind turbines as an appropriate technology for the electrification of the Caribbean Coast of Nicaragua. AIMS Energy 2015;3:41–74. https://doi.org/10.3934/energy.2015.1.41.
[5] Aaker DA, Kumar V, Day GS. Marketing research. ninth ed. John Wiley & Sons, Ltd.; 2006.
[6] Qualtrics. Marketing research solutions. 2015. https://www.qualtrics.com/uk/. [Accessed 22 March 2020].
[7] Blankenship AB, Breen GE, Dutka A. State of the art marketing research. second ed. NTC Business Books; 1998.
[8] Churchill Jr GA, Neilsen Jr AC. Basic marketing research. fourth ed. Harcourt, Inc.; 2001.
[9] AllBusiness. The five basic methods of market research. 2015. https://www.allbusiness.com/the-five-basic-methods-of-market-research-1287-1.html. [Accessed 22 March 2020].
[10] Smith SM, Albaum GS. Basic marketing research: volume 1 handbook for research professionals, vol. 1; 2012.
[11] Marandin L, Craig M, Casillas C, Sumanik-Leary J. Market assessment for small scale wind turbines in Nicaragua 2012-13. Managua. http://Windempowerment.Org/Market-Assesment-Working-Group/; 2013.
[12] Broesamle H, Mannstein H, Schillings C, Trieb F. Assessment of solar electricity potentials in North Africa based on satellite data and a geographic information system. Sol Energy 2001;70:1–12. https://doi.org/10.1016/S0038-092X(00)00126-2.
[13] Hernandez GH, Tuebke A. Techno-economic analysis of key renewable energy technologies (PV, CSP and wind). 2011. https://doi.org/10.2791/61897.
[14] Kanagawa M, Nakata T. Analysis of the energy access improvement and its socio-economic impacts in rural areas of developing countries. Ecol Econ 2007;62:319–29. https://doi.org/10.1016/j.ecolecon.2006.06.005.
[15] Painuly JP. Barriers to renewable eneryg penetration; a framework for analysis. Renew Energy 2001;24:73–89.
[16] Banks DI, Mocke F, Jonck EC, Labuschagne E, Eberhard R. Electrification planning decision support tool. Cape Town: Domest. Use Energy Conf.; 2000.
[17] Reddy S, Painuly JP. Diffusion of renewable energy technologies-barriers and stakeholders' perspectives. Renew Energy 2004;29:1431–47. https://doi.org/10.1016/j.renene.2003.12.003.

[18] Nguyen KQ. Wind energy in Vietnam: resource assessment, development status and future implications. Energy Pol 2007;35:1405–13. https://doi.org/10.1016/J.ENPOL.2006.04.011.
[19] Action Practical. Poor people's energy outlook 2010: energy for households. Rugby, UK: Practical Action; 2010.
[20] Eales A, Sumanik-Leary J, Latoufis K. Market assessment for locally manufactured small wind turbines in Ethiopia. Wind Empowerment and Mercy Corps; 2016.
[21] Sumanik-Leary J, Org M, Little M, Persson J, Kalonga C, Yona L, et al. Market assessment for locally manufactured PV-wind hybrid systems in Malawi. Lilongwe. Produced at the request of the Scottish government by wind empowerment & community energy Malawi. http://Windempowerment.Org/Market-Assesment-Working-Group/; 2016.
[22] Alsop A, Eales A, Strachan S, Leary J, Persson J, Almeyda IRIR, et al. A global market assessment methodology for small wind in the developing world. In: IEEE Glob. Humanit. Technol. Conf. 2017. vol. 2017; 2017. p. 1–6. https://doi.org/10.1109/GHTC.2017.8239226. Janua, San Jose CA (USA).
[23] Deng YY, Haigh M, Pouwels W, Ramaekers L, Brandsma R, Schimschar S, et al. Quantifying a realistic, worldwide wind and solar electricity supply. Global Environ Change 2015;31:239–52. https://doi.org/10.1016/j.gloenvcha.2015.01.005.
[24] Duma LJ. A novel rapid energy scenario visualization appraisal (RESVA) method for energy planning in developing countries: utilizing Malawi as A test bed. University of Edinburgh; 2016.
[25] EUEI-PDF. A framework for practitioners and policy makers. 2015.
[26] Consulting Forcier. Manual for conducting market assessments (South Sudan). 2013.
[27] Mentis D, Welsch M, Fuso Nerini F, Broad O, Howells M, Bazilian M, et al. A GIS-based approach for electrification planning—a case study on Nigeria. Energy Sustain Dev 2015;29:142–50. https://doi.org/10.1016/J.ESD.2015.09.007.
[28] Kamara N. Comparative review of market assessments methods, tools, approaches and findings. 2013.
[29] Action Practical. Poor People's Energy Outlook 2014: key messages on energy for poverty alleviation. UK: Rugby; 2014.
[30] Action Practical. Poor people's energy outlook 2012: energy for earning a living. Rugby, UK: Practical Action; 2012.
[31] Action Practical. Poor people's energy outlook 2013: energy for comunity services. Rugby, UK: Practical Action; 2013.
[32] Action Practical. Poor people's energy outlook 2016. UK: Rugby; 2016.
[33] Action Practical. Poor People's Energy Outlook 2017 - financing national energy access: a bottom-up approach. 2017. https://doi.org/10.3362/9781780446813.
[34] Action Practical. Poor People's Energy Outlook 2018: achieving inclusive energy access at scale. 2018. https://doi.org/10.3362/9781780447544.009.
[35] Ranaboldo M, Domenech B, Reyes GA, Ferrer-Martí L, Pastor Moreno R, García-Villoria A. Off-grid community electrification projects based on wind and solar energies: a case study in Nicaragua. Sol Energy 2015;117:268–81. https://doi.org/10.1016/j.solener.2015.05.005.
[36] Sinclair P, Cohen B, Hansen Y, Basson L, Clift R. Stakeholder engagement within the sustainability assessment of bioenergy: case studies from the UK. Africa (Lond) 2014;73. https://doi.org/10.1016/j.biombioe.2014.11.017. 7701–7701.
[37] Szabó S, Bódis K, Huld T, Moner-Girona M. Energy solutions in rural Africa: mapping electrification costs of distributed solar and diesel generation versus grid extension. Environ Res Lett 2011;6. https://doi.org/10.1088/1748-9326/6/3/034002.
[38] Gerlach AK, Gaudchau E, Cader C, Breyer C. Comprehesive country ranking for renewable energy based mini-grids providing rural off-grid electrification. In: 28th Eur. Photovolt. Sol. Energy Conf.; 2013. p. 24–8.
[39] Eales A, Strachan S, Frame D, Galloway S. Assessing the feasibility of solar microgrid social enterprises as an appropriate delivery model for achieving SDG7 assessing the feasibility of solar microgrid social enterprises as an appropriate delivery model for achieving SDG7. 2019.
[40] Runsten S, Fuso Nerini F, Tait L. Energy provision in South African informal urban Settlements - a multi-criteria sustainability analysis. Energy Strateg Rev 2018;19:76–84. https://doi.org/10.1016/J.ESR.2017.12.004.
[41] Bloomberg. Climatescope 2012 report. 2012.
[42] Kamp LM, Vanheule LFI. Review of the small wind turbine sector in Kenya: status and bottlenecks for growth. Renew Sustain Energy Rev 2015;49:470–80. https://doi.org/10.1016/j.rser.2015.04.082.
[43] Leary J, Schaube P, Clementi L. Rural electrification with household wind systems in remote high wind regions. Energy Sustain Dev 2019;52:154–75. https://doi.org/10.1016/j.esd.2019.07.008.
[44] Domenech B, Ferrer-Martí L, Pastor R. Hierarchical methodology to optimize the design of stand-alone electrification systems for rural communities considering technical and social criteria. Renew Sustain Energy Rev 2015;51:182–96. https://doi.org/10.1016/j.rser.2015.06.017.
[45] SEforALL Africa Hub. AfDB. GMG market assessment methodology green mini-grids market development program. Part 1: evaluation of methodologies and best practices available to assess GMG potential. 2017.
[46] Sumanik-Leary J, While A, Howell R. Small wind turbines for decentralised rural electrification: case studies in Peru , Nicaragua and Scotland. PhD Thesis. University of Sheffield; 2013.
[47] Yadoo A. Delivery models for decentralised rural electrification: case studies in Nepal, Peru and Kenya. Cambridge University; 2011.
[48] Sumanik-Leary J, Marandin L, Craig M, Casillas C, While A, Howell R. Participatory manufacture of small wind turbines: a case study in Nicaragua. Eng without borders enginners against poverty present going glob. 2013.
[49] Geels FW. Technological transitions and system innovations: a co-evolutionary and socio-technical analysis. Edward Elgar Publishing; 2005.
[50] IOD PARC. Case study summary - solar villages. 2012.
[51] Eales A. Renewable energy mini-grids in Malawi: status, barriers and opportunities. 2018. https://doi.org/10.13140/RG.2.2.23093.99047.
[52] Eales A. Social impact of mini-grids: monitoring , evaluation and learning tools and guidelines for practitioners and researchers. 2018.
[53] ARE. For rural electrification: hybrid mini-grids for rural electrification. 2016.
[54] Ranaboldo M, Ferrer-Martí L, Velo E. Micro-scale wind resource assessment for off-grid electrification projects in rural communities. A case study in Peru. Int J Green Energy 2014;11:75–90. https://doi.org/10.1080/15435075.2013.769878.
[55] Alstone P, Gershenson D, Kammen DM. Decentralized energy systems for clean electricity access. Nat Clim Change 2015. https://doi.org/10.1038/nclimate2512.
[56] Global IRENA. Renewable energy atlas. 2016. https://www.irena.org/globalatlas. [Accessed 22 March 2020].
[57] Kaijuka E. GIS and rural electricity planning in Uganda. J Clean Prod 2007;15:203–17. https://doi.org/10.1016/j.jclepro.2005.11.057.
[58] Iansiti M, Levien R. Strategy as ecology. Harv Bus Rev 2004 March 2004.