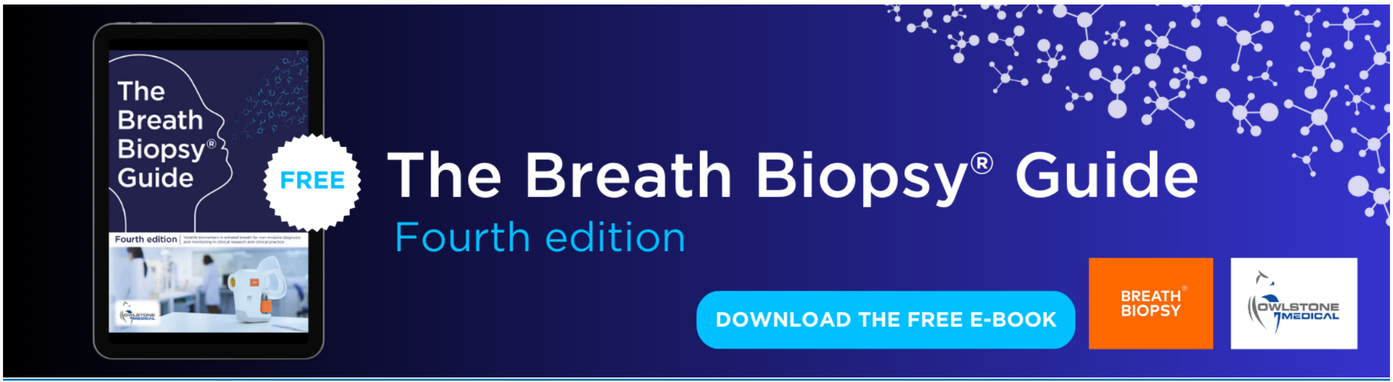
ENVIRONMENTAL RESEARCH
LETTERS

**LETTER • OPEN ACCESS**

# Comprehensive energy solution planning (CESP) framework: an evidence-based approach for sustainable energy access projects in developing countries

To cite this article: Emanuela Colombo *et al* 2024 *Environ. Res. Lett.* **19** 054059



IOP Publishing Environ. Res. Lett. 19 (2024) 054059 https://doi.org/10.1088/1748-9326/ad41ef

ENVIRONMENTAL RESEARCH
LETTERS

RECEIVED
14 August 2023

REVISED
18 March 2024

ACCEPTED FOR PUBLICATION
23 April 2024

PUBLISHED
7 May 2024

LETTER

# Comprehensive energy solution planning (CESP) framework: an evidence-based approach for sustainable energy access projects in developing countries

**Emanuela Colombo, Giacomo Crevani*, Nicolò Stevanato and Riccardo Mereu**

Department of Energy, Politecnico di Milano, Via Raffaele Lambruschini 4, Milano, Italy
* Author to whom any correspondence should be addressed.

**E-mail:** giacomo.crevani@polimi.it

**Keywords:** access to energy, project management, counterfactual analysis, energy solution planning, sustainable development

Supplementary material for this article is available online

## Abstract

Access to affordable, reliable, and modern energy remains a critical goal under the Agenda 2030 for Sustainable Development, especially in remote areas of developing countries. Based on traditional engineering approaches, many energy solution planning tools have been developed to identify the optimal solution in these areas to assess the competition across different technological options. Nevertheless, these approaches, based on an economic optimum, do not necessarily grant long-term sustainability of the solution in specific local contexts, since they are not able to capture the social implications within the Energy-Development nexus. Moreover, also in light of the 2030 Agenda, scientific and grey literature on energy access highlights how energy solutions planning methodologies developed in the last decades need to be complemented by a more comprehensive view, able to integrate evidence from various disciplines, especially engineering and social sciences. Based on the above considerations, this paper introduces a novel framework under the name of CESP, where three social sciences-based phases complement three engineering phases, each one characterized by specific tools, to offer an informed decision framework for the local planner. CESP encompasses a set of techno-economic and socio-technical actions to prevent potential failure as evidenced by a counterfactual analysis used to identify the reasons behind past project failures. The CESP framework presents a sequential and iterative structure that underlines the cyclic perspective of a holistic decision process where social sciences feed the engineering analysis and vice versa. Finally, CESP emerges as a practical and applicable framework for supporting energy access planning in critical areas.

## List of Abbreviations

| | |
|---|---|
| ADB | Asian Development Bank |
| BM | Business model |
| CESP | Comprehensive Energy Solution Planning |
| CA | Capability Approach |
| DAC | Development Assistance Committee |
| DCs | Developing Countries |
| DG | Distributed generation |
| ESMAP | Energy Sector Management Assistance Program |
| GHG | Greenhouse gases |
| GTF | Global Tracking Framework |
| LCOE | Levelised cost of electricity |
| MTF | Multi-tier Framework |
| NPC | Net present cost |
| OECD | Organization for Economic Cooperation and Development |
| PCM | Project Cycle Management |
| SHS | Solar Home System |
| SSA | Sub-saharan Africa |
| WB | World Bank |

## 1. Introduction

In the 2030 Agenda for Sustainable Development, Goal 7 aims to '*ensure access to affordable, reliable, sustainable and modern energy for all*' by 2030 [1].

However, according to the International Energy Agency (IEA)'s World Energy Outlook 2022 [2], 770 million people worldwide still live without access to electricity, and more than 2.5 billion lack access to clean cooking. The figures suggest that energy poverty will persist beyond 2030 [3]. The lowest growth rates for energy access are registered in SSA, where almost 500 million and 1 billion people still lack both electricity and clean cooking services [4]. Lack of access to energy hinders the transition towards productive uses of energy and the local development of modern societies in which economic development is sustained by energy services [5]. Energy access is not solely about the availability of energy resources; instead, it involves providing adequate energy services with attributes such as quality, reliability, and affordability [6].

Technologies for granting and upscaling access to energy constitute already a mature market [7, 8], with solutions being promoted and deployed by governments, private players, and international organizations [9]. Several energy solution planning approaches have been developed for the uptake and deployment of these technologies to support the least-cost optimal choice based on traditional engineering-oriented methodologies. Nevertheless, these approaches have been criticized for not necessarily leading to long-term sustainability in the specific local context [10, 11] due to their inability to capture the socio-economic causalities of the energy-development nexus [12] beyond the technical and economic dimensions [13]. Recent literature discusses how the just energy transition planning in DCs needs to account for social nuances [14], spacing from community consultation and involvement [13] to social acceptance [15], and behavioral dynamics [16, 17].

Both in the scientific and grey literature, as well as deriving from field experience, many scholars and practitioners have advocated for a new standard for energy access planning, encompassing a robust connection with social aspects and implications. This standard needs to account for the most recent advancements in affordable and sustainable technological solutions, with a neutral approach that evaluates the competition across different solutions based on their final impact on the economic, social, and environmental dimensions of the specific community [18]. Indeed, these three dimensions are strictly interconnected when the sustainability of off-grid energy solutions is claimed [19]. Integrated approaches between social and natural sciences must consider the relation between human and natural environments [20], supporting the project from conceptualization to planning, implementation, and impact evaluation.

Based on the above considerations, the paper introduces a structured novel framework named Comprehensive Energy Solution Planning (CESP). It complements a set of traditional engineering-oriented actions (representing the current standard for energy solution planning) with social sciences-based actions, which allow to embed holistic aspects in the project planning. In line with the literature, CESP presents an iterative structure that underlines the cyclic perspective of the two disciplines: the social analysis feeds the engineering analysis, which, as a feedback loop, provides back to the former a set of quantitative information.

The remainder of the work is structured as follows. Section 2 outlines the methodology, explaining the rationale behind the combined research method used in this study. In section 3, the results of the interdisciplinary literature review are shown. The state-of-the-art *energy solution planning* framework is presented, summarizing findings from techno-economic literature and leading to some techno-economic actions. Then, it shows the results of the *counterfactual analysis* that lead to key socio-technical actions, identifying and coding common reasons for the failure of energy access projects. Section 4 introduces CESP as the outcome of the work, organizing the techno-economic and socio-technical actions into phases, sorting them in a planning logic, and characterizing the actions performed in each phase through an interdisciplinary and practice-oriented literature review. Finally, section 5 contains the conclusions, discussing possible improvements to the proposed framework and recognizing the limitations of the work.

## 2. Methodology

The methodology adopted in this work, shown in figure 1, builds upon an interdisciplinary literature review, that is used to feed a combined approach between an engineering-based methodology, the energy solution planning, and a social sciences-based approach, the counterfactual analysis.

In the context of our study, this term refers to 'a comparison between what actually happened and what would have happened in the absence of the intervention' (e.g. Kremer *et al* [21], WB [22]). Similar approaches can be found in energy research literature. For instance, Sovacool *et al* [23] selected and studied ten case studies of energy access projects in the Asia–Pacific, analyzing the determinant factors for success. Ikejemba *et al* [24, 25] specifically focused on the failure of renewable energy projects in SSA and provided recommendations for future projects. An empirical quantitative analysis of the factors determining the success of mini-grid projects has also been provided in 2020 by Duran and Sahinyazan [26], who collected information in an open-access database. More recently, Perros *et al* [27] worked to push forward the notion of productive failure in energy and development research, both through a literature review oriented to the Global

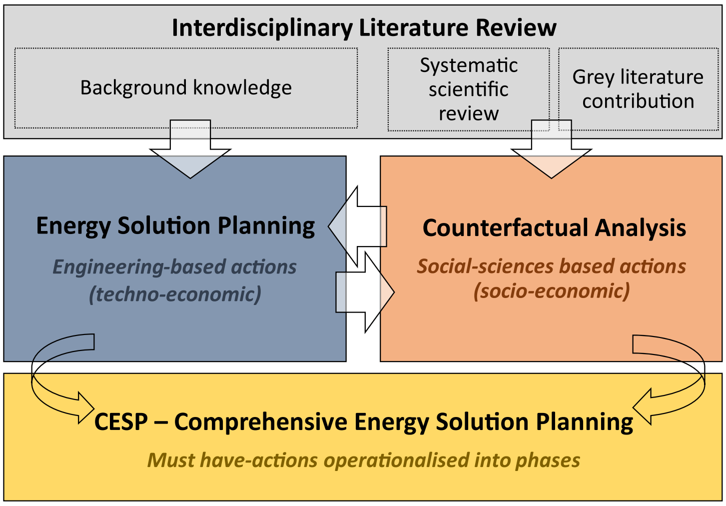


**Figure 1.** Workflow of the methodology.

South and informal interviews. Building upon such an approach, we enclose the consideration of 'failure as salient as success' as defined by Turnheim & Sovacool [28] and Sovacool [29].

More in detail, the *interdisciplinary literature review* is performed on three different sets of literature:

- The first set analyzed, feeding *energy solution planning*, concerns techno-economic background knowledge that this paper only aims to distill, basing on previous meta-analyses. These are collected from existing standards proposed by international organizations and in the scientific literature. The state-of-art *energy solution planning* results from this set of literature, providing some must-have techno-economic actions derived from the engineering practice.
- The second set of literature, feeding the *counterfactual analysis*, derives from two sources;
  - scientific literature of counterfactual cases collected through a systematic and replicable review;
  - case studies of failure taken from grey literature of on-field experiences of rural electrification programs.
- The *counterfactual analysis* is used to understand the reasons for the failure in energy projects by identifying some must-have actions to prevent the failure of energy access interventions in DCs. The analysis is built on counterfactual cases found in scientific and grey literature through a systematic and replicable literature review. Based on the missing actions derived, a list of social-oriented actions originates from the paper, representing its foreground knowledge.

Finally, the CESP originates as an evidence-based output, aggregating the must-have actions derived from the *energy solution planning* and *counterfactual analysis* methodologies in phases. The research methodology adopted provides inputs to CESP as a new energy planning framework aimed to support comprehensive strategies for energy access planning (i.e. able to complement the traditional engineering-based energy solutions planning tools with relevant inputs from social sciences' approaches).

## 3. Interdisciplinary literature review and results

### 3.1. Energy solution planning

This section consolidates some techno-economic elements that form the state-of-art *energy solution planning* approach. The reviewed technical-oriented methodologies are widely acknowledged and recognized as best practices in energy engineering. Therefore, the derived actions are considered background knowledge for the scope of this work.

Existing standards for the management and planning of energy access projects can be found in recent grey and scientific literature. International organizations majorly contributed to the definition of energy access frameworks. For instance, in 2008 a report by (the ESMAP of the WB) evidenced the lack of an approach for fostering productive uses of energy within electrification projects and advanced a possible systematic and pragmatic solution [11]. Moreover, the ADB published in 2015 a sustainable energy access planning framework [30]. The elements included in the framework are: energy poverty assessment, demand assessment, resource assessment, cost-benefit assessment, sustainability assessment, and affordability assessment.

From the scientific literature, Bengo and Arena [31] provided cases of successful integration of the social dimension, within different BMs for providing energy access. Electricity supply per-se is, indeed, not sufficient for generating effective social impact local business, requiring the adoption of holistic approaches beyond the technical design [32]. A needs-driven and participative planning, as claimed by Herington *et al* [13], is essential to improve the social sustainability of a specific intervention: community needs to be engaged [33] and decision-making power need to be spread across multiple groups (polycentricity, as reported by Sovacool [29]). This approach helps both to understand the needs of the beneficiaries and to foster recognition between stakeholders [34]. Similar considerations have been made by Akyniele *et al* [35], who introduced a sustainable planning framework for mini grid development in West Africa, suggesting qualitative must-have actions under multiple dimensions.

The pioneering work by Kumar *et al* [10] proposed a first standard decision support tool for the planning and formulation of off-grid electrification projects, introducing a three-stage procedure: project development/planning and pre-installation; detailed designing, installation and commissioning; and post-commissioning, including capacity building and monitoring and evaluation. From a systematic literature review, in 2012 Schillebeeckx *et al* [36] proposed a user-centric toolkit for solution and BM design. More recently, Bacchetti [37] presented a design-based approach applying sustainable product-service systems to the commercialization of distributed renewable energy solutions by small–medium enterprises in low-income contexts, providing tools and actions across the different dimensions of sustainability. Gambino *et al* [38] developed and tested a methodology for energy need assessment to provide reliable input data for mini-grid sizing. The methodology mentions site selection, energy resource assessment, energy need assessment, BM design, demand forecast, and sizing as crucial actions for the design of an off-grid mini-grid. A similar on-field contribution comes from Barbieri [39], who applied a holistic framework for the deployment of the SET4Food (sustainable energy technologies for food security) project for energy access in humanitarian settings. More recently, Matthey-Junod *et al* [18] expanded the notion of sustainable energy interventions in displacement settings, proposing an integrated framework for their planning also in terms of BM and tariff design.

As main result, deriving from the above literature and reports, the state-of-the-art of energy access project planning is recognized to encompass a defined set of actions, confirmed in the engineering practice. These are:

- *Resource assessment*: this action involves a thorough assessment of the local energy resources available in the project area. This evaluation enables project planners to understand the potential energy sources at their disposal, such as solar, wind, hydro, or biomass.
- *Demand assessment*: an evaluation of the current energy demand in the community is conducted while considering its future evolution through estimation or modeling techniques.
- *Technical solution identification*: based on the outcomes of the resource and demand assessment, this action identifies the most suitable technical solution (e.g.: solar-hybrid mini-grid, solar-home system, etc.),
- *Technical sizing*: this action sizes the identified technical solution, aiming at its cost-optimality.
- *Business model identification*: once the technical solution is set, a suitable BM to ensure the financial sustainability of the project is identified.
- *Business model formulation*: within this action, the financial strategy for energy service provision is established and the tariff is set.

### 3.2. Counterfactual analysis

This section aims to distill from scientific literature the common reasons that caused energy interventions to fail. The reasons are linked to some must-have actions that were not included in the traditional *energy solution planning* approach. The literature will be here systematically analyzed, providing the original contribution of the work.

A first set of scientific papers is systematically extracted from the Scopus database with the following research query in the TITLE-ABS-KEY fields:

- ('case study' OR 'project' OR 'programme' OR 'country' OR 'local case'): limits the research to real-life projects or context-specific cases of study
- W/20 ('failure' OR 'failed' OR 'failures' OR 'inaccuracy' OR 'error' OR 'errors' OR 'follow-up' OR 'lesson learnt' OR 'learning from'): this piece of string allows to search for cases of failure linked with the specific context
- AND ('energy-use' OR 'mini-grid' OR 'mini grid' OR 'micro-grid' OR 'micro grid' OR 'electrification' OR 'hybrid mini grid' OR 'hybrid mini-grid' OR 'small scale renewable energy system' OR 'solar mini-grid' OR 'local energy system' OR 'off-grid energy system' OR 'off-grid system' OR 'household energy transition' OR 'local energy transition'): this more generic piece of string limits the research to meaningful cases of electrification, whether with generic off-grid solutions or mini grids or for the residential sector perspective.

The screening process was conducted in three steps

i. An initial set of 369 papers was obtained through the research query. To refine the selection, papers were considered when meeting the following criteria: publication in the English language, publication date between 2000 and 2022, and

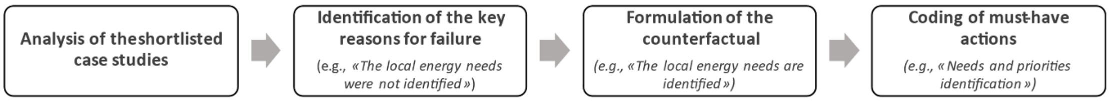


**Figure 2.** *Counterfactual analysis* process.

published in journals, books, or conference proceedings. After applying this initial filter, 299 papers remained.

ii. With a second step, the sample was further reduced excluding articles concerning topics out of scope for the present work such as residential consumption (18 papers), hydrogen (6 papers), nuclear energy (7 papers), and global decarbonization issues (57 papers). A total of 212 papers resulted from this second filter.

iii. As a third and final step, a screening was performed on the title and abstract of the papers in the sample. Papers have been automatically excluded if they concerned developed countries (including China), panel or aggregated data analyzes at national or regional scale and experimental or utility scale energy systems. In this round, papers regarding technology-specific failures have also been excluded (e.g. papers regarding sensor or automation failures not due to external factors). Papers were also excluded from the analysis if they simply derived generic lessons learnt from existing literature, with no analysis of the reasons for failure of specific interventions. Finally, a total of 25 items remained.

A review of grey literature has complemented the set of 25 papers from the systematic review. The grey literature has been sourced directly from the WB's Projects & Operations database (two end-of-project reports [40, 41]) and WB's Open Knowledge Repository (WB-OKR, with two book chapters, namely [42, 43], and one technical report [44]). By doing this, the scientific backbone of the work benefits from experiences of real rural electrification programs. The final shortlist of 30 publications has been studied in detail, following the process in figure 2.

The case studies, summarized as a supplementary material to this work, have been processed according to the workflow depicted in figure 2. After an in-depth analysis, the key reasons for failure reported in each case study are identified; then, the counterfactual is formulated turning the key reasons for failure into positive key reasons for success; then, coded into must-have actions. Two examples of the application of the process follow:

- the case study in Dutt and MacGill [45] claims that the program of electrification through mini-grids in Fiji failed for several reasons, among which the lack of ex-ante consultation of the local energy needs and aspirations; the counterfactual (positive) reason for this correspond to the identification of the local energy needs. This failure could have been prevented by including: *needs and priorities identification*. The action is therefore coded and listed in the socio-technical actions of CESP.
- Brooks and Urmee [46] investigated the failure of a SHS distribution program in the Philippines. Primary issues included insufficient training for users and local technicians, resulting in the system relying on external support and ultimately leading to its abandonment. The study emphasizes the importance of addressing local gaps in skills and capacities when designing energy interventions. An associated action: *local gaps identification and tackling* is therefore coded and listed in the socio-technical actions of CESP.

Table 1 depicts the result of this process on each of the 30 key studies. The first column highlights the must-have actions that should have been taken into consideration to ensure the success of the intervention.

Overall, the counterfactual analysis, as main result, suggested a total of four socio-technical actions:

- *Regulatory framework assessment*: the regulatory boundaries for the intervention are identified to understand which technical solutions and BMs can take place legally in the context.
- *Needs and priorities identification*: the local energy needs are identified and prioritized according to a specified metric or framework.
- *Local gaps identification and tackling*: the existing local gaps, in terms of capacity or financial resources, are identified and tackled by means of complementary social activities.
- *Impact assessment*: the impacts produced by the intervention are monitored and evaluated, under different dimensions and considering the energy needs targeted by the project.

It is noteworthy that: (i) the four newly identified socio-technical actions are directly derived from the *counterfactual analysis*, and (ii) the already identified techno-economic actions are also confirmed to be relevant in the context of the *counterfactual analysis*.

**Table 1.** Application of the counterfactual analysis on each case selected. Specific missing actions are associated with each case study. They are marked with ⦿ if they emerged from the counterfactual analysis, and with ✓ if the counterfactual analysis confirmed actions from the state-of-art energy solution planning.

| Action | [45] | [47] | [48] | [49] | [50] | [42] | [44] | [43] | [41] | [40] | [51] | [52] | [53] | [54] | [35] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Regulatory framework assessment | | | | | | ⦿ | ⦿ | | | | | | ⦿ | | ⦿ |
| Needs and priorities identification | ⦿ | | ⦿ | | ⦿ | | | | | | ⦿ | ⦿ | | | |
| Local gaps identification and tackling | | | | | ⦿ | | | ⦿ | | ⦿ | | ⦿ | | ⦿ | ⦿ |
| Impact assessment | | | | | ⦿ | | ⦿ | ⦿ | ⦿ | ⦿ | | | ⦿ | ⦿ | |
| Resource assessment | ✓ | ✓ | | | | | | | | | | | | | ✓ |
| Demand assessment | ✓ | | ✓ | ✓ | ✓ | | | | ✓ | | | | | | |
| Technical solution identification | | ✓ | | | | | ✓ | | | | | | | | |
| Technical sizing | | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | ✓ | | ✓ |
| Business model identification | | | | | | ✓ | ✓ | | | ✓ | | | | | |
| Business model formulation | | | | | | ✓ | | ✓ | | ✓ | | | | ✓ | |

| Action | [55] | [56] | [57] | [58] | [59] | [46] | [60] | [61, 62] | [63] | [64] | [65] | [66] | [67] | [68] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Regulatory framework assessment | | ⦿ | | | | | | ⦿ | | | ⦿ | | | ⦿ |
| Needs and priorities identification | ⦿ | | ⦿ | ⦿ | | | | | ⦿ | | | | ⦿ | |
| Local gaps identification and tackling | | ⦿ | | ⦿ | ⦿ | ⦿ | ⦿ | | | ⦿ | | ⦿ | ⦿ | |
| Impact assessment | | ⦿ | | | | | | | | | | | | |
| Resource assessment | ✓ | | ✓ | | | | | | ✓ | | | | | |
| Demand assessment | | | | ✓ | ✓ | | | | ✓ | | | | | |
| Technical solution identification | | ✓ | ✓ | ✓ | ✓ | | ✓ | | | ✓ | | | | ✓ |
| Technical sizing | | | | | | | | ✓ | ✓ | | | | | |
| Business model identification | | | | | ✓ | | | | | | ✓ | | ✓ | |
| Business model formulation | | | ✓ | | | | | ✓ | | | | | ✓ | |

This confirms that successful energy access planning strategies need to encompass both techno-economic and socio-technical actions, that are deeply intertwined in the practice [18].

## 4. CESP

In line with a project planning and management logic and wording used in international standards such as the Logical Framework Approach [69] or the decision-making theory [70], the must-have actions listed in the previous section are sorted in sequential and iterative phases. The phases are created by connecting some similar actions and temporally sorting, according to the two dimensions of the analysis: techno-economic and socio-technical phases, as depicted in figure 3.

The proposed list of phases is as follows:

1. *Context analysis*, analyzing the context of the action in terms of regulatory framework and local energy needs;
2. *Resource and Demand Assessment*, grouping available resource and energy demand assessments;
3. *Technical solution design*, supporting the identification and the sizing of adequate technical solutions;
4. *Business model design*, aiming to identify and formulate a consistent BM;
5. *Complementary activities:* introducing complementary activities to support the success of the intervention;
6. *Impact analysis*: providing the evaluation of the impact produced feeding it back to *Context analysis* to reevaluate the targeted local energy needs based on the impact achieved and ensure the effectiveness of the whole project.

The next sub-sections are used to consolidate each of the six phases as a part of the CESP, providing state-of-art tools and strategies to perform each action, taking references from various disciplines. This narrative literature review is presented in practical terms for each phase and action of CESP, to better detail the actions to be performed.

### 4.1. CESP1—context analysis

In the initial stage of the CESP, two actions focused on context analysis need to be performed. The first

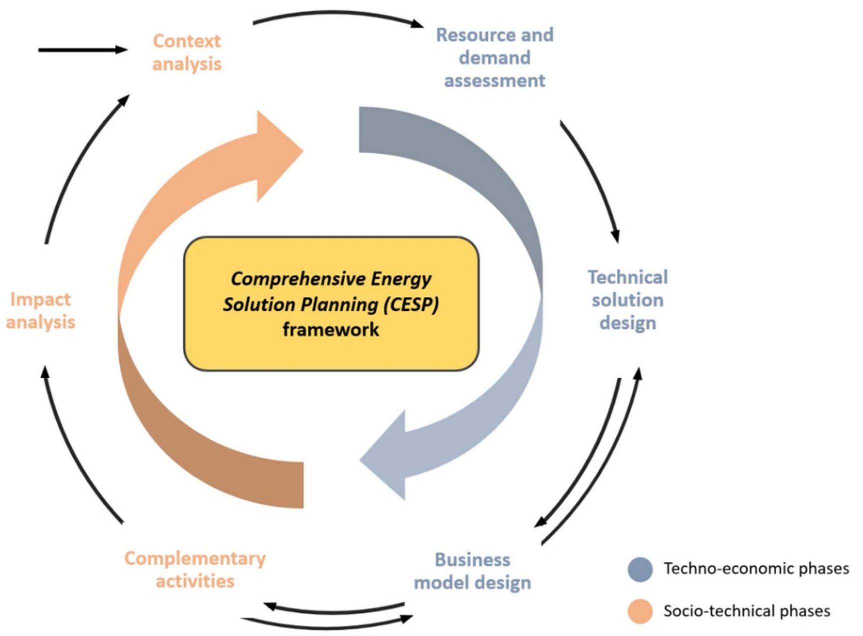


**Figure 3.** Layout of CESP, divided into techno-economic and socio-technical phases.

action aims at assessing the regulatory framework and local rules, a critical component of project design [71]. The second action identifies the needs of the beneficiaries and determines the priorities for the project to maximize policy [72] and project [73] outcomes.

#### 4.1.1. *Regulatory framework assessment*

The lack of understanding of the specific regulatory framework can hinder the successful implementation of any energy access projects in DCs [74]. Typically, there are three types of regulations in these countries [42]: technical (establishing standards for grid connections), procedural (authorization processes, bidding mechanisms), and economic (direct subsidies, cross-subsidies). Economic regulation's significance lies in incentivizing last-mile electrification, enabling communities to afford connection fees [75], and attracting private sector investment [44, 45]. Although an all-encompassing database of electrification regulatory frameworks and incentives in DCs is lacking, two reports are suggested to the energy planner in this action: 2018 International Renewable Energy Agency (IRENA)'s report [76] which offers insightful case studies, and ESMAP's Regulatory Indicators for Sustainable Energy (RISE) initiative which evaluates policy and regulatory support for access to clean cooking, energy efficiency, and renewable energy [77]. These tools can provide first indications to the project planner on the local regulatory framework.

#### 4.1.2. *Needs and priorities identification*

Energy is not an end in itself but may be considered as an instrumental right, a necessary yet not sufficient condition, supporting access to additional services and enabling development. Therefore, energy needs must first be understood from this perspective and then measured and targeted according to a proper metric, able to go beyond a binary approach to energy access. For instance, in the last decade, the GTF [78] has already introduced tiered measurements, considering attributes of energy access like maximum load (kW), energy quantity (kWh), affordability, and reliability. However, more recently, Pachauri and Rao [79] have challenged the MTF approach, suggesting it overlooks energy service diversity and practical value, thus confirming the relevance of measuring relative service gaps rather than achieved attributes [80].

Going further, a possible normative approach to unveil the use of energy for human development purposes is the capability approach (CA) [81–83]: this theory is founded on the *functionings* (doings and beings) and *capabilities* (opportunities for realizing the functionings) of the individual. CA advocates the realization of the spaces of freedom (i.e. the capabilities) to engage or not in a certain functioning: promoting capabilities instead of functionings enables an individual's freedom and self-determination. In the context of energy access, CA has been already adopted by various authors for different scopes [84–87] and to already underpin a new rationale for energy interventions, applied for on-field priority assessment by Wang *et al* [88].

As previously discussed, given the challenges faced in rural areas, energy access needs to leverage local income generating activities (also known as *productive uses of energy*) which can have the win–win effect to benefit from the energy services while contributing to pay back its investment (via tariff payment) [31]. Given the variety of needs that can span from domestic uses to productive activities, different approaches and tools may be developed for this specific phase, and different theories come to hand [89]. At any rate, two factors play a crucial role:

- The stakeholder's analysis which can employ different tools such as stakeholder matrixes or power-interest diagrams, as suggested by sectorial literature [90];
- The problem analysis, which is necessary to highlight cause-effect relationships to properly identify and then formulate the main activities of the intervention. Theorists [91] have observed that causal representations improve how evidence is sought and utilized when alternative hypotheses are evaluated.

Both the above factors are for instance well included in the Logical Framework approach to project management [69]

### 4.2. CESP2—resource and demand assessment

The second phase of CESP delves into technical data to tailor the intervention to the local context as described in CESP1. The phase comprises two actions: assessing the local availability of energy resources and the local energy demand.

#### *4.2.1. Resource assessment*

Small scale, off grid system as referred to in [92] offers the opportunity to better exploit local renewable energy. Precise deployment and sizing first necessitate local resource evaluation. Direct assessments, such as solar irradiation and wind speed measurements, require significant resources. Indirect methods, like web-based tools, offer reliable data for solar and wind availability [93, 94]. Tools like the Global Solar[1] and Wind Atlas[2] by the WB, photovoltaic geographical information system (PVGIS)[3] by the European Commission Joint Research Centre and Renewables.Ninja[4] provide information on various available renewable energy sources for specific locations. Notably, Korkovelos *et al* [95] released a geographic information system (GIS) layer mapping small hydropower potential in Africa. The derived availability of resources, at the desired temporal resolution, informs supply strategy and technological solution sizing.

#### *4.2.2. Demand assessment*

The assessment of the current energy usage is a starting point to quantify the local energy demand and associate it with the need expressed in the previous phase of the CESP. The on-field assessment entails detailed data collection. Visual tools such as Sankey diagrams can help to depict the assessment, clustering users by energy carriers and revealing key energy requirements.

Shifting from current energy needs to estimate future load demand is crucial to allow long-term project's success. This demand analysis covers diverse energy services and time resolutions, balancing data availability and precision. Formulating load curves aids system modeling [96] and aligns it with the local need and the resource assessment already completed, facilitating the upcoming phase of the sizing for the technical solution.

In general, two families of approaches for estimating current energy demand exist [97], including its long term evolution [98]:

- Top–down approaches: these set hypothetical power and energy tiers for user categories, aligning with frameworks like ESMAP's MTF [6], being in this way exposed to the criticalities highlighted in the previous section. They can also rely on standard parameters and wealth tiers and are usually adopted in large-scale applications [99] or expert-based methods [48]. It is, furthermore, likely that a successful project pushes new residential users, additional services for the community, or new productive activities to flourish and require additional energy or appliances [32, 100]. To account for this phenomenon, top-down methods can investigate the correlation of improved access with explanatory variables and forecast their evolution over time [101];
- Bottom–up approaches: these approaches build the load curve by characterizing the energy behavior of every single user and summing up the effects at the community level. Tools like LoadProGen [102] and RAMP [103] or agent-based approaches [104] aim to capture households' habit variability. Such approaches require extensive input data, obtained through on-field surveys but at the same time align with the analysis of needs performed in CESP 1, the identified needs can in fact be translated into load demand curves. In order to account for load evolution or bottom–up methods, adopting surveys and hybridizing with top–down methods to validate the on-field information collected [105, 106]. Hybrid approaches finally investigate the mechanisms of technology diffusion, adopting, among others, System Dynamics [107].

### 4.3. CESP3—technical solution design

Upon assessing resource availability and local demand, the process enters its initial planning phase. The first action involves identifying suitable technical solutions, chosen based on local resource availability and their capacity to meet assessed demand. Subsequently, the second action focuses on sizing the identified solution.

---

[1] https://globalsolaratlas.info/map.

[2] https://globalwindatlas.info/en.

[3] https://re.jrc.ec.europa.eu/pvg_tools/en/.

[4] www.renewables.ninja/.

### 4.3.1. Technical solution identification

As Mandelli *et al* [7] summarized, off-grid system (distributed or decentralized) solutions are gaining interest in DCs, where financial constraints and incomplete grid extensions persist. Various factors contribute to their appeal, spanning environmental, economic, technical, political, and social considerations. The choice of the exploited resource for energy generation (fuel-based, renewable-based, or hybrid) can influence reliability and costs [7], while the choice of the configuration of the system (stand-alone or minigrid) can have impacts on the outcomes in terms of development opportunities [108]. Several tools to support the selection of an adequate technical solution are already available. These space from GIS-based tools, which optimize the achievement of a fixed tier with the economic and spatial characteristics of a population [99, 109, 110], to multi-criteria analysis tools [73, 111, 112].

### 4.3.2. Technical sizing

The sizing of off-grid systems has been performed for years on expert-based methods. More recently, even in DCs, a scientifically sound approach towards optimized solutions is offered by energy system modeling [113].

The energy system modeling optimization approach involves numerical methods, referring to the Operations Research discipline, to determine the optimal size of electricity supply, dispatch, and storage components of the system to meet a given demand. These approaches include linear programming (LP), mixed-integer linear programming (MILP), heuristic, and metaheuristic methods [114]. LP constrained optimization, adopted in tools like HOMER® [115] and MicrogridsPy [106, 116, 117], employs linear or integer-linear constraints along with a linear objective function. This function is the overall target of the optimization and usually targets objectives like minimization of NPC or LCOE. Emerging models incorporate non-monetary, such as GHG emissions or social externalities [118].

Given the limited resources available in the African continent to be devolved to energy planning, the high cost of proprietary software can be a burden or even a limit that prevents them from being adopted. In this regard open energy modeling [63] grants free access to modeling tools, enhancing local ownership and maximizing possibility for a wide spread of capacity building activities. Energy modeling in the continent is experiencing great momentum in the last decade and has led to large communities of practice [119] and several African-led publications.

## 4.4. CESP4—BM design

Following the design of the technical solution, attention turns to the design of the corresponding BM. This phase involves understanding viable options in compliance with the local context (CESP1) and the technical design (CESP3). The synergy between BM selection and design, technical solution, and complementary activities ensures the project's long-term sustainability.

### 4.4.1. BM identification

Literature and case studies emphasize the relevance of a well-structured BM for energy access projects designed for continuous service provision, scalability, and long-term sustainability of the technological solutions proposed in CESP 4.

Peréz-Arriaga [71] outlines two pivotal BM characteristics: viability (successful functioning) and sustainability (self-sufficiency in the long run) and underlines the need for an effective regulatory framework to support these traits, enabling private sector involvement while upholding service quality for beneficiary communities.

From a practical point of view, Sovacool [29] compiled a comprehensive list of potential BMs for energy access projects, offering insights and potential references for BM selection, reported in table 2.

### 4.4.2. BM formulation

One of the most adopted tools for BM design is the BM Canvas [120], adapted for off-grid projects by the African Development Bank [121]. Some further adaptations may also be introduced to keep into consideration the peculiar situation of those who are living at the 'base of the pyramid'. For instance, the '4As Framework' requiring *Availability, Affordability, Awareness* and *Acceptance* as reported in [92] can be considered a useful tool to check the main features of the BM in the local context.

Energy solutions for off-grid electrification may be funded through different schemes like loans, equities, grants, and subsidies depending on the technological choice and the main stakeholders involved (private like independent power producer, public or public-private partnership). A thorough view is provided in [122], where the authors also offer a practical evidence-based perspective on five potential tariffs structures (uniform, cost-reflective, bid, willing buyer, willing seller, and hybrid) designed by balancing the needs of governments, developers, and customers that may represent an updated guidelines for energy planner.

## 4.5. CESP5—complementary activities for long term sustainability

This phase complements CESP 3 and 4 and aims at enhancing the long term sustainability of the project through complementary activities [123]. As already mentioned, energy access alone does not guarantee local development, as highlighted by the PRODUSE initiative [124]. This is also confirmed by a WB report [125] which suggests four categories of complementary factors to increase the economic impact of electricity access in SSA: Enhancing

**Table 2.** Summary of viable BMs for rural electrification in DCs.

| Business model | Description |
|---|---|
| Technology improvement and market development | A 'supply push' structure where the partnership develops a renewable energy technology to reduce costs |
| End-user microfinance | A 'demand pull' gives loans to energy users so that they can purchase renewable energy equipment |
| Project finance | Small and medium-scale projects supported with loans and financial assistance from commercial banks |
| Cooperative | The community owns the renewable energy system itself |
| Community mobilization fund | Revenues from renewable electricity or energy production are invested back into local communities |
| Energy services company (ESCO) 'fee-for-service' | Private sector enterprises purchase technology and then charge consumers only for the renewable energy 'service' that results |
| Cross-subsidization | Tariffs on one type of electricity are funneled into a fund to support renewable energy |
| Hybrid (e.g. end-user microfinance and ESCO 'fee-for-service') | Private sector enterprises provide technology and then charge consumers only for the renewable energy 'service' that results |

access to markets, facilitating access to microcredit, building usable skills (capacity building), and improving access to public services. Based on this report, Tonini *et al* [123] bring evidence based on a real case field study and an associated system dynamic model that confirms that the most impacting complementary activities should:

- Be identified and operate in relevant sectors for the local context (connected to CESP1).
- Be managed at local level (exogenous intervention on the contrary seems to be controversial), for instance by local cooperatives that reinvest the revenues from electricity fees provides a threefold advantage linked to CESP2:
  - * Positive market dynamics since it can increase the local demand' for goods and services in the local market which then increases the consumption of energy and therefore the need for supply;
  - * Allow demand side management and therefore a better operation of the energy supply with special attention to the optimization of variable renewable energy sources;
  - * Offer a potential realistic implementation for the CA by aligning individual energy needs with community requirements and project boundaries [107].
- Provide productive factors for new businesses and technology management:
  - * capital at a low interest rate (i.e. microcredits), connected to CESP4
  - * technical workforce on productive use of electricity (i.e. via capacity building), connected to CESP 3

The development of complementary activities with the three above-mentioned characteristics connects this phase within the CESP cycle. Moreover, it assures that long-term sustainability encompasses the economic, environmental, and social dimensions.

### 4.6. CESP6—impact analysis

The final phase of CESP consists in assessing the expected impact of the energy project. Impact evaluation is a systematic and final examination of a completed project, useful to judge the overall value of an intervention and supply lessons to improve future actions. The ability of a project to monitor, review, and evaluate its impact is envisaged with the Logical Framework approach via the Result Chain (Input-Activities-Output-Outcome-Impact) [69] and it allows stakeholders to account for its success or failure. Due to the cyclical nature of CESP, it feeds back to the context analysis in CESP1 to improve future program design or to adjust the current one.

As already anticipated, energy can be seen as an 'intermediate good', influencing a range of economic, social, and environmental outcomes through potentially long causal chains as reported by the ADB [126]. In energy access, White and Raitzer [127] claim that the majority of impact analysis techniques adopted in the field tend to assume rather than verify the causal relationships between inputs and impact, often self-selecting successful results, only. To investigate the logic of these relationships, it is important to identify and formulate a specific framework of reference, such as the theory of change [128] or the same Sustainable Development Goals, which are envisaged to be transformed into real applicative standards and not to remain only theoretical approaches, as suggested by Castor *et al* [129] and Tenenbaum *et al* [42]. For this reason, further investigation and testing are needed to provide energy access impact analysis with scientifically sound tools, such as the impact evaluation framework proposed in [130] or the evidence-based set of tools collected in [126].

Among the many challenges to impact evaluation, three are the most relevant: lack of quality data (or data at all); counterfactual and attributional effect. The lack of data [21] and or quality data can be today mitigated by the large data sets derived from administrative and commercial sources (i.e.: via metering system). The attribution gap and the counterfactual applied to energy projects for local development would require more high quality evidence [131] to be brought into the analysis, for instance, via empirical evidence, control trials or randomized control trials. At any rate, the space of research here is still very wide and calls for multidisciplinary approaches that can encompass different disciplines from social sciences to engineering.

## 5. Conclusions and future work

This article has proposed an innovative framework under the name of CESP, where three engineering phases are complemented by other three social sciences-based phases. Each phase has been characterized by specific tools to offer an informed decision framework for the local planner. CESP encompasses a set of techno-economic and socio-technical actions aiming at preventing potential failure, based on a counterfactual analysis used to identify the reasons behind past project failures.

The CESP framework, presenting a sequential but iterative structure that underlines the cyclic perspective of the two disciplines that it integrates, is divided into six consequential phases and constitutes a novel output. The original methodology of *counterfactual analysis* complements and expands traditional *energy solutions planning* methodologies. The CESP framework is arranged in a ready-to-use structure that emphasizes the importance of a deep context analysis, complete resource and demand assessment, and thorough design for the technical solution and the associated BMs. Complementary activities are then implemented to ensure the long-term sustainability of the project and increase its impact beyond the provision of energy per se. Each of the six phases is enriched in the final section with state-of-art tools to perform the must-have actions, taking references from various disciplines.

The research gap identified in the introduction, which called for multidisciplinary and needs-oriented standards to support energy access projects, has been addressed throughout this work. The CESP framework encourages the application and harmonization of socio-techno-economic approaches in energy access planning.

Future research in this field would benefit from continuous and systematic monitoring and review of the literature, and additional field case analysis to test the applicability of the CESP. Moreover, the possibility of investigating quantitatively the counterfactual case studies using regression analyzes, checking for causal correlations between variables (i.e. the presence or not of a certain action within a certain phase of CESP) and evidence of failure, would also provide additional evidence to revise and update the CESP to improve the success rate for energy access projects.

## Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

## Acknowledgments

Financial support from the European Commission H2020 funded project LEAP-RE (Long-Term Joint EU-AU Research and Innovation Partnership on Renewable Energy), Grant Number 963530 is gratefully acknowledge.

## ORCID iDs

Emanuela Colombo https://orcid.org/0000-0002-9747-5699
Giacomo Crevani https://orcid.org/0000-0002-7108-0445
Nicolò Stevanato https://orcid.org/0000-0002-3419-0389
Riccardo Mereu https://orcid.org/0000-0003-0544-595X

## References

[1] UNDESA 2015 Goal 7 (Department of Economic and Social Affairs) (available at: https://sdgs.un.org/goals/goal7) (Accessed 11 February 2022)
[2] IEA 2022 *World Energy Outlook 2022* (International Energy Agency) (available at: https://iea.blob.core.windows.net/assets/830fe099-5530-48f2-a7c1-11f35d510983/WorldEnergyOutlook2022.pdf#%5B%7B%22num%22%3A2524%2C%22gen%22%3A0%7D%2C%7B%22name%22%3A%22FitR%22%7D%2C-188%2C16%2C784%2C672%5D)
[3] IEA 2020 *World Energy Outlook 2020* (International Energy Agency)
[4] IEA 2022 *Africa Energy Outlook 2022* (International Energy Agency) (available at: www.iea.org/reports/africa-energy-outlook-2022)
[5] Sokona Y, Mulugetta Y and Gujba H 2012 Widening energy access in Africa: towards energy transition *Energy Policy* **47** 3–10
[6] ESMAP 2015 Beyond connections energy access redefined (World Bank) (available at: https://openknowledge.worldbank.org/bitstream/handle/10986/24368/Beyond0connect0d000technical0report.pdf?sequence=1&isAllowed=y)
[7] Mandelli S, Barbieri J, Mereu R and Colombo E 2016 Off-grid systems for rural electrification in developing countries: definitions, classification and a comprehensive literature review *Renew. Sustain. Energy Rev.* **58** 1621–46
[8] IRENA 2016 *Innovation Outlook Mini-Grids* (available at: www.irena.org%0Awww.irena.org/publications)

[9] ESMAP 2019 Mini grids for half a billion people: market outlook and handbook for decision makers. Executive summary *Energy Sector Management Assistance Program (ESMAP) Technical Report* 014/19 (available at: https://openknowledge.worldbank.org/handle/10986/31926)

[10] Kumar A, Mohanty P, Palit D and Chaurey A 2009 Approach for standardization of off-grid electrification projects *Renew. Sustain. Energy Rev.* **13** 1946–56

[11] de Gouvello C and Durix L 2008 Maximizing the productive uses of electricity to increase the impact of rural electrification programs *Formal Report 332/08* (ESMAP)

[12] Riva F, Ahlborg H, Hartvigsson E, Pachauri S and Colombo E 2018 Electricity access and rural development: review of complex socio-economic dynamics and causal diagrams for more appropriate energy modelling *Energy Sustain. Dev.* **43** 203–23

[13] Herington M J, van de Fliert E, Smart S, Greig C and Lant P A 2017 Rural energy planning remains out-of-step with contemporary paradigms of energy access and development *Renew. Sustain. Energy Rev.* **67** 1412–9

[14] Tarekegne B 2020 Just electrification: imagining the justice dimensions of energy access and addressing energy poverty *Energy Res. Soc. Sci.* **70** 101639

[15] Süsser D, Martin N, Stavrakas V, Gaschnig H, Talens-Peiró L, Flamos A, Madrid-López C and Lilliestam J 2022 Why energy models should integrate social and environmental factors: assessing user needs, omission impacts, and real-word accuracy in the European Union *Energy Res. Soc. Sci.* **92** 102775

[16] Nikas A, Lieu J, Sorman A, Gambhir A, Turhan E, Baptista B V and Doukas H 2020 The desirability of transitions in demand: incorporating behavioural and societal transformations into energy modelling *Energy Res. Social Sci.* **70** 101780

[17] Li F G N 2017 Actors behaving badly: exploring the modelling of non-optimal behaviour in energy transitions *Energy Strategy Rev.* **15** 57–71

[18] Matthey-Junod A, Sandwell P, Makohliso S and Schönenberger K 2022 Leaving no aspect of sustainability behind: a framework for designing sustainable energy interventions applied to refugee camps *Energy Res. Soc. Sci.* **90** 102636

[19] Mulugetta Y, Ben Hagan E and Kammen D 2019 Energy access for sustainable development *Environ. Res. Lett.* **14** 020201

[20] Liu J *et al* 2007 Complexity of coupled human and natural systems *Science* **317** 1513–6

[21] Kremer M, van Lieshout P and Went R 2009 *Doing Good or Going Better: Development Policies in a Globalising World* (Amsterdam University Press)

[22] White H and Barbu A 2006 Impact evaluation—the experience of the impact evaluation group of the world bank (World Bank) (available at: https://documents1.worldbank.org/curated/en/475491468138595632/pdf/382680Impact1e10experience01PUBLIC1.pdf)

[23] Sovacool B K 2013 A qualitative factor analysis of renewable energy and sustainable energy for all (SE4ALL) in the Asia-Pacific *Energy Policy* **59** 393–403

[24] Ikejemba E C X, Mpuan P B, Schuur P C and Van Hillegersberg J 2017 The empirical reality & sustainable management failures of renewable energy projects in Sub-Saharan Africa (part 1 of 2) *Renew. Energy* **102** 234–40

[25] Ikejemba E C X, Schuur P C, Van Hillegersberg J and Mpuan P B 2017 Failures & generic recommendations towards the sustainable management of renewable energy projects in Sub-Saharan Africa (part 2 of 2) *Renew. Energy* **113** 639–47

[26] Duran A S and Sahinyazan F G 2021 An analysis of renewable mini-grid projects for rural electrification *Socio-Econ. Plan. Sci.* **77** 100999

[27] Perros T, Bisaga I, Broad O, Macon L, Fennell P J and Tomei J 2022 Lost learnings: breaking the silence of failure in the energy and development sector *Energy Res. Soc. Sci.* **92** 102804

[28] Turnheim B and Sovacool B K 2020 Exploring the role of failure in socio-technical transitions research *Environ. Innov. Soc. Trans.* **37** 267–89

[29] Sovacool B K 2014 Defining, measuring, tackling energy poverty *Energy Poverty—Global Challenges and Local Solutions* ed B K Sovacool, A Halff and J Rozhon (Oxford University Press) pp 21–53

[30] Shrestha R M and Acharya J S 2015 *Sustainable Energy Access Planning—A Framework* vol 1 (Asian Development Bank)

[31] Bengo I and Arena M 2013 Integrating the social dimension into new business models for energy access *Renewable Energy for Unleashing Sustainable Development* (Springer) pp 203–17

[32] Ganguly R, Jain R, Sharma K R and Shekhar S 2020 Mini grids and enterprise development: a study of aspirational change and business outcomes among rural enterprise owners in India *Energy Sustain. Dev.* **56** 119–27

[33] Sgouridis S, Kimmich C, Solé J, Černý M, Ehlers M-H and Kerschner C 2022 Visions before models: the ethos of energy modeling in an era of transition *Energy Res. Soc. Sci.* **88** 102497

[34] Melloni G, Turetta A P D, Bonatti M and Sieber S 2020 A stakeholder analysis for a water-energy-food nexus evaluation in an atlantic forest area: implications for an integrated assessment and a participatory approach *Water* **12** 1–15

[35] Akinyele D, Belikov J and Levron Y 2018 Challenges of microgrids in remote communities: a STEEP model application *Energies* **11** 432

[36] Schillebeeckx S J D, Parikh P, Bansal R and George G 2012 An integrated framework for rural electrification: adopting a user-centric approach to business model development *Energy Policy* **48** 687–97

[37] Bacchetti E 2017 A design approach with method and tools to support SMEs in designing and implementing distributed renewable energy (DRE) solutions based on sustainable product-service system (S.PSS) *Proc. CIRP* **64** 229–34

[38] Gambino V, Del Citto R, Cherubini P, Tacconelli C, Micangeli A and Giglioli R 2019 Methodology for the energy need assessment to effectively design and deploy mini-grids for rural electrification *Energies* **12** 1–27

[39] Barbieri J 2018 Comprehensive energy solutions in humanitarian settlements: from the energy—food nexus to a holistic approach to energy planning *PhD Thesis* Polytechnic University of Milan

[40] World Bank 2013 Lao—first phase of the rural electrification project (English) (World Bank) (available at: http://documents.worldbank.org/curated/en/912271468045561229/Lao-First-Phase-of-the-Rural-Electrification-Project)

[41] World Bank 2019 Africa—second energy small medium enterprises support project (English), (World Bank) (available at: http://documents.worldbank.org/curated/en/251401567623794144/Africa-Second-Energy-Small-Medium-Enterprises-Support-Project)

[42] Tenenbaum B, Greacen C, Siyambalapitiya T and Knuckles J 2014 Small power producers, small power distributors, and electrification: concepts and examples *From the Bottom Up: How Small Power Producers and Grids Can Deliver Electrification and Renewable Energy in Africa* (Directions in Development—Energy and Mining) pp 31–62

[43] Tenenbaum B, Greacen C, Siyambalapitiya T and Knuckles J 2014 Regulatory decisions for small power producers serving retail customers: tariffs and quality of service *From the Bottom Up: How Small Power Producers and Grids Can Deliver Electrification and Renewable Energy in Africa* (Directions in Development—Energy and Mining) pp 239–81

[44] Tenenbaum B, Greacen C and Vaghela D 2018 Mini-grids and arrival of the main grid: lessons from Cambodia, Sri Lanka, and Indonesia *Technical report* 013/18 (ESMAP) (https://doi.org/10.1596/29018)

[45] Dutt P K and Macgill I 2013 Addressing some issues relating to hybrid mini grid failures in Fiji *IEEE Global Humanitarian Technology Conf.: South Asia Satellite, GHTC-SAS 2013* (IEEE) pp 106–11

[46] Brooks C and Urmee T 2014 Importance of individual capacity building for successful solar program implementation: a case study in the Philippines *Renew. Energy* **71** 176–84

[47] Tamir K, Urmee T and Pryor T 2015 Issues of small scale renewable energy systems installed in rural Soum centres in Mongolia *Energy Sustain. Dev.* **27** 1–9

[48] Louie H and Dauenhauer P 2016 Effects of load estimation error on small-scale off-grid photovoltaic system design, cost and reliability *Energy Sustain. Dev.* **34** 30–43

[49] Blodgett C, Dauenhauer P, Louie H and Kickham L 2017 Accuracy of energy-use surveys in predicting rural mini-grid user consumption *Energy Sustain. Dev.* **41** 88–105

[50] Ulsrud K, Winther T, Palit D, Rohracher H and Sandgren J 2011 The solar transitions research on solar mini-grids in India: learning from local cases of innovative socio-technical systems *Energy Sustain. Dev.* **15** 293–303

[51] Sovacool B K and D'Agostino A L 2012 A comparative analysis of solar home system programmes in China, Laos, Mongolia and Papua New Guinea *Prog. Dev. Stud.* **12** 315–35

[52] Schilmann A *et al* 2019 A follow-up study after an improved cookstove intervention in rural Mexico: estimation of household energy use and chronic PM2.5 exposure *Environ. Int.* **131** 105013

[53] Holtorf H, Urmee T, Calais M and Pryor T 2015 A model to evaluate the success of solar home systems *Renew. Sustain. Energy Rev.* **50** 245–55

[54] Balint P J 2006 Bringing solar home systems to rural El Salvador: lessons for small NGOs *Energy Policy* **34** 721–9

[55] Ahlborg H 2018 Changing energy geographies: the political effects of a small-scale electrification project *Geoforum* **97** 268–80

[56] Mahalingam L and Prabhu J 2017 Different models used in Africa and Asia for off grid electrification and the challenges faced *Int. J. Energy Prod. Manage.* **2** 219–24

[57] van Gevelt T, Zaman T, George F, Bennett M M, Fam S D and Kim J E 2020 End-user perceptions of success and failure: narratives from a natural laboratory of rural electrification projects in Malaysian Borneo *Energy Sustain. Dev.* **59** 189–98

[58] Sovacool B K 2013 Energy poverty and development in Papua New Guinea: learning from the teacher's solar lighting project *Forum Dev. Stud.* **40** 327–49

[59] Millinger M, Mårlind T and Ahlgren E O 2012 Evaluation of Indian rural solar electrification: a case study in Chhattisgarh *Energy Sustain. Dev.* **16** 486–92

[60] Ha Y-H and Kumar S S 2021 Investigating decentralized renewable energy systems under different governance approaches in Nepal and Indonesia: how does governance fail? *Energy Res. Social Sci.* **80** 102214

[61] Feron S and Cordero R R 2018 Is peru prepared for large-scale sustainable rural electrification? *Sustainability* **10** 1683

[62] Feron S, Cordero R R and Labbe F 2017 Rural electrification efforts based on off-grid photovoltaic systems in the Andean Region: comparative assessment of their sustainability *Sustainability* **9** 1825

[63] Murni S, Whale J, Urmee T, Davis J K and Harries D 2013 Learning from experience: a survey of existing micro-hydropower projects in Ba'Kelalan, Malaysia *Renew. Energy* **60** 88–97

[64] Zimmerle D, Santos A F B, Gasore G and Ntaganda J 2020 Learning from failure: a case study of repairing a pico-hydropower system in Rwanda *2020 IEEE PES/IAS PowerAfrica, PowerAfrica 2020* (https://doi.org/10.1109/PowerAfrica49420.2020.9219807)

[65] Agol D 2017 Lighing up rural Kenya: lessons learnt from rural electrification programmes *Energy Poverty and Vulnerability - A Global Perspective* ed N Simcock, H Thomson, S Petrova and S Bouzarovski (Routledge) (https://doi.org/10.4324/9781315231518)

[66] Berger T 2017 Practical constraints for photovoltaic appliances in rural areas of developing countries: lessons learnt from monitoring of stand-alone systems in remote health posts of North Gondar Zone, Ethiopia *Energy Sustain. Dev.* **40** 68–76

[67] Sovacool B K 2018 Success and failure in the political economy of solar electrification: lessons from world bank solar home system (SHS) projects in Sri Lanka and Indonesia *Energy Policy* **123** 482–93

[68] Derks M and Romijn H 2019 Sustainable performance challenges of rural microgrids: analysis of incentives and policy framework in Indonesia *Energy Sustain. Dev.* **53** 57–70

[69] European Commission 2004 Project cycle management guidelines *Aid delivery methods* p 149

[70] Hansson S O 1994 Decision theory: a brief introduction (available at: http://people.kth.se/∼soh/decisiontheory.pdf)

[71] Pérez-Arriaga I 2016 New regulatory and business model approaches to achieving universal electricity access *Papeles Energ.* **3** 7–48

[72] Hausmann R, Rodrik D and Velasco A 2008 Growth diagnostics *The Washington Consensus Reconsidered: Towards a New Global Governance* (*The Initiative for Policy Dialogue Series*) ed N Serra and J E Stiglits (Oxford University Press)

[73] Rahman M M, Paatero J V and Lahdelma R 2013 Evaluation of choices for sustainable rural electrification in developing countries: a multicriteria approach *Energy Policy* **59** 589–99

[74] Bawakyillenuo S 2009 Policy and institutional failures: photovoltaic solar household system (PV/SHS) dissemination in Ghana *Energy Environ.* **20** 927–47

[75] Golumbeanu R and Barnes D 2013 Connection charges and electricity access in sub-Saharan Africa *Policy Research Working Papers* (The World Bank) (https://doi.org/10.1596/1813-9450-6511)

[76] IRENA 2018 Policies and regulations for renewable mini-grids (available at: https://irena.org/-/media/Files/IRENA/Agency/Publication/2018/Oct/IRENA_mini-grid_policies_2018.pdf)

[77] ESMAP RISE 2022 regulatory indicators for sustainable energy—building resilience (available at: https://rise.esmap.org/data/files/reports/2022/RISE%202022%20Report%20Building%20Resilience.pdf)

[78] Banerjee S G *et al* 2013 Global tracking framework (available at: http://documents.worldbank.org/curated/en/2013/05/17765643/global-tracking-framework-vol-3-3-main-report)

[79] Pachauri S and Rao N D 2020 Advancing energy poverty measurement for SDG7 *Prog. Energy* **2** 043001

[80] Kalt G, Wiedenhofer D, Görg C and Haberl H 2019 Conceptualizing energy services: a review of energy and well-being along the energy service cascade *Energy Res. Soc. Sci.* **53** 47–58

[81] Sen A 1999 *Development as Freedom* (Oxford University Press)

[82] Robeyns I 2006 The capability approach in practice *J. Political Phil.* **14** 351–76

[83] Nussbaum M C 2008 Creating capabilities: the human development approach and its implementation *Hypatia* **24** 211–5

[84] Chipango E F 2021 Beyond utilitarian economics: a capability approach to energy poverty and social suffering *J. Hum. Dev. Capabilities* **22** 446–67

[85] Day R, Walker G and Simcock N 2016 Conceptualising energy use and energy poverty using a capabilities framework *Energy Policy* **93** 255–64

[86] Bartiaux F, Day R and Lahaye W 2021 Energy poverty as a restriction of multiple capabilities: a systemic approach for belgium *J. Hum. Dev. Capabilities* **22** 270–91

[87] Frigo G, Baumann M and Hillerbrand R 2021 Energy and the good life: capabilities as the foundation of the right to access energy services *J. Hum. Dev. Capabilities* **22** 218–48

[88] Wang X, Day R, Murrant D, Marín A D, Botello D C, González F L and Radcliffe J 2021 A capabilities-led approach to assessing technological solutions for a rural community *Energies* **14** 1398

[89] Shove E and Walker G 2014 What is energy for? Social practice and energy demand *Theory Cult. Soc.* **31** 41–58

[90] Bendtsen E B, Clausen L P W and Hansen S F 2021 A review of the state-of-the-art for stakeholder analysis with regard to environmental management and regulation *J. Environ. Manage.* **279** 111773

[91] Neil M, Fenton N, Osman M and Lagnado D 2021 Causality, the critical but often ignored component guiding us through a world of uncertainties in risk assessment *J. Risk Res.* **24** 617–21

[92] Colombo E, Bologna S and Masera D 2013 *Renewable Energy for Unleashing Sustainable Development* (Springer) (https://doi.org/10.1007/978-3-319-00284-2)

[93] Pfenninger S and Staffell I 2016 Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data *Energy* **114** 1251–65

[94] Staffell I and Pfenninger S 2016 Using bias-corrected reanalysis to simulate current and future wind power output *Energy* **114** 1224–39

[95] Korkovelos A, Mentis D, Siyal S, Arderne C, Rogner H, Bazilian M, Howells M, Beck H and De Roo A 2018 A geospatial assessment of small-scale hydropower potential in Sub-Saharan Africa *Energies* **11** 3100

[96] Pfenninger S, Hawkes A and Keirstead J 2014 Energy systems modeling for twenty-first century energy challenges *Renew. Sustain. Energy Rev.* **33** 74–86

[97] Swan L G and Ismet Ugursal V 2009 Modeling of end-use energy consumption in the residential sector: a review of modeling techniques *Renew. Sustain. Energy Rev.* **13** 1819

[98] Riva F, Tognollo A, Gardumi F and Colombo E 2018 Long-term energy planning and demand forecast in remote areas of developing countries: classification of case studies and insights from a modelling perspective *Energy Strategy Rev.* **20** 71–89

[99] Mentis D *et al* 2017 Lighting the world: the first application of an open source, spatial electrification tool (OnSSET) on Sub-Saharan Africa *Environ. Res. Lett.* **12** 085003

[100] Díaz P, Arias C A, Peña R and Sandoval D 2010 FAR from the grid: a rural electrification field study *Renew. Energy* **35** 2829–34

[101] Kobayakawa T and Kandpal T C 2015 Analysis of electricity consumption under a photovoltaic micro-grid system in India *Sol. Energy* **116** 177–83

[102] Mandelli S, Merlo M and Colombo E 2016 Novel procedure to formulate load profiles for off-grid rural areas *Energy Sustain. Dev.* **31** 130–42

[103] Lombardi F, Balderrama S, Quoilin S and Colombo E 2019 Generating high-resolution multi-energy load profiles for remote areas with an open-source stochastic model *Energy* **177** 433–44

[104] Dominguez C 2022 Estimating the electricity demand of rural households to improve energy access planning in developing countries *Doctoral Thesis* ETH Zurich (https://doi.org/10.3929/ethz-b-000533773)

[105] Ruijven B J V, van Vuuren D P, de Vries B J M, Isaac M, van der Sluijs J P, Lucas P L and Balachandra P 2011 Model projections for household energy use in India *Energy Policy* **39** 7747–61

[106] Stevanato N, Lombardi F, Guidicini G, Rinaldi L, Balderrama S L, Pavičević M, Quoilin S and Colombo E 2020 Long-term sizing of rural microgrids: accounting for load evolution through multi-step investment plan and stochastic optimization *Energy Sustain. Dev.* **58** 16–29

[107] Riva F, Colombo E and Piccardi C 2019 Towards modelling diffusion mechanisms for sustainable off-grid electricity planning *Energy Sustain. Dev.* **52** 11–25

[108] Stevanato N, Corigliano S, Petrelli M, Tonini F, Merlo M and Colombo E 2021 Rural areas electrification strategies through shadow costs analysis—Bolivian Highlands case study *Energy Sustain. Dev.* **65** 162–74

[109] World Bank 2021 Global electrification platform (available at: https://electrifynow.energydata.info/) (Accessed 29 June 2021)

[110] Nerini F F, Broad O, Mentis D, Welsch M, Bazilian M and Howells M 2016 A cost comparison of technology approaches for improving access to electricity services *Energy* **95** 255–65

[111] Fuso Nerini F, Howells M, Bazilian M and Gomez M F 2014 Rural electrification options in the Brazilian Amazon. A multi-criteria analysis *Energy Sustain. Dev.* **20** 36–48

[112] Cherni J A, Dyner I, Henao F, Jaramillo P, Smith R and Font R O 2007 Energy supply for sustainable rural livelihoods. A multi-criteria decision-support system *Energy Policy* **35** 1493–504

[113] Akbas B, Kocaman A S, Nock D and Trotter P A 2022 Rural electrification: an overview of optimization methods *Renew. Sustain. Energy Rev.* **156** 111935

[114] Moretti L, Astolfi M, Vergara C, Macchi E, Pérez-Arriaga J I and Manzolini G 2019 A design and dispatch optimization algorithm based on mixed integer linear programming for rural electrification *Appl. Energy* **233–234** 1104–21

[115] Lambert T, Gilman P and Lilienthal P 2006 Micropower system modeling with homer *Integr. Altern. Sour. Energy* **1** 379–418

[116] Balderrama S, Lombardi F, Riva F, Canedo W, Colombo E and Quoilin S 2019 A two-stage linear programming optimization framework for isolated hybrid microgrids in a rural context: the case study of the "El Espino" community *Energy* **188** 116073

[117] Stevanato N, Pellecchia G, Sangiorgio I, Shendrikova D, Soares C A, Mereu R and Colombo E 2023 Planning third generation minigrids: multi-objective optimization and brownfield investment approaches in modelling village-scale on-grid and off-grid energy systems *Renew. Sustain. Energy Transit.* **3** 100053

[118] Petrelli M, Fioriti D, Berizzi A, Bovo C and Poli D 2021 A novel multi-objective method with online Pareto pruning for multi-year optimization of rural microgrids *Appl. Energy* **299** 117283

[119] Climcate Compatible Growth (CCG) 2023 Energy modelling platform for Africa (EMP-A) (available at: https://climatecompatiblegrowth.com/emp-a/) (Accessed 11 August 2023)

[120] Osterwalder A, Pignerure Y and Clark T 2010 *Business Model Generation: A Handbook for Visionaries, Game Changers and Challengers* (Strategyzer Serires)

[121] African Development Bank 2020 Green mini-grid developers help desk *Green Minigrid HelpDesk* (available at: https://greenminigrid.afdb.org) (Accessed 14 August 2023)

[122] Babayomi O O, Olubayo B, Denwigwe I H, Somefun T E, Adedoja O S, Somefun C T, Olukayode K and Attah A 2023 A review of renewable off-grid mini-grids in Sub-Saharan Africa *Front. Energy Res.* **10** 1089025

[123] Tonini F, Sanvito F D, Colombelli F and Colombo E 2022 Improving sustainable access to electricity in rural tanzania: a system dynamics approach to the matembwe village *Energies* **15** 1902

[124] GIZ, BMZ and ESMAP 2013 Productive use of energy—PRODUSE—measuring impacts of electrification on small and micro-enterprises *PRODUSE initiative*

[125] Blimpo M P and Cosgrove-Davies M 2019 *Electricity Access in Sub-Saharan Africa: Uptake, Reliability, and*

*Complementary Factors for Economic Impact* (World Bank) (https://doi.org/10.1596/978-1-4648-1361-0)

[126] Raitzer D A, Blondal N and Sibal J 2019 Impact evaluations of energy interventions: a review of the evidence (Asian Development Bank) (https://doi.org/10.22617/TCS190113-2)

[127] White H and Raitzer D A 2017 Impact evaluation of development interventions: a practical guide

[128] OECD 2021 Evaluation criteria—OECD (available at: www.oecd.org/dac/evaluation/daccriteriaforevaluatingdevelopmentassistance.htm) (Accessed 7 November 2021)

[129] Castor J, Bacha K and Fuso Nerini F 2020 SDGs in action: a novel framework for assessing energy projects against the sustainable development goals *Energy Res. Social Sci.* **68** 101556

[130] Colombo E, Romeo F, Mattarolo L, Barbieri J and Morazzo M 2018 An impact evaluation framework based on sustainable livelihoods for energy development projects: an application to Ethiopia *Energy Res. Soc. Sci.* **39** 78–92

[131] Trafimow D and Osman M 2022 Barriers to converting applied social psychology to bettering the human condition *Basic Appl. Soc. Psychol.* **44** 1–11