**Grid versus off-grid electricity access options: A review on the economic and environmental impacts**

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**Abstract**

This research reviews the economic and environmental impacts of grid-extension and off-grid systems, to inform the appropriate electrification strategy for the current population without electricity access. The principal technologies reviewed are centralised conventional fossil-fuel grid-extension and mainly solar PV and batteries off-grid systems. It finds that relatively few studies explicitly compare grid-extension electricity costs against off-grid systems costs and that there is a lack of consistency in the methodologies used to determine the least-cost solution. Nevertheless, the studies reviewed show a range of around $0.2-1.4/kWh for off-grid electricity access, compared to a range of below $0.1/kWh to more than $8/kWh for grid access, pointing to a number of cases in which off-grid access may already be the more cost-effective option. Existing literature on the environmental impacts primarily focuses on greenhouse gas emissions from electricity generation, with off-grid (solar PV and storage) systems’ emissions in the range of 50-130 gCO2-eq/kWh and grid generation from close to 0 gCO2-eq/kWh (for renewables and nuclear sources) to over 1,000 gCO2-eq/kWh (for coal). Emissions impacts stemming from transmission and distribution grids suggest a range of 0-30 gCO2-eq/kWh. Assessments of other environmental impacts such as water use, land use, biodiversity and e-waste are often absent in studies, whilst few studies explicitly compare the environmental impacts of grid versus off-grid systems. Further research should focus on comparing the costs of electricity access options using consistent metrics, expanding the scope of environmental impacts analysis, and integrating environmental and economic impacts into a comprehensive sustainability assessment of different options.

**Keywords:** Energy access, rural electrification, grid extension, off-grid systems, economic implications, environmental impacts

**Highlights**

* Comprehensive review of grid versus off-grid costs and environmental impacts
* Off-grid costs in range $0.2-1.4/kWh; grid extension < $0.1/kWh to > $8/kWh
* Solar PV off-grid emissions range 50-130 gCO2-eq/kWh, grid ~0 to >1,000 gCO2-eq/kWh
* Studies differ in cost methodology used, and lack wider environmental analysis
* Methods integrating cost and environment impact required for holistic comparisons

**Word count:** 7954

**Abbreviations:**

BOS: Balance of systems

CBA: Cost-benefit analysis

CED: Cumulative energy demand

CO2: Carbon dioxide

CO2-eqPBT: Carbon dioxide equivalentpayback time

EIA: Environmental impact assessment

EPBT: Energy payback time

ESMAP: Energy Sector Management Assistance Programme

EYR: Energy yield ratio

GER: Gross energy requirement

GHG: Greenhouse gas

Gt: gigatonnes

GWP: Global warming potential

HOMER: Hybrid Optimisation Model for Electric Renewables

HV: High -voltage

IEA: International Energy Agency

IPCC: Intergovernmental Panel on Climate Change

IRENA: International Renewable Energy Agency

ISO: International Organisation for Standardisation

km: kilometre

kWh: kilowatt-hour

LCA: Life cycle assessment

LCC: Life cycle costing

LCOE: Levelised cost of electricity

LCSA: Life cycle sustainability assessment

LV: Low -voltage

MCDM: Multi-criteria decision-making

MTF: Multi-tier framework

MV: Medium -voltage

MW: megawatt

NER: Net energy ratio

NOx: Nitrogen oxides

N2O: Nitrous oxide

PV: Photovoltaics

PVLCC: Present Value of life cycle costing

SDG: Sustainable Development Goal

SEA: Strategic environmental assessment

SF6: Sulphur hexafluoride

SHS: Solar home systems

SOx: Sulphur oxides

SO2: Sulphur dioxide

T&D: Transmission and distribution

UN: United Nations

UNSD: United Nations Statistics Division

USD: United States Dollar

WB: World Bank

WHO: World Health Organisation

WTA: Willingness to accept

WTP: Willingness to pay

**Nomenclature:**

*It* investment expenditure in year *t*

*Ft* fuel expenditures

*Et* electricity generation

*r* discount rate used to calculate the present value of all other costs

*n* lifetime of the system

*IC* investment costs in year *t*

*N* length of the study period

*COM* operating, maintenance and repairs costs

*R* replacement costs

*F* fuel costs

*S* residual value

1. **Introduction**

Lack of access to electricity and clean cooking are the main indicators of energy poverty [1]. In 2018, 789 million people lacked access to electricity; moreover, household access remained unreliable or unaffordable in many countries [2]. This situation is especially pronounced in rural regions of developing countries. Sustainable Development Goal (SDG) 7 aims to provide universal access to affordable, reliable and modern energy services for all by 2030 [3]. A key facet of SDG7 is to close the gap of people without energy access. Several governments have plans to address this issue, but the International Energy Agency’s (IEA) Stated Policies Scenario[[1]](#footnote-1) suggests that around 620 million people would still lack access to electricity in 2030 [4].

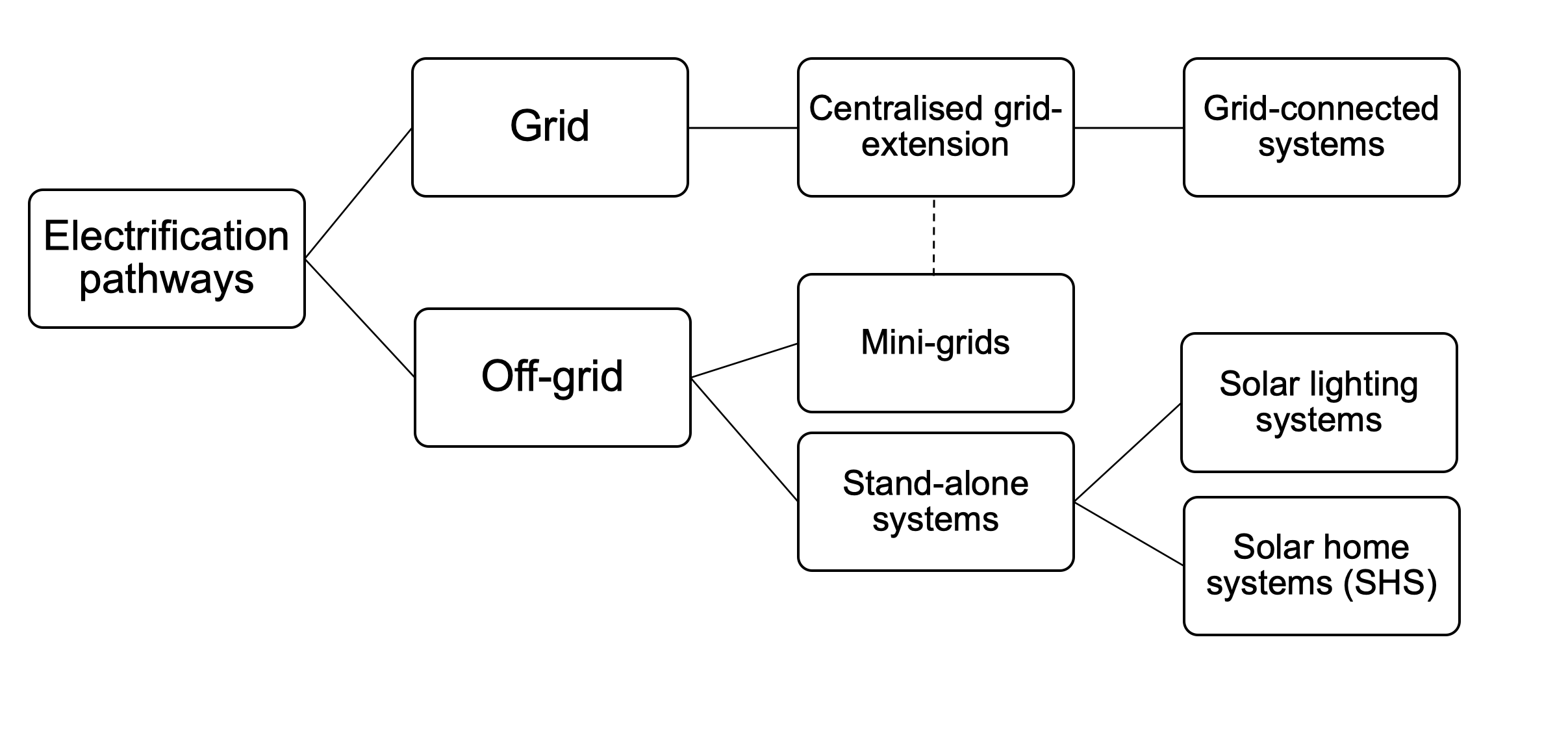
Globally, grid-extension has been the predominant approach for electricity provision. Around 600 million people (representing 97% of new connections) gained access mainly via grid-extension, powered by fossil fuels, between 2000-2016 [1]. The main advantage of grid networks is the supply of low-cost power and high-power levels (depending on grid reliability) once the connection has been made [5]. The grid can supply large quantities of electricity which enable the operation of high-power and very high-power appliances such as cooling, heating and refrigeration; allowing households to meet all their electricity needs [6]. It can also enable commercial and industrial applications [5]. Another advantage of the grid is that it is generally cheap, if the option of connection is available, especially for households located in densely populated areas and/or with high consumption [1,7]. Furthermore, a grid connection potentially allows the choice of several electricity retail providers, with this competition amongst providers placing a downward pressure on costs and prices. Ancillary services help the grid maintain its stability and reliability [8]. However, grid-extension has been carbon-intensive, requires large capital investments, needs long-time for its infrastructure construction and the electricity supply is often unreliable in some locations [5,9,10]. Alstone et al. [5] showed that since the late 1800s, global population growth has outpaced grid-extension, demonstrating that there has been a consistent gap of 1-2 billion people without electricity access. Moreover, despite countries with significant electricity access, supply is unreliable and weak. For example, in Mexico whereby 99% of households are connected to the grid [11], ranked 72 out of 137 countries in the ‘Quality of electricity supply’ indicator measured by the World Bank (WB), which compares interruptions and voltage fluctuations in different countries to assess reliability of supply [12]. In addition, the combustion of fossil fuels is the major driver of climate change [5,9,13], it has historically caused air pollution [14], likewise having a negative impact on health. Thus, fossil fuels are not a cost-effective electrification option when environmental externalities are considered [15,16]. It is important to note that there are grids with a high share of renewable sources as it is the case of Denmark; almost half of the country’s electricity consumption was sourced from wind power in 2019 [17]. At the same time, rural electrification interventions in developing countries have frequently used fossil-fuel off-grid systems such as diesel generators, which are also carbon-intensive [15].

There is an alternative to grid-extension through technology innovations such as off-grid renewables. Steady cost decreases in solar photovoltaics (PV) and battery storage coupled with the growth of mini-grids and stand-alone systems provide an opportunity to achieve SDG7 through off-grid low-carbon electricity systems, capitalising on the significant renewable resources available in many developing countries. It has been noted that many such countries, particularly in Sub-Saharan Africa, have the opportunity to establish a more decentralised and renewable energy provision [18] without heavily investing in centralised and often fossil-fuel based solutions. Nevertheless, a recent study predicts that the share of non-hydro renewable sources in electricity generation will likely remain below 10% in Africa by 2030; posing risks of high-carbon lock-in in this region [19]. From the renewable options available, solar technologies have emerged as a power generation alternative to fossil fuels owing to their scalability and increasing cost reductions. Solar PV modules costs have dropped 90% since 2010, whilst the global cost of electricity from utility-scale solar PV has decreased 82% since 2010, reaching a global weighted-average levelised cost of electricity (LCOE) of 0.068 USD$/kWh in 2019 [20]. Lead-acid and lithium-ion batteries are commonly used in renewable energy systems, but this increases the costs of electricity provision [9,16]. However, storage technology costs are projected to reduce considerably in the future [21,22]. In addition to solar technologies, other renewable sources such as wind [23], hydropower [24] and biomass [25,26] have been analysed in the literature as potential electrification solutions in developing countries. In recent years, off-grid systems have been increasing electricity supply around the world. In 2018, over 35 million people had access to Tier 1 and above through stand-alone systems and mini-grids. Tier 1 refers to an electricity supply which is able to support very low-power appliances such as task lighting and phone charging [6]. In 2010, around one million people had access to electricity services below Tier 1, mainly via solar home systems (SHS) and solar lighting, compared to 136 million people in 2018 [2]. Hence, off-grid renewable energy systems are an essential intermediate step to improve electricity provision [5] and are crucial for last-mile electricity provision [27]. In spite of their advantages, off-grid renewable systems require high upfront capital investments and power is supplied intermittently [7,16]. Other drawbacks of these systems are limited capacity of electricity supply compared to the grid [6,7,28], lower power quality [29,30], and lack of local skillful staff to operate and maintain the systems [7,31]. The arrival of the grid can result in technical and financial challenges for off-grid systems [28]. Moreover, in some cases even with off-grid access available, the community aspires to be connected to the grid [32,33,34].

Thus, it is important to assess the relative costs and benefits of grid-extension and off-grid systems to meet the needs of the population that does not currently have electricity access. At this time, there is no thorough assessment of how the attributes of these different approaches compare. The current literature has specific studies evaluating particular aspects of the issue, such as understanding the relative costs or carbon dioxide (CO2) emissions of electricity generated in certain regions. These studies are discussed in detail in Section 2 and 3. Few other studies have reviewed the methods available to compare different electrification strategies. For example, Morrissey [35] carried out a systematic review comparing the results of least-cost electrification models with study limitations noted due to the different geographies, technologies and parameters used. Similarly, Ciller and Lumbreras [36] reviewed the tools available for rural electrification planning and concluded that most tools focus on economic optimisation only. In order to provide an up-to-date and comprehensive review, we evaluate grid and off-grid systems, considering their major implications, crucially including their environmental and economic implications. In addition to the most studied environmental impact, greenhouse gas (GHG) emissions, here we consider grid and off-grid electrification impacts on biodiversity, land footprint and electronic waste (e-waste) generated. Moreover, we look at the integration of economic and environmental metrics to undertake a comprehensive assessment of electrification options.

In brief, this review compiles and synthesises a wide range of literature on the economic, environmental and other non-technical implications of each solution to evaluate the appropriate rural electrification strategy for different regions. We also discuss the advantages and the limitations of each electrification solution. By critically reviewing this literature for its completeness and comparability, we aim to identify evidence gaps which must be addressed in order to understand the performance and suitability of these two electrification strategies in different situations. These gaps are, most importantly, the lack of consistency in the methodologies used to determine the least-cost solution and the limited scope and coverage of the environmental impacts of grid and off-grid systems.

Before embarking on this review, it is important to define key terms used in this research area. Typically, energy access has been used as a binary metric to describe if there is a grid connection in a household, an electric pole in a village or an electric bulb in a house [6]. The multi-tier framework (MTF) was set out by the World Bank (WB) to devise a more comprehensive definition, including off-grid systems, and considering energy attributes previously overlooked in binary metrics such as capacity, duration, reliability, quality, affordability, legality, and health and safety (see Appendix A) [6]. For the purpose of this review, grid electricity access refers to conventional centralised grid-extension systems typically powered by fossil-fuels and off-grid refers to decentralised solutions including stand-alone and mini-grid technologies powered mainly by renewables such as solar PV and batteries. Decentralised and off-grid systems are considered synonyms in this context. We acknowledge the term micro-grid is used widely on the literature, for simplicity we grouped it in the mini-grid category. For this study, stand-alone systems refer mainly to solar lighting systems and SHS. Grid-connected refers to independent decentralised systems connected to a grid network [9], in this case that is mini-grids connected to the grid (see Figure 1).



**Figure 1:** Typology used for electrification pathways. The present study uses solar as a typical example for off-grid, but off-grid could also include biomass, wind, diesel, small hydro, or any combination of these technologies (hybrid systems).

Off-grid systems are independent of electricity generated and supplied by the centralised grid and have a (semi)-autonomous capability to cover electricity demand through local power generation [37]. Stand-alone are small systems for individual appliances or users with a capacity of up to 100 Watts [37]. Mini-grids are localised power networks serving multiple customers with a capacity of up to 100 MW; they have a distribution system and can be connected to the grid or interlinked with other mini-grids [37].

The remainder of this paper is set out as follows, Section 2 describes metrics and modelling tools used to compare grid versus off-grid costs and reviews the literature available on economic comparisons. The environmental impacts of each system beyond GHG emissions and electricity generation are reviewed and illustrated in Section 3. Then, Section 4 presents techniques to carry out a comprehensive evaluation of impacts and overviews previous studies that have applied this analysis in an energy access context. Finally, Section 5 concludes the main research gaps and challenges and proposes recommendations for future work to undertake a truly comprehensive and meaningful comparison between grid and off-grid strategies.

1. **Comparing grid versus off-grid costs**

Palit & Bandyopadhyay [10] assert that ultimately the criteria that govern the choice between grid-extension and off-grid systems are the least-cost technology option with minimum maintenance requirements. However, several other factors have been identified as important, including policy decisions, existing electricity infrastructure, energy resource availability, technology costs and socio-economic conditions of the country [5,38]. For example, Kaundinya et al. [9] state that, regardless of the system configuration, it is important to make a techno-economic and environmental assessment to determine the feasibility of an energy system. Since most of the comparison between electrification pathways focus on the economic criteria [35,36], we reviewed the literature available to analyse the underlying sources of variability across economic comparisons (see Section 2.5).

The economic feasibility of grid-extension depends on the distance from the grid, topology, population density and electricity demand [15,38]. Distribution costs are higher for villages located in hilly terrains than for ones located in plain terrains [39]. Distance from the grid is the most important economic consideration in choosing locations for off-grid deployment. The breakeven distance determines the maximum distance after which off-grid systems are more economically viable than grid-extension [16]. The suitability of grid-extension, mini-grids installation or stand-alone systems deployment depend on the characteristics of a given population. Rural areas are often characterised as being remotely located in complex terrains with small and sparsely populated communities such that providing electricity supply in these areas with centralised systems is prohibitively expensive. Mini-grids and stand-alone systems become more cost-effective in this case [9,38,40]. Previous studies have emphasised the importance of considering different electrification pathways as complementary solutions to enhance energy security. Hence, they mentioned that integral solutions need to be contemplated by governments when planning for electricity infrastructure [10,38]. However, it is not possible to define a one-size-fits-all solution given each country’s social, political, environmental and technical differences [10,41].

***2.1 Metrics used to compare grid-extension with off-grid system costs***

The most common metric used to compare the costs of different electrification pathways is the LCOE, which is the final price of electricity required for the energy system to achieve breakeven of the project’s total costs over its lifetime. It includes the net present value of all the costs incurred during the system lifetime divided by the discounted electricity generated [42]. The LCOE formula is represented as:

(1)

*It* represents the investment expenditure in year *t, COMt* are the operation and maintenance expenditures, *Ft* are the fuel expenditures, *Et* is the electricity generation, *r* is the discount rate and *n* is the lifetime of the system [42].

Another approach used is the life cycle costing (LCC) method, where all the costs incurred by the main producer or user during the life cycle of a product are considered. This conventional LCC assessment includes the purchase price of the product and the discounted costs over its lifetime. The formula to calculate the Present Value of LCC (PVLCC) is:

(2)

*IC* represents investment costs in year *t*. *N* is the length of the study period and *r* is the discount rate used to calculate the present value of all other costs. *COM* represents operating, maintenance and repairs costs; *R,* replacement costs; *F,* fuel costs and *S,* residual value [43].

Another type of LCC is Environmental LCC, which considers the costs borne by other actors and, hence, it includes the internalisation of externalities costs. Some examples for externalities costs are waste disposal costs, CO2 taxes and climate adaptation costs [44,45]. Despite these differences, both metrics are used in the literature as a basis to calculate the breakeven or economical distance limit to determine the critical distance beyond which off-grid systems are the least-cost option versus grid-extension [13,32,39,46]. Some authors compare the LCOE of off-grid systems with the average connection costs per household [42,47], while others define the breakeven electricity consumption level for which the cost of an off-grid system is equivalent to a grid connection cost [48,49].

***2.2 Modelling tools for energy access planning***

A number of modelling tools can be used for comparing electrification strategies. For instance, the Hybrid Optimisation Model for Electric Renewables (HOMER) optimises the system design based on technical properties and the LCC of the system and calculates the breakeven distance [50]. Narula, Nagai and Pachauri [51], compared the cost effectiveness of centralised and decentralised distributed generation technologies in the South Asian region, using a variant of the Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE-Access model). In addition, several modelling tools have been developed to support rural electrification planning by comparing grid-extension, mini-grids and stand-alone options. Ciller and Lumbreras [36] classified these tools according to their modelling complexity. The authors noted that most rural electrification tools focus on economic optimisation only. Moreover, Morrissey [35] compared the results of existing models. Although a detailed description of these tools and their comparison is beyond the scope of this review, Table 1 summarises selected modelling tools according to Ciller and Lumbreras [36] classification framework.

**Table 1:** Summary of selected modelling tools for energy access planning. Adapted from [35,36].

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Classification | Model name/Institution | Technologies considered | Case studies | References |
| Pre-feasibility studies | OnSSET/Royal Institute of Technology (KTH) | Grid, mini-grid (PV, wind, diesel, hydro), stand-alone (PV) | Nigeria, Ethiopia, Sub-Saharan Africa, Kenya | [52-55] |
| Pre-feasibility studies | ECJRC/RE2nAF | Grid, mini-grid (diesel, PV, hydro), stand-alone (PV) | Africa, Burkina Faso | [18,56,57] |
| Intermediate analysis | Network Planner/Columbia University | Grid, mini-grid (diesel), stand-alone (PV) | Kenya, Senegal, Liberia, Ghana, Nigeria | [46,47,58-60] |
| Intermediate analysis | Reiner Lemoine Institut (RLI) | Grid, mini-grid (diesel and/or renewables+storage), stand-alone (PV) | Nigeria, Sub-Saharan Africa, Global (52 countries with low electrification rates) | [61-63] |
| Intermediate analysis | World Bank (WB) | Grid, mini-grid (PV, wind, diesel, PV, wind, biodiesel), stand-alone (PV, wind, diesel) | Ghana, Ethiopia, Kenya | [64] |
| Detailed generation and network designs | Reference Electrification Model/Massachusetts Institute of Technology (MIT) | Grid, mini-grid (PV, diesel), stand-alone (PV, diesel) \* | India, Kenya, Peru | [65-67] |

*\*Generation sources might vary depending on study*

Pre-feasibility tools generally group the electricity consumers into cells and compare electrification pathways based on their LCOE calculation. Although they do not compute the grid-extension network layout nor off-grid systems sizing, pre-feasibility tools offer valuable information with short computation time. Intermediate analysis tools calculate network layouts and some tools additionally size off-grid systems generation using analytic expressions and iterative methods. The third category refers to detailed generation and network analysis tools, which have the highest level of modelling complexity and thus the lowest computation speed. These tools provide accurate calculations of generation and network designs for grid-extension and off-grid solutions at a consumer level whilst considering electric constraints, topography and different sizes for lines and transformers. The Reference Electrification Model, developed by MIT, was the only tool belonging to this category [36].

***2.3 Costs of grid-extension***

Centralised grid system costs generally comprise extension of high-voltage (HV) transmission lines, medium-voltage (MV) and low-voltage (LV) distribution lines, transformers, and additional connection costs per household, which are costs for metering and wiring [46,68]. Investments required for grid-extension increase with longer distances between the load centre and the existing grid point, lower load factors, longer distribution lines and associated higher electrical transmission and distribution (T&D) losses [13]. For example, Narula et al. [51] found that every additional 1 MW of demand satisfied in unelectrified households by grid-extension costs four times as much as satisfying this demand through decentralised systems, in a so-called ‘minimum threshold scenario’, with a demand of 65 kWh per household per year, in the South Asian region. One reason for this is that LV lines for last-mile connectivity are the major component of cost for T&D [51]. Centralised generation costs are highly variable depending on the grid electricity mix and global fuel prices. Countries with high fossil fuels subsidies tend to favour these generation sources over renewables [49]. Out of 39 utilities in Sub-Saharan Africa, only two charged electricity tariffs that allowed them to reach cost-recovery; the average cost-reflective tariff for the region is 0.27 USD2016 $/kWh [69].

***2.4 Costs of off-grid systems***

Off-grid electricity generation costs are determined by the technology, resource availability and other operating factors [39]. For stand-alone systems, costs involve electricity generation and additional wiring costs. Supplementary equipment, known as balance of systems (BOS), is required to condition, transmit and store the surplus electricity. Typical components of BOS equipment include batteries, charge controller, power conditioning equipment (that is inverters to convert electricity for AC appliances), safety equipment and meters and instrumentation [70]. Solar PV mini-grids include costs of the PV module and BOS components comprising battery storage. An additional expenditure for mini-grids is the LV lines needed for distribution [68]. For both systems, associated costs are installations costs which can involve labour, design, management and insurance scaffolding [71]. Although up-front costs represent the major portion of the levelised costs of PV systems, the costs of key solar mini-grid components have fallen by 62-85% in the last 10 years [69]. In hybrid systems, diesel generators are usually used as a backup resource due to their lower up-front capital expenditures per kilowatt installed. However, fuel cost variability and fuel transport increase their costs, making fuel consumption the major contributor of the levelised cost for diesel generators [56]. Thus, depending on the power source, mini-grid costs can vary considerably [72]. A cost analysis of 12 mini-grids (solar and solar-hybrid) in Africa and Asia, undertaken by the WB, resulted in a mini-grid LCOE between 0.55-0.85 USD2019$/kWh, with a projected decrease to 0.22 USD$/kWh by 2030 [69].

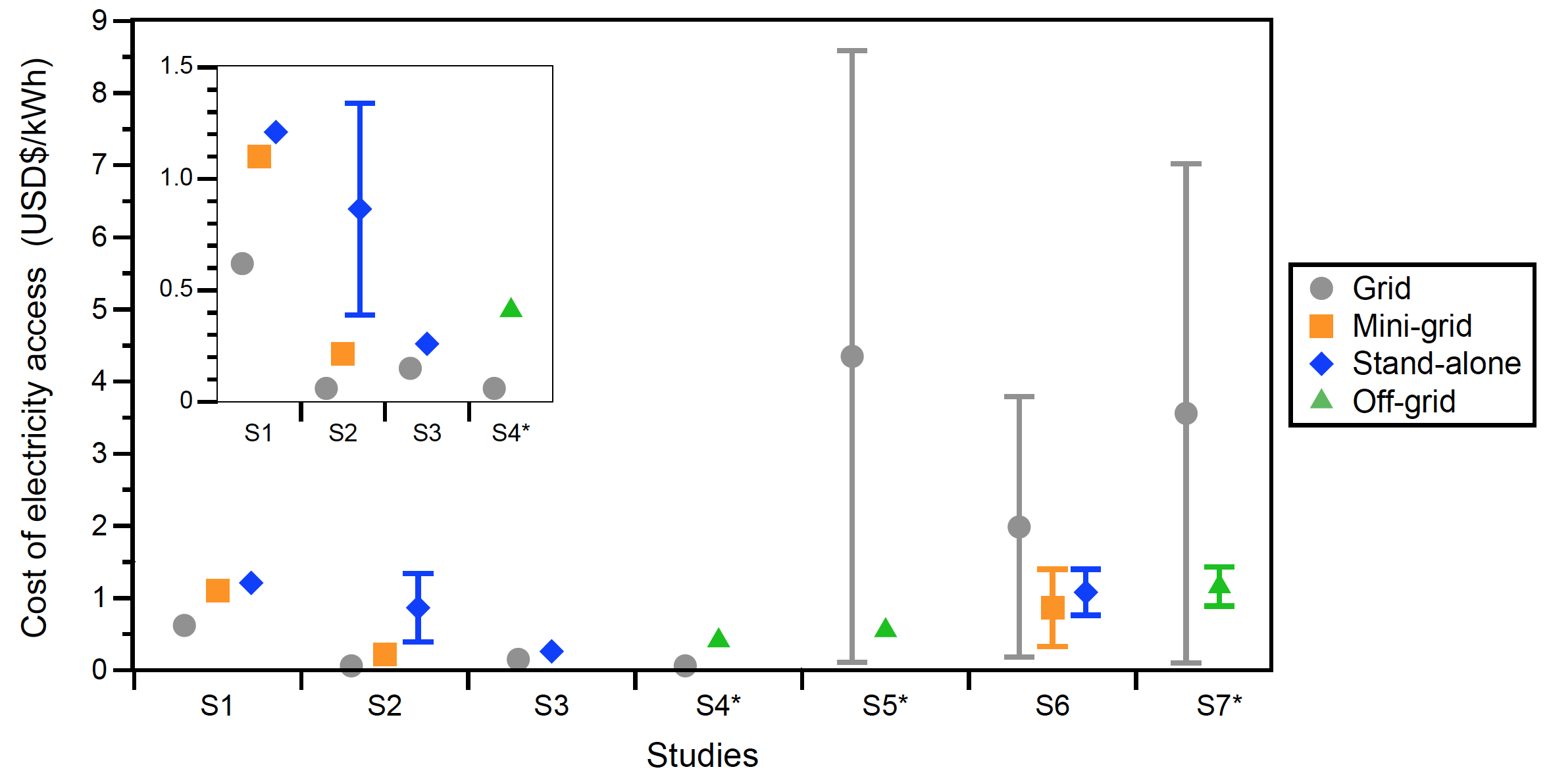
***2.5 Review of publications comparing grid and off-grid costs***

We have identified 16 peer-reviewed publications which explicitly compare grid-extension and off-grid systems (see Appendix B). There are numerous other publications that analyse off-grid system costs and a few others that evaluate grid-extension costs in isolation, but for the purpose of this research we focus only on studies that make an inter-comparison of both options. The generation sources analysed in these studies include fossil-fuel power plants, diesel generators, solar PV, wind, battery storage, hydroelectric, biomass and biogas, or a combination of these technologies, known as hybrid systems. For the most part, grid-extension is the least-cost option, but given that its cost range can vary widely, off-grid systems are the preferred option in some cases.

Out of these 16 publications, only 7 of them provide evidence of costs explicitly comparing these options, either using generation costs, levelised costs or LCC metrics. The other 9 studies also aim to find the least-cost option to meet the electricity demand of a target population and some of them even analyse the influence of certain parameters on energy access dynamics, namely population density, target level and quality of access, local energy resources, among others [42]. However, these papers do not disclose all the estimated costs of their analysis. The main findings of the studies not included in Table 2 are mentioned at the end of this section. Table 2 lists the final selection of the papers to illustrate the differences in costs between grid-extension, mini-grids and stand-alone systems in Figure 2. For the selected studies, we adjusted their values to 2018[[2]](#footnote-2) USD using the Consumer Price Index and converted to USD when the original data was reported in another currency. It is important to note that for off-grid systems, this chart only presents the costs of solar PV technologies; in some studies, various generation sources were modelled.

**Table 2:** List of papers comparing grid-extension and off-grid systems costs. Studies\* do not explicitly explain if off-grid refers to stand-alone or mini-grids.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Study | Reference | Location | Demand type | System architecture (SA) | Considered technologies | Notes |
| S1 | [46] | Ghana | Household, productive, commercial & institutional | SA #1: Mini-grid | Diesel generator with LV distribution | LCOE, costs include generation, T&D. |
| SA #2: Stand-alone | SHS with diesel generator |
| S2 | [68] | Worldwide regions | Household level | SA #1: Mini-grid: | Wind or diesel | Only LCOE generation values reported. |
| SA #2: Stand-alone: | Solar PV |
| S3 | [73] | Kenya | Household level | SA #1: Stand-alone | PV system (panels and batteries) | Costs in optimal solution of baseline scenario. |
| S4\* | [13] | India | Household level | Off-grid (unspecified) | PV-battery systems | LCC values of off-grid biomass gasifier not disclosed. LCC value of grid considered a conservative estimate by authors. |
| S5\* | [32] | Bangladesh | Household level | Off-grid (unspecified) | Solar PV | Levelised cost of delivered electricity by grid expansion varies (load and line lengths). Other generation sources analysed. |
| S6 | [64] | Ethiopia | Household level | SA #1: Mini-grid | Combined solar PV-wind system with batteries | Baseline estimates of levelised costs. Other generation sources modelled. |
| SA #2: Stand-alone | PV solar |
| S7\* | [39] | India | Household level | Off-grid (unspecified) | PV electricity generator | Delivered cost of grid electricity. Levelised unit cost of electricity for decentralised generation and supply. |



**Figure 2:** Chart illustrating the evidence of costs from different electrification strategies in USD2018. Studies\* refer to off-grid unspecified (studies do not explicitly explain if off-grid refers to stand-alone or mini-grids). The circle in the middle of the whisker plot represents the midpoint of each range. The inset in the top left corner is a higher resolution plot of studies S1 to S4. Depending on the study, the cost of electricity access was calculated using different metrics (e.g. LCOE, LCC) as indicated in Table 2.

Figure 2 shows that grid-extension is the least-cost option in most of the selected studies, but it also shows that grid extension costs are highly dependent on assumptions made. For example, in study S5 [32], the wide variation in the range of the delivered costs of grid electricity (0.11-8.59 USD$/kWh) is explained by the different line lengths (1-25 km) and load conditions (5-50 kW) calculated in remote areas of Bangladesh. Similarly, study S6 [64] concluded that stand-alone renewables are cost competitive in rural areas while grid-extension is more cost-effective in denser areas. Likewise, the wide range of the estimated delivered cost of the Indian grid electricity (0.10-7.02 USD$/kWh) is because study S7 [39] considered plain and hilly areas with different peak loads and load factors for their calculations. In brief, as shown in studies S5, S6 and S7, it is clear that the cost range of extending the grid can vary widely. Thus, there is an opportunity for off-grid systems to meet electricity needs where the grid is too costly to do so, and this may increasingly be the case given the significant cost reductions projected for such systems [69].

Previous studies concluded that renewable off-grid systems are the least-cost option to supply electricity in small remote villages, with low load demand, in India and Bangladesh [13,32,39]. For example, Narula et al. [51], found that in their scenario considering lower demand levels (electricity consumption of 65 kWh per household per year versus scenario with higher demand of 420 kWh per household per year), decentralised technologies were more cost-effective than the grid to achieve 100% electrification by 2030 in the South Asian region. Likewise, Amutha and Rajini [50] showed that a hybrid system, comprised of solar, wind, hydropower and battery storage, was the cost-optimal solution to cover the electricity needs of a village in South India. Zeyringer et al. [73] concluded that off-grid PV systems were cheaper than grid-extension in most regions of Kenya, while Parshall et al. [47] demonstrated that grid-extension was the least-cost option in this case. These contrasting results can be explained because the latter study used higher demand values and lower grid-extension costs than Zeyringer et al. [73].

Notably, a study conducted by Kemausuor et al. [46] found grid-extension as the cost-optimised solution for more than 85% of the 2,600 un-electrified communities analysed in Ghana, due to the country’s extensive pre-existing grid network coverage. Since grid supply was found to be cheaper than off-grid systems in densely populated areas of Ethiopia, Ghana and Kenya, Deichmann et al. [64] emphasised the importance of decarbonising the electricity mix for centralised power generation in Africa. According to Nerini et al. [42], grid-extension is the least-cost solution for the majority of the newly electrified households in Nigeria and Ethiopia, at 85% and 93%, respectively. However, the authors showed that mini-grids and off-grid systems are more cost-effective to reach the remaining low-density populations in both countries. This is in line with the findings from Szabó et al. [18] and Dagnachew et al. [7] for Sub-Saharan Africa. Some studies also demonstrate that the least-cost option can vary depending on the different electricity access targets considered [7,42,49]. Similarly, van Ruijven et al. [68] concluded that mini-grids and stand-alone systems will have a greater cost-effective potential in rural areas of Africa and Latin America due to the high grid connection investments needed in low population density areas. Finally, Levin and Thomas [49] stated the key role of SHS in cost-effectively providing universal access to basic energy services, equivalent to Tier 1 and Tier 2, in developing countries. They suggested that this approach should be complemented with centralised systems to improve access to Tier 4 and Tier 5 standards, as demand grows.

***2.6 Major analytical gaps in understanding the relative economic costs***

One of the main challenges of comparing existing studies is that authors use different metrics to determine the least-cost option. Some authors report LCOE for generation only [68], whereas other studies calculate the delivered costs of electricity which include the levelised unit cost of generation and T&D [32,39,64]. In some studies, the national costs of grid electricity or tariffs are used as a proxy for centralised grid costs [18], which can be heavily subsidised and thus make the fossil fuel options appear more competitive. The levelised cost of used electricity is an alternative metric that could be applied to consider the electricity that is of actual value to the community [74].

Moreover, there can be large uncertainty ranges for the generation costs of grid and off-grid options, due to uncertainty in the investment costs for grid electrification, in particular [68]. For example, Blechinger et al. [63] estimated the initial investment needed globally by 2030 for the implementation of three different scenarios for electrification pathways. However, grid-extension costs excluded investment in centralised power generation in their analysis. For each scenario, the authors considered grid-extension costs of 2,500 USD per household connection (representing grid infrastructure investments), mini-grid investment costs between 1,000-6,000 USD, and SHS costs of 300-1,300 USD, per household connection. The study concluded that off-grid technologies often require lower initial investments than grid-extension to achieve SDG7 [63].

Another challenge is in the assumptions used to estimate the current electricity demand and expected demand growth in the future. For instance, Zeyringer et al. [73] calculated demand growth based on economic and population growth. In contrast, in the study conducted by Deichmann et al. [64], population growth is not considered. For these reasons, most of the studies include sensitivity analysis to assess the influence of certain variables in the optimal electrification solution. In general, the key parameters changed are costs, electricity demand, population density, distances and target level of access. Nevertheless, understanding relative costs of grid-extension and off-grid systems, considering all relevant costs and using consistent metrics, remains a critical area for further research in order to provide a complete and useful cost comparison.

The findings of the studies reviewed in this section are summarised in Table 3.

**Table 3:** Summary of findings of least-cost option for each electrification strategy.

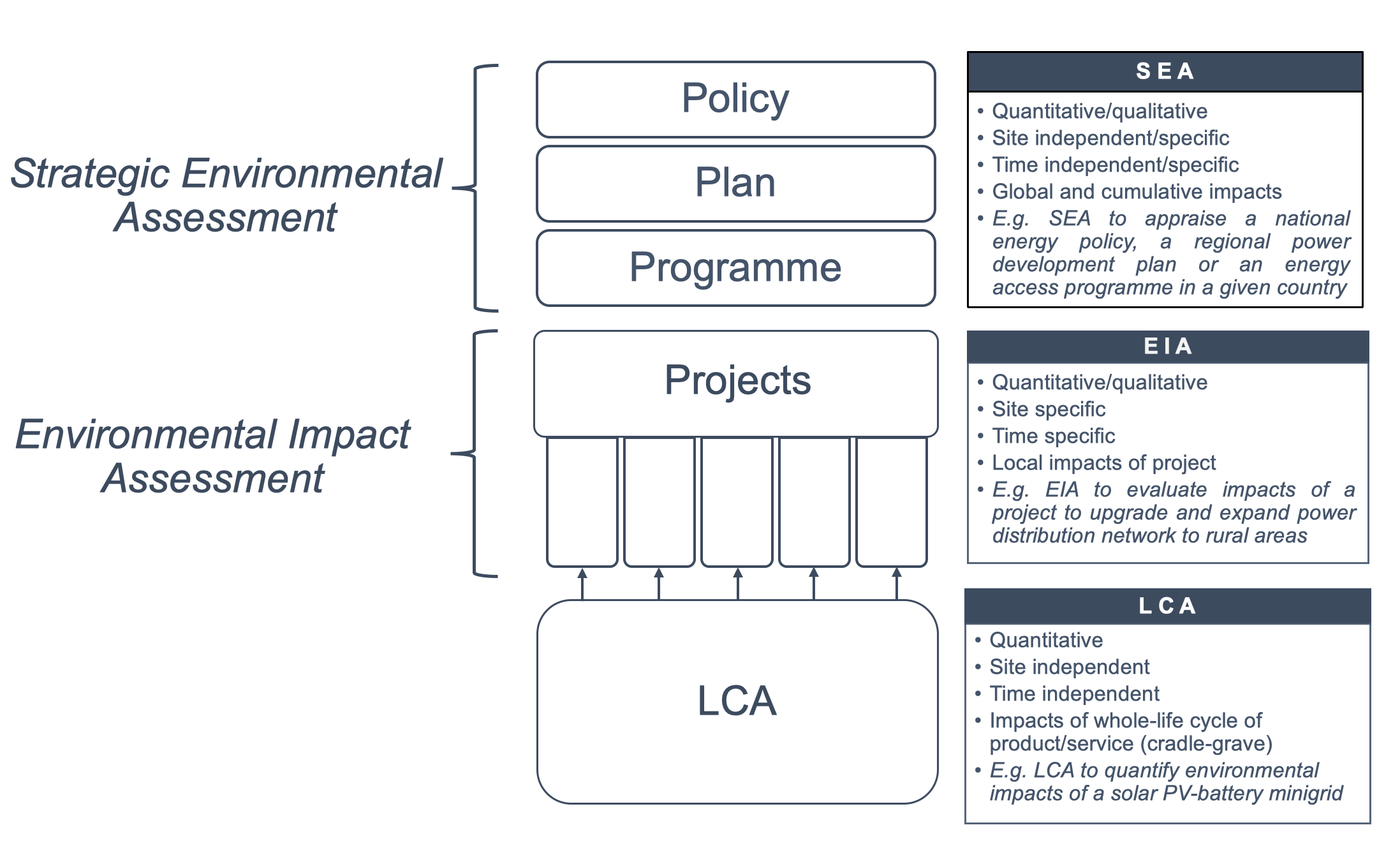
|  |  |  |  |
| --- | --- | --- | --- |
| Least-cost option | Study | Characteristics involved | Gaps and challenges |
| **Grid-extension** | [47] | Densely populated areas  Higher demand levels  Proximity to the grid  Pre-existing grid network coverage  Access to higher energy services (Tier 4 and 5) | -Different metrics used to determine the least-cost option, e.g. LCOE generation vs delivered costs (includes T&D) vs costs of grid tariffs as proxy (can be heavily subsidised)  -Large uncertainty ranges for generation costs given uncertainty in grid investment costs    -Assumptions used to estimate current demand and expected growth in the future |
| **Off-grid** | [13]  [32]  [39]  [50]  [51]  [73] | Rural areas, low-density populations  Lower demand levels  Large distance from the grid  Local renewable sources supplying electricity to remote villages with low load demand  High grid connection investments needed  Access to universal access to basic energy services (Tier 1 and 2) |
| **Combination** (depends on community’s characteristics) | [7]  [18]  [42]  [46]  [48]  [49]  [56]  [64]  [68] | Wide variations in cost range of grid-extension due to different line lengths, load conditions, peak demand, topography (plain/hilly areas), assumed costs, target level of access |

1. **Comparing grid versus off-grid environmental impacts**

***3.1 How have environmental impacts of grid-extension and off-grid electrification been considered?***

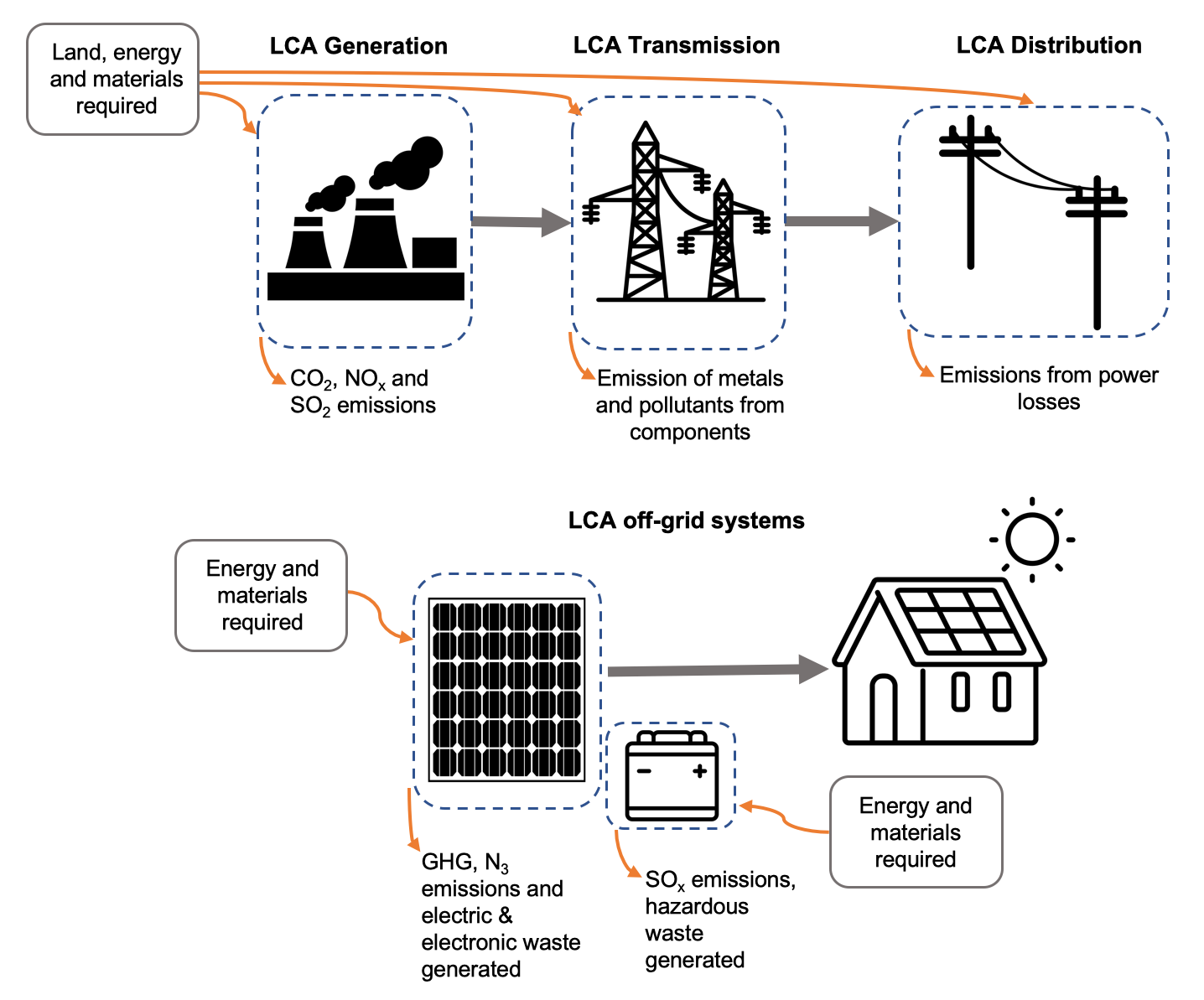
Aside from cost, environmental impacts are a critical consideration in comparing different electrification options to meet SDG7, since these touch on a number of other SDGs (including SDG6, Clean water and sanitation; SDG13, Climate action; and SDG15, Life on land). As already noted, some studies consider environmental externalities in their analysis and include them in their calculations of LCC, as well as LCOE. For example, Mainali and Silveira [15] incorporated the environmental costs by considering emissions factors from different generation technologies and monetising the burdens caused by these emissions, using the damage cost or external cost of energy ($/kWh). The impacts of energy use considered were CO2, nitrogen oxides (NOx) and sulphur oxides (SOx) emissions at each stage of the life cycle activities, including construction, operation, dismantling and fuel cycle of the technologies assessed.

Multi-criteria decision-making (MCDM) methods also consider factors in their environmental dimension to compare different technologies (see Section 4 below). The criteria chosen depends on the study, but generally include pollution emissions, including GHG emissions, local environmental impact, noise emissions, and aesthetics [32,75]. Environmental Impact Assessment (EIA) and Strategic Environmental Assessment (SEA) are specific tools to evaluate potential environmental impacts and propose mitigation strategies to prevent and limit them. EIA focuses on a specific project and the measures suggested to manage its negative impacts whereas SEA appraises the environmental impacts of a proposed policy, plan or programme, and thus their scope is more comprehensive, as illustrated in Figure 3. SEAs aim to improve strategic decision-making towards sustainable solutions. For instance, EIA could evaluate the potential effects of a utility scale solar farm project while SEA will be a useful method to appraise the energy policies developed in a given country, taking into account many projects encompassed by those policies [76,77].



**Figure 3:** Image showing methods to assess environmental impacts. ‘Site independent’ and ‘time independent’ indicate that no consideration is given to when and where the impacts occurred, producing a site-generic result. Adapted from [76,78].

As shown in Figure 3, a method widely used to quantify the environmental impacts of energy systems is Life Cycle Assessment (LCA) analysis. The International Organisation for Standardisation (ISO), through ISO 14040 and 14044, serves as a standard for the LCA methodology [79]. LCA assesses the impacts of products and services by identifying the energy and materials used and waste released into the environment throughout their life cycle. In the impact assessment phase of the LCA analysis, the aim is to understand and evaluate the extent and significance of the potential environmental impacts of a certain product. To carry this out, different categories representing environmental issues and interventions such as climate change, loss of biodiversity and ecotoxicity, among others, are included. For energy systems, the functional unit typically used to evaluate the related environmental impacts is the delivery of 1 kWh of electricity to end users [80,81]. Depending on the scope of the LCA study, the impacts could be on the generation, transmission or distribution of electricity (see Figure 4). However, most studies focus on the environmental consequences of electricity generation. Few studies assess the impacts from T&D of electricity. Furthermore, Turconi, Simonsen, Byriel, and Astrup [82] found only one LCA study that explicitly covers the impacts of both generation and T&D in their analysis. Environmental impacts of grid-extension versus off-grid systems using LCA analysis centre on climate change as an impact category.



**Figure 4:** Schematic of severalenvironmental impacts of grid-extension and off-grid systems.

Electricity provision requires energy and materials for the extraction of raw inputs, manufacture, transport, installation and maintenance of grid and off-grid systems. The construction of these systems involves mining scarce materials such as copper, steel and aluminium for its components manufacture. At the same time, waste is released back to the environment from the production and operation of these energy systems. For instance, centralised grid systems generate emissions of heavy metals and pollutants such as ozone, nitrous oxide (N2O) and sulphur hexafluoride (SF6) leakages. On the other hand, PV module and batteries manufacture also release GHG emissions and produce electrical and electronic waste, which is hazardous, at the end of life of off-grid systems or when these break down [79,81-85]. The main inputs and outputs relevant to the environmental impacts of grid-extension and off-grid electricity systems are shown in Figure 4.

***3.2 What metrics are associated with reporting the different environmental impacts?***

Commonly, LCA studies produce a broad range of metrics that provide an environmental profile. Once the impact categories of the analysis are chosen, a characterisation method is needed to quantify the impact of environmental interventions related to each category. The characterisation factor associated with energy systems is generally the Global Warming Potential (GWP), a metric developed by the Intergovernmental Panel on Climate Change (IPCC) to define the GWP of GHG emissions [80]. In the energy context, it examines the carbon footprint of electricity. The indicator result unit is expressed in grams of CO2-equivalentemissions per kWh (gCO2-eq/kWh) [81] or absolute emissions [86].

Energy analyses consists of calculating the input of primary energy to manufacture a good or provide a service from all the resources needed. Carrying out energy analyses is more appropriate than LCAs when the system under study is extensive or the data is limited [87]. The two indicators used in energy analyses are [81]:

* Cumulative Energy Demand (CED), which estimates all the energy consumed during the life cycle of a product.
* Gross Energy Requirement (GER), which accounts for the life cycle primary energy inputs required to deliver a good or service to the point of interest.

Additional energy indicators used to compare environmental impacts of fossil-fuel electricity generation versus renewables are [81]:

* Net Energy Ratio (NER), which shows the efficiencies of energy extraction and conversion systems [88]. It represents the amount of energy that a technology can produce relative to the total amount of energy that was consumed, over the total life cycle. Technologies are considered renewables when their NER is higher than 1.
* Energy Payback time (EPBT) is a parameter of the time during which the energy system will produce the same energy used for its construction.
* CO2-eqPayback time (CO2-eqPBT) is the time required for the energy system to save the total amount of CO2-eq emitted throughout its entire life cycle. For PV systems, the CO2-eqPBT is determined by the amount of kWh produced by the system and the grid emission factor (CO2-eq/kWh) of the grid system whose emissions are avoided as a result of using the PV system [81].

***3.3 What are the GHG impacts of these options?***

This review centres on the comparison between centralised fossil-fuel based grid-extension and off-grid renewable systems, namely solar energy and battery solutions. Most of the environmental impacts mentioned in the literature focus on climate change mitigation analysis, that is, on quantifying the opportunities to reduce GHG emissions [9]. For example, Alstone et al. [5] found that substituting kerosene lighting with either grid-extension connection or off-grid systems is a mitigation opportunity in Kenya as the emissions intensities of such systems are much lower. For grid-connected systems, power generation based on fossil fuels produces emissions of CO2, NOx and sulphur dioxide (SO2), largely during the plants’ operation [89]. In 2018, global energy-related CO2 emissions increased by 1.7%; approximately two-thirds of this growth were accounted to the power sector. Currently, the average carbon intensity of electricity generated equals 475 gCO2-eq/kWh [90].

The main benefit of renewable energy technologies, such as solar PV, is the abatement of GHG emissions and local air pollution mitigation relative to fossil-based electricity. The environmental impacts from the operation of solar PV systems are negligible since GHG or other pollutants are not produced [89]. A review of life-cycle GHG emissions of different electricity generation technologies by the IPCC[[3]](#footnote-3), reported values between 675 – 1,689 gCO2-eq/kWh electricity for coal combustion. In contrast, the harmonised life-cycle GHG emissions for solar PV was 5-217 gCO2-eq/kWh [91]. This includes emissions from the energy input required to manufacture PV modules and install them [85]. The WB estimates a potential of 1.5 billion tons of CO2 emissions avoided by 2030 if solar PV-battery mini-grids coupled with energy efficient appliances are installed [69].

***3.4 What are the non-GHG environmental impacts of these options?***

It is equally relevant to investigate other impacts from the manufacturing and operation of energy technologies beyond GHG emissions. PV production requires scarce metals which involve mining activities. Other negative impacts are the use of toxic compounds, explosive gases and corrosive liquids in material processing [89,91]. The highest environmental impact of solar PV is due to the PV cell manufacturing process [81].

In contrast to off-grid systems, centralised grid systems require large infrastructures for electricity transmission. Environmental concerns around the construction of new transmission lines focus on the materials and energy needed for construction, maintenance and end-of-life processes (the latter refers to the recycling, disposal and waste derived). Another negative impact is the emission of metals and pollutants from the components [40,79].

Renewable sources are generally considered as low-carbon technologies, hence, other environmental impacts such as water use, land footprint and biodiversity are often neglected [92]. The land use impacts of PV systems installation differ in size for grid-extension and off-grid systems [89]. All technologies deployed at a large-scale application, even renewable energies, have environmental impacts [91]. Utility scale solar PV can affect ecosystems and biodiversity by clearing vegetation, fragmenting habitats and preventing movement of species, for instance. In contrast, roof-top PV systems have lower impacts as they are typically mounted on already existing structures [93].

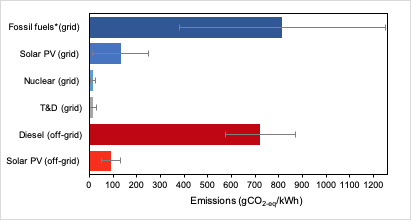
In general, the decentralisation of power generation or small-scale schemes have lower biodiversity impacts [94]. However, a growing environmental concern is the e-waste generated from solar PV and battery systems when there is a lack of repair schemes or when technologies stop operating or break down [83]. A study conducted by Ristic et al. [92] used a range of values as input data to assess the aggregate footprint of electricity generation technologies in the European Union. The authors concluded that low-carbon technologies are preferable to fossil fuels for electricity generation when considering water and land footprints, with the exceptions of biomass, owing to its land footprint [92]. This concern is highlighted in many other studies [41,89,95]. Other non-GHG impacts of renewables often cited are the modification of water flow regimes caused by hydroelectric plants affecting fish migrations and the collision risks to birds due to wind farms installations [93]. However, renewable energy sources have been estimated to have lower impacts on soil, water and air pollution than fossil-fuel sources [96].

Unlike with cost data as presented in Section 2, fewer studies make direct comparisons of environmental impacts of grid and off-grid systems [89,97-100]. Studies about environmental impacts of grid-extension systems, focusing where possible on generation and transmission elements separately, and off-grid systems, focusing on solar PV technologies, are summarised in Table 4. Figure 5 shows the emissions from grid and off-grid systems as indicated in Table 4.

**Table 4:** Overview of publications about environmental impacts of grid-extension (generation, transmission and distribution of electricity) and off-grid systems (solar PV technologies and diesel generators).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Reference | Technology specifications | Scope of study | Method | Location | Key metrics\* |
| Transmission and/or Distribution networks | | | | | |
| [101] | Fossil fuels and renewables | T&D | LCA | 55 countries | Transmission extension infrastructure: 12.6 - 336 tons of CO2-eq/km |
| [79] | Renewable sources generation (wind and solar) | Transmission grid expansion needed (45,300 km) to accommodate renewables. Considers upgrading of existing equipment. | LCA | Europe | 10.7 Mton CO2-eq; 0.074 gCO2-eq/kWh  Metal depletion: 11.2 Mton Fe-eq; 0.08 Fe-eq/kWh.  Land required: 58 ha/MW |
| [102] | Norwegian electricity mix assumed | Transmission grid network | LCA | Norway | 1.3-1.5 gCO2-eq/kWh |
|  | European power mix assumed |  |  | Average European mix | 10.6-11.8 gCO2-eq/kWh |
| [103] | Great Britain’s generation mix | Transmission network | LCA | Great Britain | 11 gCO2-eq/kWh |
| [82] | Danish electricity mix considered | Distribution networks (including T&D – infrastructure and power losses) | LCA | Denmark | Transmission: over 15 gCO2-eq/kWh |
| Distribution: nearly 30 gCO2-eq/kWh (2 gCO2-eq/kWh from infrastructure within distribution) |
| Generation | | | | | |
| [97] | Traditional electrification (home diesel generators and central grid electricity) | Marginal electricity grid production (excluding impacts of grid expansion –new power plants and transmission infrastructure) | LCA | Kenya | **Home diesel genset:** CED= 4,852,745 MJ; EYR= 5.45  **Marginal grid mix:** CED= 3,192,795 MJ; EYR= 3.59 |
| [104] | Fossil fuels and renewables | Generation | Review of LCA studies | Generic (any site) | **Solar PV generation:** 13-190 gCO2-eq/kWh  **Gas:** 380-1,000 gCO2-eq/kWh  **Oil:** 530-900 gCO2-eq/kWh  **Coal:** 660-1,050 gCO2-eq/kWh |
| [105] | Fossil, nuclear and renewable energy technologies | Generation | Review LCA studies | Generic | **Nuclear:** 2.8-24 gCO2-eq/kWh  **Solar PV:** 43-73 gCO2-eq/kWh  **Gas:** 440-780 gCO2-eq/kWh  **Oil:** 500-1,200 gCO2-eq/kWh  **Coal:** 750-1,250 gCO2-eq/kWh |
| [106] | Fossil fuels and renewables | Generation | LCA | Japan | **Solar PV:** 53.4 gCO2-eq/kWh  **Gas:** 518.8-607.6 gCO2-eq/kWh  **Oil:** 742.1 gCO2-eq/kWh  **Coal:** 975.2 gCO2-eq/kWh |
| [107] | Utility-scale solar energy | Upstream, operational and downstream processes | Review LCA literature | Generic | **PV solar technologies :** 14-45 gCO2-eq/kWh |
| [101] | Fossil fuels and renewables | Electricity production | LCA | 55 countries | **Electricity production:** 6 - 1,110 gCO2-eq/kWh |
| [108] | Utility-scale solar energy | Impacts on regional biodiversity | Spatial multi-criteria analysis | California | Compatibility indices mapped for solar energy development and biodiversity conservation in California. |
| [109] | PV technologies (mono- and multi-crystalline silicon, ribbon-silicon and cadmium telluride) | Cradle-grave PV modules and BOS | LCA | Southern Europe and U.S. | **CdTe PV modules:** 24 gCO2-eq/kWh; EPBT= 1.1 years  **Si modules:** 30-45 gCO2-eq/kWh; EPBT= 1.7-2.7 years. |
| [110] | Large-scale solar power plants | Installation and operation | LCA | U.S. | **Solar power plant**: 16-86 gCO2-eq/kWh |
| [111] | Renewable sources | Generation | Review of LCA studies | Several countries (Japan, Germany, Italy, Singapore, U.S., Greece) | **PV system:** 53.4–250 gCO2-eq/kWh |
| Off-grid systems – Generation | | | | | |
| [97] | Three PV microgrids (PV-battery, PV-diesel, PV-hybrid systems) | Systems modelled to meet community’s maximum daily electricity demand with minimum environmental impact | LCA | Kenya | **PV-battery:** CED= 306,165 MJ; EYR[[4]](#footnote-4)= 0.37; EPBT 9.2 years.  **PV-Hybrid:** CED= 612,278 MJ; EYR= 0.69.  **PV-diesel:** CED= 3,758,010 MJ; EYR= 4.22. |
| [98] | Solar PV power system | 62.7 kW PV plant, demand of 175 kWh/d with 1% annual load growth | LCA | Nigeria | **PV power system:**  Emission rate: 50 gCO2-eq/kWh; GWP: 4,307-5,400 kgCO2-eq |
|  | Diesel generator | Diesel generator for 24, 27 and 30 houses | LCA (diesel gen) and review |  | **Diesel generator:** Emission rate: 572-636gCO2-eq/kWh  **Diesel generator (review):** Emission rate: 762-869 gCO2-eq/kWh |
| [89] | Solar PV systems deployment | Reduction of emissions from renewable generation (instead of fossil-fuel consumption) by 2030 | Review | Developing countries | **Emission savings from PV:** 530 gCO2-eq/kWh  **Emissions reductions:** 69–100 million tons CO2; 126,000–184,000 tons SO2; 68,000–99,000 tons NOx |
| [112] | Residential PV systems (installed in slanted roofs; non-integrated) | 3 kWp PV system  Production of 1 kWh of PV electricity | LCA | Regions with low solar irradiation (Northern Europe and Canada) | **PV electricity:** 80 gCO2-eq/kWh (PV-system used 30 years); 120-130 gCO2-eq/kWh (PV-system used 20 years)  EPBT= less than 5 years |

*\*Key metrics reported in study including Global warming potential (GWP) and / or value of another key metric, as specified. Cumulative energy demand (CED), Energy payback time (EPBT) and Energy yield ratio (EYR). Bilich et al. [97] define EYR as CED/Energy consumed by community.*



**Figure 5:** Chart showing emissions from grid and off-grid systems; bars indicate median values of emissions as reviewed in Table 4. Fossil fuels\* include gas, oil and coal; with the range varying from the low end of gas (380 gCO2-eq/kWh) to the high end of coal (1,250 gCO2-eq/kWh).

***3.5 Where are the major analytical gaps in understanding the relative environmental costs and benefits of different electrification strategies?***

As shown in Table 4, comparative data of environmental impacts of grid and off-grid systems is lacking. Few studies evaluate the environmental feasibility of off-grid systems [9] in a comprehensive way. Environmental impacts of off-grid systems are focused on CO2 emissions reduction, often through kerosene replacement [113,114]. As has been noted (see Table 4), LCA studies focus on electricity generation rather than on the impacts from T&D [82]. Furthermore, there is little evidence of the ecological impacts of utility scale solar PV [93]. Other gaps in the literature are the consequences of the disposal and recycling of PV systems and batteries [83]. Similarly, the negative impacts on land use and biodiversity [93], as well as on local communities, due to the development of large-scale projects have been overlooked [115,116]. Moreover, only a limited number of studies assess electricity technologies across multiple environmental impacts directly [92]. For the most part, there is a lack of studies on the impacts of power production on biodiversity (see Table 4). Future research should put emphasis on identifying and providing evidence of the best pathways to optimise mitigation, adaptation and biodiversity in the energy sector [94].

1. **Towards a comprehensive assessment of options**

Sections 2 and 3 show that a number of studies have made progress in allowing a comparison of the economic and environmental implications of grid and off-grid systems. However, for many countries seeking to rapidly expand their electrification rate, it is critical to make decisions on the basis of both of these factors in a consolidated analysis. The benefit of considering economic and environmental impacts simultaneously is to avoid unintended consequences [117]. For example, by providing universal electricity access through cost-effective solutions whilst increasing GHG emissions or biodiversity loss. This section therefore discusses how these different factors can be combined to provide a comprehensive assessment of electrification options.

***4.1 How can we construct an analytical framework to compare different electrification strategies?***

At its most basic level of analysis, indicators that reflect single aspects, such as economic and environmental impacts, can be used to compare different rural electrification strategies. In a similar manner, more complex methods, namely systems-based and participatory approaches, have been developed [75]. Bhattacharyya [75] identified four analytical approaches used in the energy systems literature to decide on an appropriate electricity supply for rural areas. This included indicator-based analysis, optimisation techniques, MCDM and systems analysis approaches. These different approaches are not mutually exclusive and can be combined for a more comprehensive evaluation of impacts. Bhattacharyya [75] suggested that a hybrid tool, for instance using a system optimisation such as HOMER and a MCDM tool, will provide a better methodological approach for the analysis of off-grid electricity access projects or programmes. Rahman et al. [32] determined the most suitable option to provide access in a rural village in Bangladesh by first comparing the levelised cost of delivered electricity via grid versus off-grid. Since the grid-extension was not viable, the authors then used a MCDM approach to determine the preferred off-grid alternative. This study considered 24 criteria under five sustainability dimensions (technical, economic, environmental, social and policy) [32]. A similar two-phased methodology was developed by Juanpera et al. [118] to compare rural electrification systems with solar PV, wind and diesel generation in Nigeria. Firstly, the study applied a techno-economic optimisation model to generate electrification designs, followed by a multicriteria procedure consisting of 12 criteria representing four dimensions (economic, technical, socio-institutional and environmental) to determine the recommended electrification strategy [118]. Trutnevyte et al. [119] proposed a methodology for linking visions with energy scenarios and MCDM. Their framework consists of four steps [119]:

1. Devise qualitative visions of an ideal energy system
2. Analyse specific, quantitative energy scenarios in terms of their technical feasibility to implement the vision
3. Carry out a stakeholder-based MCDM assessment
4. The information derived from the previous steps is given to the actors involved and integrated in a discourse or decision-making.

Aberilla et al. [117] develop future scenarios to evaluate transition pathways of energy and water supply in remote communities by 2030. The authors also applied a MCDM to perform an integrated sustainability assessment including economic, environmental and social dimensions. Furthermore, this study presents a complete approach by integrating energy systems design, techno-economic analysis, LCA, social impact assessment and MCDM. Finally, another study applied a combination of indicators to assess the sustainability performance (technical, economic, environmental, social and institutional dimensions) of six existing off-grid renewable projects in Indonesia. The authors also considered the Institutional Analysis and Development (IAD) framework, developed by Ostrom, to explain the endurance of these electricity projects under commons conditions [34].

***4.2 How can we combine economic and environmental metrics?***

Typically, the starting point of an environmental LCA and economic Cost-Benefit Analysis (CBA) is EIA. The increasing use of these and other existing sustainability assessment tools, such as LCC analysis and SEAs, that have different methodologies, can lead to conflicting and biased results [44,120]. It should be noted that LCC mentioned previously in this review refers to financial LCC, meaning that only economic costs are considered. Environmental LCC is another type of LCC which extends the analysis to include life cycle costs borne by other actors known as externalities, as explained in Section 2.1. In either case, both tools can be used in sustainability assessment methods to add the economic dimension in the analysis [44]. Previous studies provide guidance on the analytical tools that can be used in the process of an EIA [121] and a SEA [76]. For example, Hoogmartens et al. [44] developed a framework for the complementary use of different tools. To perform a full sustainability assessment, the authors suggest using:

* LCA and LCC in parallel to include the environmental and economic dimensions in the comparative assessment of products. This approach gives insights on different sustainability attributes.
* CBA to evaluate the lifetime effects of a specific project or policies. It estimates environmental impacts in terms of money values and thus it allows for a full sustainability assessment.
* Life Cycle Sustainability Assessment (LCSA), refers to combining elements and sub-methodologies of LCC and LCA tools for a complementary approach.

Regardless of the framework used, some tools involve the monetary valuation of external environmental impacts. CBA requires valuation while for LCA, LCC, and SEA, monetary valuation and weighting, based on value judgment, is optional [120]. In their previous analysis, Gasparatos and Scolobig [121] identified a research gap in the sustainability assessment literature on ways to integrate the outputs of biophysical and monetary tools.

Multicriteria decision analysis provides a variety of methods to combine economic and environmental indicators [75,117]. This flexible tool can incorporate a more comprehensive representation of sustainability and capture a wider range of perspectives. Although it recognises different criteria, the lack of indicator aggregation makes it a tool closer to a strong sustainability perspective [121]. In ecological economics, a strong sustainability approach considers natural capital as non-substitutable with other forms of capital, notably man-made capital, human and social capital [122]. Amongst the advantages of MCDM methods is the possibility to include technical and non-technical aspects as well as allow the active participation of stakeholders [75,96]. Table 5 shows key findings of studies that applied MCDM methods to assess different electrification options in specific locations whilst analysing their economic, environmental, social and other implications. Some studies use a combination of MCDM methods, techno-economic optimisation tools, LCA analysis and other techniques to determine the preferred electrification choice considering different sustainability dimensions.

**Table 5:** Review of publications applying MCDM methods to compare electrification pathways.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Reference | Location | Options considered | Criteria included | Weighting method | Key findings |
| [117] | Prototypical remote community  (small-islands in the  Philippines selected as representative) | -Off-grid: synergistic  generation system of energy and water supply  -Five future (2030) scenarios quantified: Current (diesel),  BAU (diesel),  Transition (diesel, PV, wind, biomass),  Independent (PV, wind, biomass, li-ion battery), Advanced (diesel, biomass, li-ion battery),  Advanced Independent (PV, biomass, li-ion battery) | Social, environmental and economic sustainability | -Social assessment: various estimation methods for 16 indicators considered  -Environmental assessment: LCA  -Economic assessment:  LCC  -Integrated sustainability assessment:  MCDM – VIKOR method | -Best option socially: Transition scenario  -Best option environmentally: Independent and Advanced Independent scenario  -Most sustainable option overall: Independent scenario  -Less sustainable option overall:  BAU |
| [23] | Brazil | Grid: identifies  potential sites for deployment of wind distributed generation | Environmental, social, technical and economic | Various MCDM  methods: Rank Sum, Analytical Hierarchy Process (AHP), Weighted Linear Combination, fuzzy logic | -Each method results on trade-offs between criteria  -All methods  converge objectively to some regions with common characteristics |
| [123] | Philippines | Off-grid: eight technology combination options considered (diesel, solar PV, li-ion storage, and others) | Socio-economic, environmental and technical | -Quantitative performance assessment (via techno-economic simulations) and qualitative  assessment (via expert estimates)  -MCDM methods: Fuzzy AHP and Grey Relational Analysis (GRA) | -Most important criteria: system reliability and social acceptability  -Highest performance score: diesel-solar PV hybrid system and diesel-solar PV-li-ion hybrid system |
| [124] | Cuba | Off-grid: five energy  technologies considered (current silicon PV modules, new silicon PV, thin-film PV, organic PV, diesel generator) | Natural, physical, social, human and financial | Multi-criteria systems approach: SURE-Decision Support System; uses LCA to assess environmental impacts | -All PV technologies meet electrification demands of community, but emissions mitigation varies  -Organic PV will avoid most emissions |
| [125] | Venezuela | Grid and off-grid: 13 alternatives proposed including  dispersed (e.g. SHS) or compact decentralised generation (mini-grid) and grid extension. Various renewables and fossil-fuel options. | Technical, economic, environmental and social | Combination of MCDM methods: AHP and VIKOR | -Best electrical supply option for rural locations: Mini-grids (renewables and storage)  -Grid extension and SHS are not adequate solutions |
| [32] | Bangladesh | Grid and off-grid (solar PV, wind turbine, biogas plant, mini-hydro, PV-wind-hybrid, diesel generator) | Technical, economic, social, environmental and policy /regulation | For off-grid evaluation:  MCDM – SMAA-2 method (Stochastic Multicriteria Acceptability Analysis) | Most preferable off-grid alternatives: Solar PV and biogas plants |
| [126] | Colombia | Off-grid options: current diesel, micro-hydro, solar PV, biomass, current diesel + biomass, current diesel + solar PV, current diesel + micro-hydro | Financial, infrastructural, natural, social and human | Multicriteria decision-support model, using sustainable livelihoods approach | Most sustainable option: biomass power plant |
| [127] | Corsica island | Grid: assessment of 16 proposed PV plant projects to connect to the grid network | Energy, geo-economic, ecological, visual impact, territorial use and financial effect | MCDM –  ELECTRE IS  method | Four projects selected |
| [128] | Germany | -Grid: distributed generation  -Four future (2025) scenarios: differ in degree of decentralisation of the grid and share of renewables in the energy mix; other assumed technical, economic and social conditions. | Economic, environmental and security of supply | MCDM – AHP method | -Decentralised generation can contribute to climate protection  -Performance of scenarios is positive/negative depending on the degree of decentralisation of supply |
| [129] | Spain | Regional energy system planning  focusing on renewables | Technological, environmental, socio-economic and Delphi criterion (expert opinion) | Combination of MCDM – PROMETHEE method, expert opinion and SWOT analysis | Increase of 42% of renewables from current situation, mainly solar energy (thermal and PV) |

***4.3 What are other considerations of different electrification options?***

It is also important to note other considerations beyond technological aspects, specifically economic and environmental, that influence the deployment and uptake of renewable electrification solutions in developing countries (see Table 5). Technical expertise is not only important during the initial stages of rural electrification projects but also during the system’s operation to avoid maintenance issues. Similarly, it is essential that there is an adequate financial model in place to support the ongoing operation of the system [41]. Successful and resilient rural power systems need to have access to financing options, which are usually in the form of funding or aid grants, although one of the project’s aim should be to become economically self-sufficient in the long-term [95]. Amongst the key social aspects that contribute to long-term success of these projects is community involvement and empowerment. Project developers should engage the local community at all stages of the project development, specially through local consultations since its beginning. Furthermore, resilient rural power systems need to be able to adapt to the changing needs and conditions of the community [41,95]. Shahsavari & Akbari [89] identified barriers to solar energy deployment in developing countries. Amongst these are the lack of government policy and regulation support, shortage of qualified engineers to address technical issues and non-existent appropriate infrastructure to reach target communities. Also, the low price of fossil fuels and the subsidies given by some countries cause renewable energies to be less competitive [89].

Cherni [96] evaluated the sustainability of renewable energy technologies in Colombia, Cuba and Peru. The author developed a methodology of multi-criteria analysis to appraise the technical and non-technical factors of rural energy systems. Cherni [96] stresses the importance of non-technical factors to ensure the sustainability of the systems. In this context, sustainability refers to the technical effectiveness and efficiency of the renewable energy technology as well as the affordability of the system’s maintenance and operation. In addition, it involves its capacity to fulfil the needs and priorities of the users whilst socially improving their livelihoods with a minimum negative environmental impact. Moreover, for the system to be sustainable, these features should remain constant in the long term [96].

In the same way, politics play a key role in the implementation and success of electrification projects. Rural areas present different development challenges than urban areas and thus the adaptation of different policies is necessary. It is equally important that policymakers create clearly defined future directions that are consistent to provide certainty to project developers [41]. Additionally, a major concern of mini-grids systems developers is the uncertainty of their investment once the main grid arrives. An extreme outcome of this is the abandonment of the systems which has been the case in Cambodia, Sri Lanka and Indonesia [33]. To avoid this, policies and regulatory frameworks coupled with new technologies that facilitate the integration of these two rural electrification strategies must be devised. Currently grid and off-grid systems are seen as separate and competing electrification pathways. However, an integral strategy that considers all different electrification solutions will be needed to accelerate universal access [38].

1. **Conclusion and recommendations**

This review focuses on comparing, where possible, the economic and environmental impacts of grid and off-grid systems. It finds that in terms of the economics, there is a wide variation in grid-extension costs depending on distance, terrain, population density, load conditions and other assumptions made. Across each of the grid-extension studies, costs ranged between almost two orders of magnitude, from as low as 0.1 to as high as 9 USD2018$/kWh. Thus, in areas where grid-extension is prohibitively expensive, off-grid systems are an important intermediate step to provide energy access and stand-alone systems are key to supply access to basic electricity services (below Tier 1 and above). In terms of the environmental impacts, few studies directly compare the impacts of grid versus off-grid electrification strategies. However, where grids are dominated by fossil fuels, they are likely to have much higher life-cycle GHG emissions stemming primarily from the generation side (with emissions intensities from below 400 gCO2-eq /kWh for gas, to more than four times this for some coal generation). For transmission and distribution, there is a wide range of estimates, from below 1 gCO2-eq/kWh to almost 30 gCO2-eq/kWh. This compares to a range of life-cycle emissions for solar PV off-grid systems from as low as 5 to more than 200 gCO2-eq/kWh.

Overall, the review finds a number of evidence and methodological gaps which should be addressed with increasing urgency in order that a fully informed comparison of grid versus off-grid electrification strategies can be made at this crucial time when countries strive towards meeting their SDG7 goals. Firstly, few studies explicitly compare grid-extension costs against off-grid systems costs. As highlighted in Section 2, there is a lack of consistency in the methodologies used to determine the least-cost option. In some studies, subsidised tariffs are applied, which do not reflect the true costs of grid electricity supply, whilst in other cases the environmental costs or externalities are not integrated in the analysis. Moreover, assumptions considered to forecast electricity demand might also lead to different results. Given how crucial it is to rapidly provide electricity access and in view of the important role off-grid systems are gaining as a viable sustainable alternative, research should focus on comparing the costs of these options using a consistent metric and ensuring electricity consumption calculations include realistic demand assumptions. Here the levelised cost of used electricity is a suitable metric which comprehensively captures the costs to communities of electricity access. The authors suggest undertaking economic comparisons of grid-extension and off-grid systems whilst developing a robust methodology that uses this levelised cost measure, whilst at the same time clearly and explicitly accounting for subsidies, externalities as well as the emissions and potential decarbonisation of centralised power generation. It is also essential to understand the needs of the target community.

A second challenge is that the literature on the environmental impacts of grid and off-grid systems is limited in its scope and coverage of the full range of impacts. The analysis generally focusses on GHG emissions impacts and on the environmental consequences of electricity generation only. Hence, other environmental impacts such as water usage, land use, biodiversity and e-waste generated are often ignored. Similarly, there is little attention on the impacts from T&D of electricity and on the changes on the electrification mix due to the decarbonisation of the grid. To address this, it is important to understand the environmental impacts of the entire electricity system, including T&D and appraise other non-GHG impacts of electricity supply to carry out a complete environmental impact assessment. Based on this review, it is recommended that climate change metrics continue to be used when comparing environmental impacts of electrification strategies. However, other recognised metrics from wider LCA assessments, representing resource depletion, impacts on biodiversity, as well as water and land footprints, should also be measured and included to enable a complete comparison. As summarised in Section 4, a variety of methods and techniques to combine economic and environmental indicators have been applied in specific case studies. A further suggestion derived from this review is to apply a mix of techno-economic modelling tools, LCA analysis and thorough multi-criteria assessments for a comprehensive sustainability assessment of electrification pathways.

Another important consideration is the lack of financial models that support the electrification project’s self-sufficiency in the long-term. For this reason, research is needed to identify whether there have been successful financial models designed for this purpose in specific contexts. Finally, the design and implementation of policy and regulatory frameworks to integrate different electrification strategies to support access is a research challenge. Thus, efforts to investigate policies that combine electrification solutions are also needed.

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**References**

[1] International Energy Agency (IEA). Energy Access Outlook 2017. IEA; 2017 [Online]. Available: <https://www.iea.org/reports/energy-access-outlook-2017>

[2] International Energy Agency (IEA), International Renewable Energy Agency (IRENA), United Nations Statistics Division (UNSD), World Bank (WB), and World Health Organization (WHO).Tracking SDG 7: The Energy Progress Report 2020. World Bank; 2020 [Online]. Available: <https://trackingsdg7.esmap.org/>. [Accessed 11 May 2020].

[3] United Nations. Sustainable Development Goal 7, <https://sdgs.un.org/goals/goal7>; 2019 [Accessed 8 August 2019].

[4] International Energy Agency (IEA). World Energy Outlook 2019. IEA; 2019 [Online]. Available: <https://www.iea.org/reports/world-energy-outlook-2019>

[5] Alstone P, Gershenson D, Kammen DM. Decentralized energy systems for clean electricity access. Nat Clim Chang 2015;5:305–14. <https://doi.org/10.1038/nclimate2512>.

[6] Bhatia M, Angelou N. Beyond Connections: Energy Access Redefined. World Bank; 2015 [Online]. Available: <https://openknowledge.worldbank.org/handle/10986/24368>. [Accessed 2 October 2019].

[7] Dagnachew AG, Lucas PL, Hof AF, Gernaat DEHJ, de Boer HS, van Vuuren DP. The role of decentralized systems in providing universal electricity access in Sub-Saharan Africa – A model-based approach. Energy 2017; 139: 184-195. <https://doi.org/10.1016/j.energy.2017.07.144>.

[8] ScienceDirect. Ancillary service, <https://www.sciencedirect.com/topics/engineering/ancillary-service>; 2021 [accessed 12 January 2021].

[9] Kaundinya DP, Balachandra P, Ravindranath NH. Grid-connected versus stand-alone energy systems for decentralized power-A review of literature. Renew Sustain Energy Rev 2009;13:2041–50. <https://doi.org/10.1016/j.rser.2009.02.002>.

[10] Palit D, Bandyopadhyay KR. Rural electricity access in South Asia: Is grid extension the remedy? A critical review. Renew Sustain Energy Rev 2016;60:1505–15. <https://doi.org/10.1016/j.rser.2016.03.034>.

[11] INEGI. Primera Encuesta Nacional sobre Consumo de Energéticos en Viviendas Particulares (ENCEVI),<https://www.inegi.org.mx/contenidos/saladeprensa/boletines/2018/EstSociodemo/ENCEVI2018.pdf>; 2018 [Accessed 21 October 2019].

[12] World Bank. Quality of electricity supply,<https://govdata360.worldbank.org/indicators/heb130a3c?country=BRA&indicator=547&viz=line_chart&years=2007,2017>; 2020 [Accessed 21 January 2020].

[13] Mahapatra S, Dasappa S. Rural electrification: Optimising the choice between decentralised renewable energy sources and grid extension. Energy Sustain Dev 2012;16:146–54. <https://doi.org/10.1016/j.esd.2012.01.006>.

[14] DEFRA. Causes of air pollution, <https://uk-air.defra.gov.uk/air-pollution/causes>; 2019 [Accessed 15 October 2019].

[15] Mainali B, Silveira S. Alternative pathways for providing access to electricity in developing countries. Renew Energy 2013;57:299–310. <https://doi.org/10.1016/j.renene.2013.01.057>.

[16] Sandwell P, Chan NLA, Foster S, Nagpal D, Emmott CJM, Candelise C, et al. Off-grid solar photovoltaic systems for rural electrification and emissions mitigation in India. Sol Energy Mater Sol Cells 2016;156:147–56. <https://doi.org/10.1016/j.solmat.2016.04.030>.

[17] Gronholt-Pedersen J. Denmark sources record 47% of power from wind in 2019. Reuters; 2020 [Online]. Available: <https://www.reuters.com/article/us-climate-change-denmark-windpower/denmark-sources-record-47-of-power-from-wind-in-2019-idUSKBN1Z10KE>. [accessed 12 January 2021].

[18] Szabó S, Bódis K, Huld T, Moner-Girona M. Sustainable energy planning: Leapfrogging the energy poverty gap in Africa. Renew Sustain Energy Rev 2013;28:500–9. <https://doi.org/10.1016/j.rser.2013.08.044>.

[19] Alova G, Trotter PA, Money A. A machine-learning approach to predicting Africa’s electricity mix based on planned power plants and their chances of success. Nat Energy 2021. <https://doi.org/10.1038/s41560-020-00755-9>

[20] International Renewable Energy Agency (IRENA). Renewable power generation costs in 2019. IRENA; 2020 [Online]. Available:<https://irena.org/publications/2020/Jun/Renewable-Power-Costs-in-2019>

[21] Schmidt O, Hawkes A, Gambhir A, Staffell I. The future cost of electrical energy storage based on experience rates. Nat Energy 2017;2:17110. <https://doi.org/10.1038/nenergy.2017.110>.

[22] Schmidt O, Melchior S, Hawkes A, Staffell I. Projecting the Future Levelized Cost of Electricity Storage Technologies. Joule 2019;3:81–100. <https://doi.org/10.1016/j.joule.2018.12.008>.

[23] Cardoso de Lima GS, Lopes EC, Motta JG, Asano R, Valverde M, Suyama R, et al. Sustainable development enhanced in the decision process of electricity generation expansion planning. Renew Energy 2018;123:563–77. <https://doi.org/10.1016/j.renene.2018.02.012>.

[24] Gurung A, Gurung OP, Oh SE. The potential of a renewable energy technology for rural electrification in Nepal: A case study from Tangting. Renew Energy 2011;36:3203–10. <https://doi.org/10.1016/j.renene.2011.03.012>.

[25] Dasappa S. Potential of biomass energy for electricity generation in sub-Saharan Africa. Energy Sustain Dev 2011;15:203–13. <https://doi.org/10.1016/j.esd.2011.07.006>.

[26] Chambon CL, Karia T, Sandwell P, Hallett JP. Techno-economic assessment of biomass gasification-based mini-grids for productive energy applications: The case of rural India. Renew Energy 2020;154:432–44. [https://doi.org/https://doi.org/10.1016/j.renene.2020.03.002](https://doi.org/https:/doi.org/10.1016/j.renene.2020.03.002).

[27] International Renewable Energy Agency (IRENA). Off-grid Renewable Energy Solutions. IRENA; 2018 [Online]. Available: <https://www.irena.org/publications/2018/Jul/Off-grid-Renewable-Energy-Solutions>

[28] Narayan N, Vega-Garita V, Qin Z, Popovic-Gerber J, Bauer P, Zeman M. The Long Road to Universal Electrification: A Critical Look at Present Pathways and Challenges. Energies 2020;13:508. <https://doi.org/10.3390/en13030508>

[29] Misak S, Stuchly J, Vramba J, Prokop L, Uher M. Power quality analysis in off-grid power Platform. Power Eng and Electrical Eng 2014; 12(3).

[30] Hojabri M, Toudeshki A. Power quality consideration for off-grid renewable energy systems. Energy and Power Eng 2013; 5(5): 377-383. doi: 10.4236/epe.2013.55039.

[31] Peters J, Sievert M, Toman MA. Rural electrification through mini-grids: Challenges ahead. Energy Policy 2019; 132: 27-31. <https://doi.org/10.1016/j.enpol.2019.05.016>.

[32] Rahman MM, Paatero J V., Lahdelma R. Evaluation of choices for sustainable rural electrification in developing countries: A multicriteria approach. Energy Policy 2013;59:589–99. <https://doi.org/10.1016/j.enpol.2013.04.017>.

[33] Tenenbaum B, Greacen C, Vaghela D. Mini-Grids and the Arrival of the Main Grid: Lessons from Cambodia, Sri Lanka, and Indonesia. World Bank; 2018 [Online]. Available: <https://openknowledge.worldbank.org/handle/10986/29018>. [Accessed 3 September 2019].

[34] Lestari H, Arentsen M, Bressers H, Gunawan B, Iskandar J, Parikesit. Sustainability of renewable off-grid technology for rural electrification: A comparative study using the IAD framework. Sustainability 2018; 10(12): 4512. <https://doi.org/10.3390/su10124512>

[35] Morrissey J. Achieving universal electricity access at the lowest cost: A comparison of published model results. Energy Sustain Dev 2019;53:81–96. <https://doi.org/10.1016/j.esd.2019.09.005>.

[36] Ciller P, Lumbreras S. Electricity for all: The contribution of large-scale planning tools to the energy-access problem. Renew Sustain Energy Rev 2020;120:109624. [https://doi.org/10.1016/j.rser.2019.109624](https://doi.org/https:/doi.org/10.1016/j.rser.2019.109624).

[37] International Renewable Energy Agency (IRENA). Off-grid renewable energy systems: Status and methodological issues. IRENA; 2015 [Online]. Available: <https://www.irena.org/documentdownloads/publications/irena_off-grid_renewable_systems_wp_2015.pdf>

[38] SEforALL. Integrated Electrification Pathways for Universal Access to Electricity: A Primer. SEforALL; 2019 [Online]. Available: <https://www.seforall.org/system/files/2019-06/SEforALL_IEP_2019.pdf>. [Accessed 9 September 2019].

[39] Nouni MR, Mullick SC, Kandpal TC. Providing electricity access to remote areas in India: Niche areas for decentralized electricity supply. Renew Energy 2009;34:430–4. <https://doi.org/10.1016/j.renene.2008.05.006>.

[40] Mandelli S, Barbieri J, Mereu R, Colombo E. Off-grid systems for rural electrification in developing countries: Definitions, classification and a comprehensive literature review. Renew Sustain Energy Rev 2016;58:1621–46. <https://doi.org/10.1016/j.rser.2015.12.338>.

[41] Almeshqab F, Ustun TS. Lessons learned from rural electrification initiatives in developing countries: Insights for technical, social, financial and public policy aspects. Renew Sustain Energy Rev 2019;102:35–53. <https://doi.org/10.1016/j.rser.2018.11.035>.

[42] Nerini FF, Broad O, Mentis D, Howells M, Welsch M, Bazilian M. A cost comparison of technology approaches for improving access to electricity services. Energy 2016;95:255–65. <https://doi.org/10.1016/j.energy.2015.11.068>.

[43] Naves AX, Fernández AI, Haddad AN, Boer D. Life cycle costing as a bottom line for the life cycle sustainability assessment in the solar energy sector: A review. Sol Energy 2019;192:238–62. <https://doi.org/10.1016/J.SOLENER.2018.04.011>.

[44] Hoogmartens R, Van Passel S, Van Acker K, Dubois M. Bridging the gap between LCA, LCC and CBA as sustainability assessment tools. Environ Impact Assess Rev 2014;48:27–33. [https://doi.org/https://doi.org/10.1016/j.eiar.2014.05.001](https://doi.org/https:/doi.org/10.1016/j.eiar.2014.05.001).

[45] Hunkeler D, Lichtenvort K, Rebitzer G. Environmental Life Cycle Costing. New York: Society of Environmental Toxicology and Chemistry (SETAC); 2008.

[46] Kemausuor F, Adkins E, Adu-Poku I, Brew-Hammond A, Modi V. Electrification planning using Network Planner tool: The case of Ghana. Energy Sustain Dev 2014;19:92–101. <https://doi.org/10.1016/j.esd.2013.12.009>.

[47] Parshall L, Pillai D, Mohan S, Sanoh A, Modi V. National electricity planning in settings with low pre-existing grid coverage: Development of a spatial model and case study of Kenya. Energy Policy 2009;37:2395–410. <https://doi.org/10.1016/j.enpol.2009.01.021>.

[48] Levin T, Thomas VM. Least-cost network evaluation of centralized and decentralized contributions to global electrification. Energy Policy 2012;41:286–302. <https://doi.org/10.1016/j.enpol.2011.10.048>.

[49] Levin T, Thomas VM. Can developing countries leapfrog the centralized electrification paradigm? Energy Sustain Dev 2016;31:97–107. <https://doi.org/10.1016/j.esd.2015.12.005>.

[50] Amutha WM, Rajini V. Cost benefit and technical analysis of rural electrification alternatives in southern India using HOMER. Renew Sustain Energy Rev 2016;62:236–46. <https://doi.org/10.1016/j.rser.2016.04.042>.

[51] Narula K, Nagai Y, Pachauri S. The role of Decentralized Distributed Generation in achieving universal rural electrification in South Asia by 2030. Energy Policy 2012;47:345–57. <https://doi.org/10.1016/J.ENPOL.2012.04.075>.

[52] 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/https://doi.org/10.1016/j.esd.2015.09.007](https://doi.org/https:/doi.org/10.1016/j.esd.2015.09.007).

[53] Mentis D, Andersson M, Howells M, Rogner H, Siyal S, Broad O, et al. The benefits of geospatial planning in energy access - A case study on Ethiopia. Appl Geogr 2016;72:1–13. <https://doi.org/10.1016/j.apgeog.2016.04.009>.

[54] Mentis D, Howells M, Rogner H, Korkovelos A, Arderne C, Zepeda E, et al. Lighting the world: The first application of an open source, spatial electrification tool (OnSSET) on sub-Saharan Africa. Environ Res Lett 2017; 12 (8) (Aug. 2017):085003.

[55] Moksnes N, Korkovelos A, Mentis D, Howells M. Electrification pathways for Kenya–linking spatial electrification analysis and medium to long term energy planning. Environ Res Lett Sep. 2017; 12 (9):095008.

[56] 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>.

[57] Moner-Girona M, Bódis K, Huld T, Kougias I, Szabó S. Universal access to electricity in Burkina Faso: scaling-up renewable energy technologies. Environ Res Lett Aug. 2016;11(8):084010.

[58] Sanoh A, Parshall L, Sarr OF, Kum S, Modi V. Local and national electricity planning in Senegal: Scenarios and policies. Energy Sustain Dev 2012;16:13–25. [https://doi.org/https://doi.org/10.1016/j.esd.2011.12.005](https://doi.org/https:/doi.org/10.1016/j.esd.2011.12.005).

[59] Modi V, Adkins E, Carbajal J, Shepa S. Liberia power sector capacity building and energy master planning. Final Report. Phase 4: National Electrification Master Plan. 2013 [Online]. Available: <https://qsel.columbia.edu/assets/uploads/blog/2013/09/LiberiaEnergySectorReform_Phase4Report-Final_2013-08.pdf>. [Accessed 7 May 2020].

[60] Ohiare S. Expanding electricity access to all in Nigeria: a spatial planning and cost analysis. Energy Sustain Soc 2015;5:8. <https://doi.org/10.1186/s13705-015-0037-9>.

[61] Bertheau P, Cader C, Blechinger P. Electrification Modelling for Nigeria. Energy Procedia 2016;93:108–12. [https://doi.org/https://doi.org/10.1016/j.egypro.2016.07.157](https://doi.org/https:/doi.org/10.1016/j.egypro.2016.07.157).

[62] Bertheau P, Oyewo A, Cader C, Breyer C, Blechinger P. Visualizing National Electrification Scenarios for Sub-Saharan African Countries. Energies 2017;10:1899. <https://doi.org/10.3390/en10111899>**.**

[63] Blechinger P, Köhler M, Juette C, Berendes S, Nettersheim C. Off-Grid Renewable Energy for Climate Action – Pathways for change. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ); 2019. [Online]. Available: <https://reiner-lemoine-institut.de/en/off-grid-renewable-energy-opens-up-pathways-for-electricity-access-and-climate-action/>. [Accessed 22 April 2020].

[64] Deichmann U, Meisner C, Murray S, Wheeler D. The economics of renewable energy expansion in rural Sub-Saharan Africa. Energy Policy 2011;39:215–27. <https://doi.org/10.1016/j.enpol.2010.09.034>.

[65] Ellman D. The Reference Electrification Model: A Computer Model for Planning Rural Electricity Access. Master thesis. Massachusetts Institute of Technology. Engineering Systems Division; 2015.

[66] González-García A, Amatya R, Stoner R, Pérez-Arriaga JI. Evaluation of universal access to modern energy services in Peru. Case study of scenarios for Electricity Access in Cajamarca. Enel Foundation Working Papers. Enel Foundation; 2016 [Online]. Available: <http://universalaccess.mit.edu/#/publications>

[67] Mwalenga L, Amatya R, González-García A, Stoner R, Pérez-Arriaga JI. A Comprehensive Computer-Aided Planning Approach for Universal Energy Access. Case study of Kaloleni, Kilifi County, Kenya. Enel Foundation Working Papers. Enel Foundation; 2016 [Online]. Available: <http://universalaccess.mit.edu/#/publications>. [Accessed 7 May 2020].

[68] van Ruijven BJ, Schers J, van Vuuren DP. Model-based scenarios for rural electrification in developing countries. Energy 2012;38:386–97. <https://doi.org/10.1016/j.energy.2011.11.037>.

[69] Energy Sector Management Assistance Program (ESMAP). Mini Grids for Half a Billion People: Market Outlook and Handbook for Decision Makers. World Bank; 2019 [Online]. Available: <https://openknowledge.worldbank.org/handle/10986/31926>. [Accessed 22 April 2020].

[70] U.S. Department of Energy. Balance-of-System Equipment Required for Renewable Energy Systems,<https://www.energy.gov/energysaver/balance-system-equipment-required-renewable-energy-systems>; 2019 [Accessed 4 November 2019].

[71] Azzopardi B, Emmott CJM, Urbina A, Krebs FC, Mutale J, Nelson J. Economic assessment of solar electricity production from organic-based photovoltaic modules in a domestic environment. Energy Environ Sci 2011;4:3741–53. <https://doi.org/10.1039/c1ee01766g>.

[72] Practical Action. Poor people’s energy outlook 2019. Practical Action Publishing; 2019 [Online]. Available:<https://practicalactionpublishing.com/book/1669/poor-peoples-energy-outlook-2019>. [Accessed 24 April 2020].

[73] Zeyringer M, Pachauri S, Schmid E, Schmidt J, Worrell E, Morawetz UB. Analyzing grid extension and stand-alone photovoltaic systems for the cost-effective electrification of Kenya. Energy Sustain Dev 2015;25:75–86. <https://doi.org/10.1016/j.esd.2015.01.003>.

[74] Sandwell P, Ekins-Daukes N, Nelson J. What are the greatest opportunities for PV to contribute to rural development? Energy Procedia 2017; 130: 139-146. <https://doi.org/10.1016/j.egypro.2017.09.416>

[75] Bhattacharyya SC. Review of alternative methodologies for analysing off-grid electricity supply. Renew Sustain Energy Rev 2012;16:677–94. <https://doi.org/10.1016/j.rser.2011.08.033>.

[76] Finnveden G, Nilsson M, Johansson J, Persson Å, Moberg Å, Carlsson T. Strategic environmental assessment methodologies - Applications within the energy sector. Environ Impact Assess Rev 2003;23:91–123. <https://doi.org/10.1016/S0195-9255(02)00089-6>.

[77] IEMA. Life Cycle Assessment, Environmental Impact Assessment and Strategic Environmental Assessment; 2017. Available: <https://www.internationalworkplace.com/>. [Accessed 17 October 2019].

[78] Organisation for Economic Co-operation and Development (OECD). Applying Strategic Environmental Assessment. OECD Publishing; 2006 [Online]. Available: <https://www.oecd.org/environment/environment-development/37353858.pdf>. [Accessed 2 October 2019].

[79] Jorge RS, Hertwich EG. Grid infrastructure for renewable power in Europe: The environmental cost. Energy 2014;69:760–8. [https://doi.org/https://doi.org/10.1016/j.energy.2014.03.072](https://doi.org/https:/doi.org/10.1016/j.energy.2014.03.072).

[80] Guinée JB. Handbook on Life Cycle Assessment: Operational guide to the ISO standards. London: Kluwer Academic Publishers; 2002.

[81] Kabakian V, McManus MC, Harajli H. Attributional life cycle assessment of mounted 1.8kWp monocrystalline photovoltaic system with batteries and comparison with fossil energy production system. Appl Energy 2015;154:428–37. <https://doi.org/10.1016/j.apenergy.2015.04.125>.

[82] Turconi R, Simonsen CG, Byriel IP, Astrup T. Life cycle assessment of the Danish electricity distribution network. Int J Life Cycle Assess 2014;19:100–8. <https://doi.org/10.1007/s11367-013-0632-y>.

[83] Cross J, Murray D. The afterlives of solar power: Waste and repair off the grid in Kenya. Energy Res Soc Sci 2018;44:100–9. <https://doi.org/10.1016/j.erss.2018.04.034>.

[84] Gaines L. The future of automotive lithium-ion battery recycling: Charting a sustainable course. Sustain Mater Technol 2014;1:2–7. <https://doi.org/10.1016/j.susmat.2014.10.001>.

[85] International Energy Agency (IEA). *Technology Roadmap: Solar photovoltaic energy 2014*. IEA; 2014 [Online]. Available: <https://www.iea.org/reports/technology-roadmap-solar-photovoltaic-energy-2014>

[86] Khan I. Importance of GHG emissions assessment in the electricity grid expansion towards a low-carbon future: A time-varying carbon intensity approach. J Clean Prod 2018;196:1587–99. [https://doi.org/https://doi.org/10.1016/j.jclepro.2018.06.162](https://doi.org/https:/doi.org/10.1016/j.jclepro.2018.06.162).

[87] Patel MK. 4: Gross energy requirements (GER) and gross CO2 emissions for products of the organic chemical industry 1998:67–84.

[88] Brandt AR, Dale M. A general mathematical framework for calculating systems-scale efficiency of energy extraction and conversion: Energy return on investment (EROI) and other energy return ratios. Energies 2011;4:1211–45. <https://doi.org/10.3390/en4081211>.

[89] Shahsavari A, Akbari M. Potential of solar energy in developing countries for reducing energy-related emissions. Renew Sustain Energy Rev 2018;90:275–91. <https://doi.org/10.1016/j.rser.2018.03.065>.

[90] International Energy Agency (IEA). Global Energy & CO2 Status Report 2019. IEA; 2019 [Online]. Available: <https://www.iea.org/reports/global-energy-co2-status-report-2019>

[91] Bruckner T, Bashmakov IA, Mulugetta Y, Chum H, de la Vega Navarro A, Edmonds J, et al. Energy Systems. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, et al., editors. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge and New York: Cambridge University Press; 2014, p. 511-597.

[92] Ristic B, Mahlooji M, Gaudard L, Madani K. The relative aggregate footprint of electricity generation technologies in the European Union (EU): A system of systems approach. Resour Conserv Recycl 2019;143:282–90. <https://doi.org/10.1016/j.resconrec.2018.12.010>.

[93] Gasparatos A, Doll CNH, Esteban M, Ahmed A, Olang TA. Renewable energy and biodiversity: Implications for transitioning to a Green Economy. Renew Sustain Energy Rev 2017;70:161–84. <https://doi.org/10.1016/j.rser.2016.08.030>.

[94] Berry PM, Paterson JS. Energy mitigation, adaptation and biodiversity: Synergies and antagonisms. IOP Conf Ser Earth Environ Sci 2009;8:012023. <https://doi.org/10.1088/1755-1315/8/1/012023>.

[95] Mazur C, Hoegerle Y, Brucoli M, van Dam K, Guo M, Markides CN, et al. A holistic resilience framework development for rural power systems in emerging economies. Appl Energy 2019;235:219–32. <https://doi.org/10.1016/j.apenergy.2018.10.129>.

[96] Cherni JA. The Sustainability of Renewable Energy Technology for Isolated Rural Areas. Studies in Colombia, Cuba and Peru, <http://www.seeds.usp.br/pir/arquivos/congressos/CLAGTEE2003/Papers/RNCSEP%20B-248.pdf>; 2015 [Accessed 24 September 2019].

[97] Bilich A, Langham K, Geyer R, Goyal L, Hansen J, Krishnan A, et al. Life cycle assessment of solar photovoltaic microgrid systems in off-grid communities. Environ Sci Technol 2017;51:1043–52. <https://doi.org/10.1021/acs.est.6b05455>.

[98] Akinyele DO, Rayudu RK. Comprehensive techno-economic and environmental impact study of a localised photovoltaic power system (PPS) for off-grid communities. Energy Convers Manag 2016;124:266–79. [https://doi.org/https://doi.org/10.1016/j.enconman.2016.07.022](https://doi.org/https:/doi.org/10.1016/j.enconman.2016.07.022).

[99] Rathod UK, Modi B. Modeling, simulation and comparison of a hybrid power system for economic analysis and environmental impact. 2016 Int. Conf. Recent Adv. Innov. Eng., 2016, p. 1–5. <https://doi.org/10.1109/ICRAIE.2016.7939497>.

[100] Durlinger B, Reinders A, Toxopeus M. A comparative life cycle analysis of low power PV lighting products for rural areas in South East Asia. Renew Energy 2012;41:96–104. [https://doi.org/https://doi.org/10.1016/j.renene.2011.10.006](https://doi.org/https:/doi.org/10.1016/j.renene.2011.10.006).

[101] Itten R, Frischknecht R, Stucki M. Life cycle inventories of electricity mixes and grid. Uster, Switzerland: ESU-services Ltd.; 2014.

[102] Jorge RS, Hertwich EG. Environmental evaluation of power transmission in Norway. Appl Energy 2013;101:513–20. [https://doi.org/https://doi.org/10.1016/j.apenergy.2012.06.004](https://doi.org/https:/doi.org/10.1016/j.apenergy.2012.06.004).

[103] Harrison GP, Maclean E (Ned) J, Karamanlis S, Ochoa LF. Life cycle assessment of the transmission network in Great Britain. Energy Policy 2010;38:3622–31. <https://doi.org/10.1016/j.enpol.2010.02.039>.

[104] Turconi R, Boldrin A, Astrup T. Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. Renew Sustain Energy Rev 2013;28:555–65. <https://doi.org/10.1016/j.rser.2013.08.013>.

[105] Weisser D. A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies. Energy 2007;32:1543–59. <https://doi.org/10.1016/j.energy.2007.01.008>.

[106] Hondo H. Life cycle GHG emission analysis of power generation systems: Japanese case. Energy 2005;30:2042–56. <https://doi.org/10.1016/j.energy.2004.07.020>.

[107] Hernandez RR, Easter SB, Murphy-Mariscal ML, Maestre FT, Tavassoli M, Allen EB, et al. Environmental impacts of utility-scale solar energy. Renew Sustain Energy Rev 2014;29:766–79. <https://doi.org/10.1016/j.rser.2013.08.041>.

[108] Stoms DM, Dashiell SL, Davis FW. Siting solar energy development to minimize biological impacts. Renew Energy 2013;57:289–98. <https://doi.org/10.1016/j.renene.2013.01.055>.

[109] Fthenakis VM, Kim HC. Photovoltaics: Life-cycle analyses. Sol Energy 2011;85:1609–28. <https://doi.org/10.1016/j.solener.2009.10.002>.

[110] Turney D, Fthenakis V. Environmental impacts from the installation and operation of large-scale solar power plants. Renew Sustain Energy Rev 2011;15:3261–70. <https://doi.org/10.1016/j.rser.2011.04.023>.

[111] Varun, Bhat IK, Prakash R. LCA of renewable energy for electricity generation systems-A review. Renew Sustain Energy Rev 2009;13:1067–73. <https://doi.org/10.1016/j.rser.2008.08.004>.

[112] Laleman R, Albrecht J, Dewulf J. Life cycle analysis to estimate the environmental impact of residential photovoltaic systems in regions with a low solar irradiation. Renew Sustain Energy Rev 2011;15:267–81. <https://doi.org/10.1016/j.rser.2010.09.025>.

[113] Akikur RK, Saidur R, Ping HW, Ullah KR. Comparative study of stand-alone and hybrid solar energy systems suitable for off-grid rural electrification: A review. Renew Sustain Energy Rev 2013;27:738–52. <https://doi.org/10.1016/j.rser.2013.06.043>.

[114] Katre A, Tozzi A, Bhattacharyya S. Sustainability of community-owned mini-grids: Evidence from India. Energy Sustain Soc 2019;9. <https://doi.org/10.1186/s13705-018-0185-9>.

[115] Villavicencio Calzadilla P, Mauger R. The UN’s new sustainable development agenda and renewable energy: the challenge to reach SDG7 while achieving energy justice. J Energy Nat Resour Law 2018;36:233–54. <https://doi.org/10.1080/02646811.2017.1377951>.

[116] Yenneti K, Day R, Golubchikov O. Spatial justice and the land politics of renewables: Dispossessing vulnerable communities through solar energy mega-projects. Geoforum 2016;76:90–9. <https://doi.org/10.1016/j.geoforum.2016.09.004>.

[117] Aberilla JM, Gallego-Schmid A, Stamford L, Azapagic A. An integrated sustainability assessment of synergistic supply of energy and water in remote communities. Sustain Prod Consum 2020;22:1–21. [https://doi.org/https://doi.org/10.1016/j.spc.2020.01.003](https://doi.org/https:/doi.org/10.1016/j.spc.2020.01.003).

[118] Juanpera M, Blechinger P, Ferrer-Martí L, Hoffmann MM, Pastor R. Multicriteria-based methodology for the design of rural electrification systems. A case study in Nigeria. Renew Sustain Energy Rev 2020;133(110243). <https://doi.org/10.1016/j.rser.2020.110243>.

[119] Trutnevyte E, Stauffacher M, Scholz RW. Supporting energy initiatives in small communities by linking visions with energy scenarios and multi-criteria assessment. Energy Policy 2011; 39(12):7884-7895. <https://doi.org/10.1016/j.enpol.2011.09.038>.

[120] Ahlroth S. The use of valuation and weighting sets in environmental impact assessment. Resour Conserv Recycl 2014;85:34–41. <https://doi.org/10.1016/j.resconrec.2013.11.012>.

[121] Gasparatos A, Scolobig A. Choosing the most appropriate sustainability assessment tool. Ecol Econ 2012;80:1–7. <https://doi.org/10.1016/j.ecolecon.2012.05.005>.

[122] Daly HE. Beyond Growth. Boston: Beacon Press; 1996.

[123] Ocon JD, Cruz SMM, Castro MT, Aviso KB, Tan RR, Promentilla MAB. Optimal Multi-criteria Selection of Hybrid Energy Systems for Off-grid Electrification. Chem Eng Trans 2018;70:367-72. <https://doi.org/10.3303/CET1870062>.

[124] Cherni JA, Olalde Font R, Serrano L, Henao F, Urbina A. Systematic Assessment of Carbon Emissions from Renewable Energy Access to Improve Rural Livelihoods. Energies 2016;9:1086. <https://doi.org/10.3390/en9121086>.

[125] Rojas-Zerpa JC, Yusta JM. Application of multicriteria decision methods for electric supply planning in rural and remote areas. Renew Sustain Energy Rev 2015;52:557–71. [https://doi.org/https://doi.org/10.1016/j.rser.2015.07.139](https://doi.org/https:/doi.org/10.1016/j.rser.2015.07.139).

[126] Henao F, Cherni JA, Jaramillo P, Dyner I. A multicriteria approach to sustainable energy supply for the rural poor. Eur J Oper Res 2012;218:801–9. [https://doi.org/https://doi.org/10.1016/j.ejor.2011.11.033](https://doi.org/https:/doi.org/10.1016/j.ejor.2011.11.033).

[127] Haurant P, Oberti P, Muselli M. Multicriteria selection aiding related to photovoltaic plants on farming fields on Corsica island: A real case study using the ELECTRE outranking framework. Energy Policy 2011;39:676–88. [https://doi.org/https://doi.org/10.1016/j.enpol.2010.10.040](https://doi.org/https:/doi.org/10.1016/j.enpol.2010.10.040).

[128] Karger CR, Hennings W. Sustainability evaluation of decentralized electricity generation. Renew Sustain Energy Rev 2009;13:583–93. [https://doi.org/https://doi.org/10.1016/j.rser.2007.11.003](https://doi.org/https:/doi.org/10.1016/j.rser.2007.11.003).

[129] Terrados J, Almonacid G, Pérez-Higueras P. Proposal for a combined methodology for renewable energy planning. Application to a Spanish region. Renew Sustain Energy Rev 2009;13:2022–30. [https://doi.org/https://doi.org/10.1016/j.rser.2009.01.025](https://doi.org/https:/doi.org/10.1016/j.rser.2009.01.025).

**Appendix A: Multi-tier matrix for access in the household locale [6].**

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  | Tier 0 | Tier 1 | Tier 2 | Tier 3 | Tier 4 | | Tier 5 |
| Electricity Supply Attributes | Capacity | Power  (W) | Not specified | ≥ 3 | ≥ 50 | ≥ 200 | ≥ 800 | | ≥ 2,000 |
| Daily capacity (Wh) | ≥ 12 | ≥ 200 | ≥ 1,000 | ≥ 3,400 | | ≥ 8,200 |
| Duration | Hours per day | Not specified | Min 4 | Min 4 | Min 8 | Min 16 | | Min 23 |
| Hours per evening | Min 1 | Min 2 | Min 3 | Min 4 | | Min 4 |
| Reliability | Not specified | | | | | Max 14 disruptions per week | | Max 3 disruptions per week of <2 hrs |
| Quality | Not specified | | | | | Voltage problems do not affect the use of desired appliances | | |
| Affordability | Not specified | | | | Cost of a standard consumption package of 365 kWh/year <5% of household income | | | |
| Legality | Not specified | | | | | Bill is paid to the utility, prepaid card seller, or authorised representative | | |
| Health and Safety | Not specified | | | | | Absence of past accidents and perception of high risk in the future | | |
| Electricity Services | Tier Criteria | | Not specified | -Task lighting  -Phone charging | -General lighting -Phone charging *If needed:*  -TV -Fan | Tier 2 AND any \*medium-power appliances | Tier 3 AND any \*\*high-power appliances | Tier 2 AND any \*\*\*very high-power appliances | |

*\*Medium-power appliances may include air cooler, refrigerator, freezer, food processor, water pump, rice cooker*

*\*\*High-power appliances may include washing machine, iron, hair dryer, toaster, microwave*

*\*\*\*Very high-power appliances may include air conditioner, space heater, vacuum cleaner, water heater, electric cooker*

**Appendix B: Methods**

For the present study, we used ‘Web of Science’ database and ‘Google Scholar’ search engine. In undertaking the review of literature available, we considered the following search terms on Web of Science: (energy OR electricity) AND access; AND grid\*; AND {off grid OR off-grid} OR {minigrid OR mini-grid} AND {review OR literature review}. We also searched the following keywords to delve into more detail on the specific economic and environmental impacts of different electricity systems: economic; environmental; impact; grid\*; {off grid OR off-grid}; {minigrid OR mini-grid}; (energy OR electricity) AND systems. The criteria we then used to prioritise the research carried out focused mainly on papers comparing grid and off-grid systems based on economic and/or environmental impacts, papers regarding rural electrification or energy access in developing countries, papers considering residential demand or demand at a household level, and papers including solar technologies. We further researched all the relevant literature cited on the papers selected using Google Scholar; we also used this search engine to identify relevant grey literature. For the economic review, we summarised the following elements for each paper to facilitate comparison between the 16 studies: ‘Study Location’, ‘Research Question/objective’, ‘Demand Type’, ‘System Architecture’, ‘Considered Technologies’, ‘Methodology’, ‘Software/model used’, ‘Evidence of Costs’, ‘Metrics used’, ‘Results’. In conducting the review of environmental impacts, we considered electricity systems in general, that is generation, transmission and distribution of grid-extension as well as impacts of solar PV technologies in developed and developing countries. We recognise that during this process, it is likely that our search method might have neglected some studies.

1. This scenario considers policy initiatives announced by governments. For SDG7, relevant policies are the Nationally Determined Contributions, pledged in the Paris Agreement, and other policies [4].   [↑](#footnote-ref-1)
2. We assumed the previous year to the publication of the paper as the original reported value date.   [↑](#footnote-ref-2)
3. Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) report cited by the IPCC [91]. [↑](#footnote-ref-3)
4. Energy yield ratio as CED/Energy consumed by community [97]. [↑](#footnote-ref-4)