Analytical Frameworks and an Integrated Approach for Mini-Grid-Based Electrification

Subhes C. Bhattacharyya, Arabinda Mishra and Gopal K. Sarangi

Abstract Although rural electrification using mini-grids has attracted recent global attention, the concept has been there for quite some time. Consequently, a number of analytical approaches exist to support the decision-making process. This chapter first provides a review of literature dealing with analytical frameworks for off-grid and mini-grid based electrification projects. The range of analytical options includes simple worksheet-based tools to more sophisticated optimisation tools for technology selection as well as assessments based on multi-criteria analysis. This is followed by an evaluation of mini-grid based off-grid electrification projects in India that allows the identification of critical factors for the success of such projects. Finally, the chapter proposes an integrated approach for analysing decentralised mini-grid projects in a holistic manner.

1 Introduction

Decentralised electricity supply using local grids is a complex undertaking that requires all the activities of a conventional electricity supply system at a smaller scale in a remote area. Being a small, self-contained system, any such project requires careful preparation and planning, operation, control and maintenance as well as appropriate organisational arrangement, although it may not enjoy the

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benefits of accumulated expertise, resources of a large organisation, or the support of a large resource and consumer base to offer stability and diversity. Accordingly, it is important to undertake a careful study prior to any investment decision. This is increasingly gaining importance with private sector gradually venturing into the decentralised energy space as a potential actor.

Developing countries are increasingly looking forward to off-grid solutions like mini-grids not as an isolated form of energy provision, but in the overall context of community life and as an integral component of other rural improvement efforts [50]. For project developers of decentralised mini-grid systems, some inherent constraints arise because of high upfront costs, 'thin' rural markets due to small size of buyers and sellers, difficulty in arranging institutional finance and ambiguous government policies. More specifically on the policy front, the existing responses are limited to pilot scale implementation models and do not have a clear framework to mainstream decentralised systems in the national planning process [46]. A greater challenge to promote and accelerate the off-grid process in developing economies is linked to inadequate capacities at the community or village level to effectively operate and maintain the infrastructure. Studies point that capacity building efforts are central to wider replication of these systems [19, 114].

A review of literature reveals that there is a dearth of studies with integrated frameworks of analysis. Most of the studies either focus on techno-economic assessments or present policy narratives without adequate attention to local contexts and key determinants shaping the development trajectory of these projects. To bridge the gap, this chapter reviews alternative methodological options and presents an integrated framework for mini-grid analysis. We shall rely on the relevant literature to perform the above tasks. The chapter is organised as follows: Sect. 2 provides a review of literature covering the wide variety of approaches that have been used in the past and includes techno-economic feasibility studies, various analytical approaches such as indicators, optimisation, multi-criteria decision-making and systems approach and project-based literature (including project reports, manuals and best practices). Section 3 then considers the field-level experience from India while Sect. 4 presents an integrated approach for mini-grid interventions at the country level. Finally, a concluding section captures the main findings of this chapter.

2 Literature Review

The literature[1] on renewable energy and electricity supply is very well developed, and a number of strands can be identified from this body of knowledge.

(a) First, the focus of most of the literature is on the technical design of the system and its cost effectiveness analysis using some economic indicators (see [9] for a review of literature on hybrid renewable energy systems). Given the

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[1] This section is based on Bhattacharyya [11].

technological diversity of renewable energies, this set of literature has often relied on the case study approach where the application of individual technologies or a combination of technologies has been considered to meet the energy demand. Some studies provide a review of the technological and economic readiness of alternative energies as well.

(b) Second, a number of tools have been used by various authors. For example, Hybrid Optimisation Model for Electric Renewables (HOMER), developed by National Renewable Energy Laboratory, USA (NREL), appears repeatedly in the literature as a preferred tool. It can handle a large set of technologies (PV, wind, hydro, fuel cells, boilers, etc.), loads (AC/DC, thermal and hydrogen), and can perform hourly simulations. Table 1 provides a list of some examples of HOMER application. HOMER is an optimisation tool that is used to decide the system configuration for decentralised systems. Other software tools include HYBRID2 developed by the Renewable Energy Research Laboratory (RERL) and Hybird Optimisation by Genetic Algorithms developed by the University of Zaragoza, Spain (HOGA), which are available freely.[2]

The use of optimisation approach has a long tradition in rural energy supply analysis. The most common application relies on linear programming due to its ease of use but more advanced applications have also been reported. In addition, simulations, multi-objective evolutionary programmes, and multi-criteria decision-making approach have been used. Given that the decision-making often involves trade-offs amongst various competing objectives and because such decisions may change depending on the stakeholder preferences, MCDM provides an effective alternative for reconciling conflicting viewpoints.

(c) Third, the practice-oriented literature (such as manuals and best-practice experiences) also provides some guidelines on decentralised electricity supply and in some cases recommends steps or critical factors for such projects.

In this section, we shall review some literature covering all three areas. Given the vastness of the literature and scarcity of resources, the review will necessarily be a partial one but we shall try to capture the essential points from each of the above sets.

2.1 Techno-Economic Feasibility Studies

There is a large volume of literature available of this sort that focuses on various technologies and country cases. These studies generally follow a common approach—assessment of technological appropriateness, evaluation of economic viability and determination of financial or other incentives required to make the

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[2] For a list of such tools and their characteristics see [9].

Table 1 Some examples of HOMER application

Reference	Technology application	Country of application
Sen and Bhattacharyya [92]	Mini-hydro, solar, bio-diesel, wind	India
Demiroren and Yilmaz [23]	Wind, PV, wind-PV hybrid, and diesel generator	Turkey—Island example
Lau et al. [62]	PV-diesel hybrid	Malaysia
Weis and Ilinca [112]	PV-diesel	Canada
Setiawan et al. [93]	PV-diesel, wind-diesel, PV-wind-diesel	Maldives
Himri et al. [45]	Wind-diesel hybrid	Algeria
Nandi and Ghosh [69]	Wind-PV-battery	Bangladesh
Turkey and Telli [106]	Wind, solar, hydrogen	Turkey
Dalton et al. [21, 22]	PV, diesel, wind	Australia—energy supply options for a large hotel
Khan and Iqbal [58]	Wind, diesel, battery, fuel cell	Newfoundland, Canada
Shaahid and Elhadidy [94–98]	PV-diesel-battery	Saudi Arabia
Nfah et al. [70]	PV, micro-hydro, LPG generator, battery	Cameroon
Bekele and Palm [7]	PV-wind hybrid	Ethiopia
Prodromidis and Coutelieris [82]	PV, wind, battery	Greek Islands

Source Based on Bhattacharyya [11]

project viable at a given location [57]. Most of these studies compare the grid and off-grid investment options using a financial or economic cost-benefit evaluation.

Reddy et al. [86] provided a comparative costing of grid-connected, off-grid and energy conservation systems in the Indian context. This study highlighted the importance of improved technology for rural energy services and provided a detailed evaluation of grid-connected, off-grid and energy conservation options using the life cycle costing approach. Sinha and Kandpal [97] compared the cost of electricity supply through grid extension against the cost of supply from decentralised sources for rural India. This study considered the cost of extending the grid in terms of investments for the distribution network. It also considers the cost of grid electricity at various distances from the grid as well as for different levels of load factors and transmission-distribution losses. The cost of electricity supply from alternative sources is then considered and compared to see how the cost effectiveness changes as the distance from the main grid increases, the load factor changes and peak demand increases. The study using data from late 1980s found that the decentralised solutions are viable in isolated, small villages with low load factors. Similarly, for villages located 25 km away from the 33 kV grid, decentralised options become viable. It might be useful to undertake such a study using more recent data and taking other country examples.

Bernal-Agustin and Dufo-Lopez [8] have performed an evaluation of the grid-connected solar PV system in the Spanish case. The study analysed the economic and environmental benefits of a PV project considering the net present value and pay-back periods. The paper considered the initial cost of the grid-connected PV system (i.e. the cost of the generator, the cost of the inverter, and the cost related to installation) along with any subsidy that is available to the investor. The net cash flow generated by the project per year is estimated taking income and expenses into consideration. Income is generated either by selling electricity to the grid or by reducing electricity purchase through auto-consumption of electricity generated through the PV system. Expenses include costs related to operations and maintenance of the system, insurance and financing the project. Given that cash flow occurs over the lifetime of the project and that the investment is an initial cost, the net present value of the investment is considered assuming a life of 25 years for the project. The paper then applies this to a case in Zaragoza (Spain) and analyses the NPV and payback period for different electricity prices, interest rates, and subsidy sizes. The paper also considered the environmental benefits of PV electricity by considering the amount of emissions avoided and CO_2 emission mitigated. It then estimated the avoided costs of externality in monetary terms considering different scenarios of electricity substitution by the PV system (e.g. avoidance of thermoelectric power, power from sub-bituminous coal, etc.).

Chakraborti and Chakraborti [17] analysed the case of solar PV for an island use in Sagar Dweep, India. The study considered PV and grid extensions as alternative systems and evaluated the options from economic and environmental perspectives. The study shows that grid extension over long distances is not cost-effective.

2.2 Analytical Approaches

In this section, we shall review a number of alternative approaches that are found in the literature that have been used to analyse and decide the appropriate energy systems for rural areas.

2.2.1 Levelised Cost of Supply

The levelised cost of supply is a common indicator used for comparing cost of electricity supply options. The levelised cost is the real, constant cost of supplying electricity that if recovered from consumers over the lifetime of the plant would meet all costs associated with construction, operation and decommissioning of a generating plant. This generally considers capital expenditures, operating and maintenance costs, fuel costs, and any costs involved in dismantling and decommissioning the plant. It can also consider the external costs and other relevant costs such as costs of back-up power in the case of intermittent energies. This indicator has been routinely used to analyse the cost effectiveness of renewable energy options compared to other conventional energies. Examples include IEA [16, 48, 49, 88, 102].

However, care has to be taken in using this method due to a number of factors:

(1) First, the levelised cost is calculated based on a specific rate of utilisation (capacity factor) of a technology. Technologies with similar utilisation rate can be easily compared using this method but technologies with different load profiles or loading patterns can give misleading results. For example, if a technology is used for base load and the other for peaking purposes, the levelised cost for the base load plant will always be favourable due to higher level of utilisation.
(2) Second, in many cases, the variability of fuel costs is inadequately captured (or underestimated), making fossil fuel-based plants more cost effective.
(3) Third, for non-firm supply technologies, the cost of back-up or standby power could be inappropriately considered.
(4) Finally, this often ignores the external costs related to fossil fuel use, thereby putting the renewable energies at a disadvantage.

For decentralised electricity supply in developing countries, the levelised cost approach has been used in a number of studies. Banerjee [6] has presented a detailed study of cost estimations in the Indian context. Similarly, Nouni et al. [72–74] presented cost estimations for specific technologies in the Indian context.

Nouni et al. [71] has used this approach to identify the potential areas for decentralised electricity supply in India. They considered the delivered cost of electricity supply for different load factors and for villages located within a radius of 5–25 km from an existing 11 kV substation for two cases: plain terrain and hilly terrain, where the cost of local distribution tends to be higher. They also considered the cost of supply from decentralised renewable energy options. Considering typical village load data from 1991 Census statistics, they estimated that the average peak load of a remote rural household to be 0.675 kW. Considering the population of villages, they suggested that villages with <50 kW peak load could be considered for decentralised electricity supply through renewable energy technologies. The authors then considered the trade-off between grid extension and off-grid supply to find the cost effective electricity supply option for remote villages. While this provides a framework of analysis from the cost of supply perspective, the analysis does not consider the external costs related to fossil fuel use, cost of security of supply, cost of stand-by power for renewable energies. Accordingly, the study is likely to favour fossil fuels and undermines the potentials of renewable energies.

Kolhe et al. [59] presented a life cycle cost comparison between a stand-alone PV system and a diesel power plant in India. The study followed an approach similar to levelised costs but derived these using specific parameters for diesel plants and PV systems.

Perhaps the most comprehensive study of alternative generating technologies suitable for energy access projects is found in ESMAP [33]. This study presents a review of a range of technologies covering a wider spectrum of capacities—50 W to 500 MW. The review is presented for 37 technologies (renewable, conventional and emerging) under three categories—off-grid, mini-grid and grid-connected electricity supply. The report provides the technical features of alternative technologies, presents alternative configurations that are used in practice and discusses the cost and performance assumptions of each technology used in the analysis.

The study has assessed the economics of the above technologies using the levelised cost method and presented the results for three different time horizons—2005, 2010 and 2015, to reflect the effect cost reduction in some technologies. The study also considers the effect of sensitivity of key variables on the economic viability of technological options. The costs of local distribution as well as long distance transmission are also considered where applicable. However, the study does not include the external costs and security of supply concerns for fossil fuels and stand-by power costs for renewable energies.

The levelised cost of electricity supply for renewable energy options is presented in Table 2, while the levelised cost of conventional/emerging electricity supply technologies is presented in Table 3. As can be seen from these tables,

- The cost of off-grid options is generally higher than that of conventional energies;
- The cost of supply reduces as the size of plant increases. Electricity supplied from small-sized off-grid plants tends to cost much higher than the bigger sized plants of same technology.
- Some renewable technologies are either cost effective or reaching cost effectiveness.

However, the levelised cost approach, despite its wider use, is a one-dimensional indicator and fails to capture any dimension beyond costs. In addition, the external costs due to environmental effects and security of supply were not captured in the above study. This limitation needs to be kept in mind while using this comparator.

2.2.2 Weighted Score System

Lhendup [63] presented a weighted score system where a number of aspects (such as technical, regulatory features, environmental and social aspects) related to rural energy supply options are considered. A set of indicators is then identified for each aspect and a weight is given based on the importance of the indicator. Each option is tested against a set of indicators and a score is given depending on the performance of the option against the indicator. The product of the score and the weight for a particular indicator gives the weighted score. The process is repeated for all indicators and the sum of the weighted scores for any option gives its total score. Supply options were ranked based on their weighted scores (see Table 4). Lhendup [63] used a performance scale of 1 (low) to 5 (high) and a total weight of 100 for 18 indicators. The paper explains the justification for each ranking in an appendix and indicates that the methodology can be implemented in a simple spreadsheet model.

Table 2 Levelised cost for renewable energy technologies (2005, US cents/kWh)

Technology		Rated output kW	Levelised cost components				
			Capital	Fixed O&M	Variable O&M	Fuel	Average
Solar PV		0.05	45.59	3	13		61.59
		0.3	45.59	2.5	8		56.09
		25	42.93	1.5	7		51.43
		5,000	40.36	0.97	0.24		41.57
Wind		0.3	26.18	3.49	4.9		34.57
		100	13.55	2.08	4.08		19.71
		10,000	5.85	0.66	0.26		6.77
		100,000	5.08	0.53	0.22		5.83
PV-wind hybrid		0.3	31.4	3.48	6.9		41.78
		100	22.02	2.07	6.4		30.49
Solar thermal	With storage	30,000	10.68	1.82	0.45		12.95
	Without storage	30,000	13.65	3.01	0.75		17.41
Geothermal	Binary	200	12.57	2	1		15.57
	Binary	20,000	5.02	1.3	0.4		6.72
	Flash	50,000	3.07	0.9	0.3		4.27
Biomass gasifier		100	4.39	0.34	1.57	2.66	8.96
		20,000	3.09	0.25	1.18	2.5	7.02
Biomass steam		50,000	2.59	0.45	0.41	2.5	5.95
MSW/Landfill gas		5,000	4.95	0.11	0.43	1	6.49
Biogas		60	3.79	0.34	1.54	1.1	6.77
Pico/Micro-hydro		0.3	14.24	0	0.9		15.14
		1	12.19	0	0.54		12.73
		100	9.54	1.05	0.42		11.01
Mini-hydro		5,000	5.86	0.74	0.35		6.95
Large hydro		100,000	4.56	0.5	0.32		5.38
Pumped storage		150,000	34.08	0.32	0.33		34.73

Source ESMAP [33]

Table 3 Levelised cost of conventional/emerging technologies (2005, US cents/kWh)

Technology		Rated output kW	Levelised cost components				
			Capital	Fixed O&M	Variable O&M	Fuel	Average
Diesel/Gasoline generator		0.3	5.01		5	54.62	64.63
		1	3.83		3	44.38	51.21
		100	0.98	2	3	14.04	20.02
	Baseload	5,000	0.91	1	2.5	4.84	9.25
	Peakload	5,000	7.31	3	2.5	4.84	17.65
Microturbines		150	1.46	1	2.5	26.86	31.82
Fuel cell		200	5.6	0.1	4.5	16.28	26.48
		5,000	5.59	0.1	4.5	4.18	14.37
Combustion turbines	Natural gas	150,000	5.66	0.3	1	6.12	13.08
	Oil		5.66	0.3	1	15.81	22.77
Combined cycle	Natural gas	300,000	0.95	0.1	0.4	4.12	5.57
	Oil		0.95	0.1	0.4	10.65	12.1
Coal steam with FGD and SCR	Sub-critical	300,000	1.76	0.38	0.36	1.97	4.47
		500,000	1.67	0.38	0.36	1.92	4.33
	Supercritical	500,000	1.73	0.38	0.36	1.83	4.3
	Ultra-super critical	500,000	1.84	0.38	0.36	1.7	4.28
Coal IGCC (without FGD and SCR)		300,000	2.49	0.9	0.21	1.73	5.33
		500,000	2.29	0.9	0.21	1.73	5.13
Coal AFBC (without FGD and SCR)		300,000	1.75	0.5	0.34	1.52	4.11
		500,000	1.64	0.5	0.34	1.49	3.97
Oil steam		300,000	1.27	0.35	0.3	5.32	7.24

Source ESMAP [33]

Note FGD: Flue gas desulphurisation; IGCC—Integrated Gasification Combined Cycle
AFBC—Atmospheric Fluidised Bed Combustion
SCR—Selective Catalytic Reduction

Although this attempts to capture various dimensions in a simple way, there is some inherent subjectivity involved here in terms of weights attached and ranking given to each factor. However, if a participatory approach is used in deciding the weights and the ranks for a given locality or case, this method can turn out to be a useful tool.

2.2.3 Sustainability Indicators

Ilskog [51] presented a set of 39 indicators for assessing rural electrification projects. These indicators considered five sustainability dimensions—technical sustainability, economic sustainability, social/ethical sustainability, environmental sustainability and institutional sustainability. This is presented in Fig. 1.

Table 4 Provides the criteria suggested by Lhendup [63] and their weights

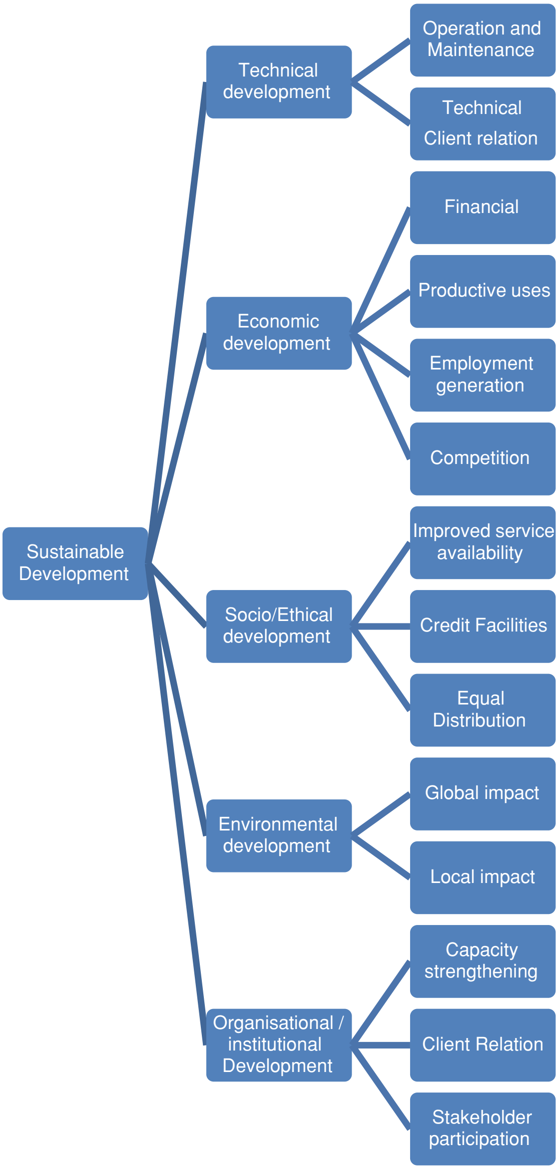
Criteria	Weight	Ranking	
		1	5
1 Technical features	60		
1.1 Energy density of the system	8	Low	Very high
1.2 Ability to meet the anticipated demand	8	Not at all	Fully
1.3 Energy payback ratio	8	Low	High
1.4 Lifespan of the system	7	Short	Very long
1.5 Quality of supply	6	Poor	Very good
1.6 Weather and climatic condition dependence	6	Fully dependent	Not at all
1.7 Availability of local skills and resources	5	Not available	Available
1.8 Incremental capacity of the system	5	Difficult	Easy
1.9 Dependence on fossil fuels	4	Fully dependent	Not at all
1.10 Other infrastructure development	3	Required	Not required
2 Government regulations	15		
2.1 Tax incentives	5	Not provided	Provided
2.2 Regulation on use of local resources	5	Regulated	No regulation
2.3 Opportunity for private participation	5	Low	High
3 Environmental and social aspects	25		
3.1 Public and political acceptance	6	Not acceptable	Acceptable
3.2 Land requirement and acquisition	6	High	Low
3.3 Hazard rating	5	High	Low
3.4 Environmental pollutants	5	High	Low
3.5 Interference with other utility infrastructure	3	High	Low
Total	100		

Source Lhendup [63]

Ilskog and Kjellstrom [52] presented an assessment of rural electrification cases using 31 of these indicators. Each indicator was scored on a scale of 1–7, with 7 representing the best performance. The total score was obtained by simple averaging of the scores, implying that all indicators received same weight. The scoring was based on interviews with 800 randomly selected stakeholders and the performance comparison of projects was done using these indicator scores. The paper considered that ‘the technical sustainability is facilitated if the technical infrastructure locally available meets the requirements of the technology installed, if the technology used can provide the service needed and if favourable technical performance leads to low costs for the services’ [52]. Table 5 compiles the indicators under five sustainability dimensions.

This method was clearly applied keeping the stakeholder participation in mind. Therefore, it is compliant with the participatory approach and can be used either at the local level or at a higher level of aggregation. It can also capture qualitative factors and offers the flexibility that additional factors can be added while any factor that is not relevant for a given application can be removed. This can be easily adapted to include concerns of energy security and governance. However, several factors will require additional estimation/calculation and therefore will require a systematic tool to implement this approach.

Fig. 1 Sustainability indicators process. *Source* Ilskog [51]



2.2.4 Optimisation Techniques

Optimisation has been widely used in energy analysis since the 1970s but applications for rural energy supply systems started in the 1980s. Parikh [76] presented a linear programming model to capture the interactions between energy and agriculture in rural areas of developing countries. The model considered 12

Table 5 Indicators used for rural electrification analysis

Technical sustainability	Economic sustainability	Social/Ethical sustainability	Environmental sustainability	Institutional sustainability
Operation and maintenance—conforms with national standards	Financial perspective—profitability (%)	Improved availability of social electricity services—number of street lights in the area, number per 1,000 population	Global impact—share of renewable energy in production, %	Capacity strengthening—share of staff and management with appropriate education, %
Technical losses, %	Financial perspective—O&M costs USD/kWh	Credit facilities—Micro-credit possibilities available for electricity services connection (yes/no)	Global impact—Emission of CO_2 from production, kg CO_2/kWh	Degree of local ownership, %
Technical client-relation issues—daily operation service (%)	Financial perspective—Costs for capital and installation, USD/kWh	Equal distribution—share of population with primary school education (%)	Local impact—share of electrified households where other energy sources for lighting has been replaced, %	Number of shareholders (number)
Technical client-relation issues—availability of services (%)	Financial perspective—Share of profit set aside for reinvestment, %	Share of population with access to electricity, %	Local impact—share of electrified households where other energy sources for cooking main meals has been replaced, %	Share of women in staff and management, %
	Financial perspective—Tariff lag, USD, kWh	Share of electricity consumers in high income category, %	Any serious local environment impact identified, yes/no	Number of years in business (number)
	Development of productive uses—share of electricity consumed by business, %	Subsidy offered for electricity services, USD, kWh		Client-relation—Share of non-technical losses (%)

(continued)

Table 5 (continued)

Technical sustainability	Economic sustainability	Social/Ethical sustainability	Environmental sustainability	Institutional sustainability
	Share of electricity used by households for income-generating activities, %			Level of satisfaction with energy services (%)
	Competition—number of electricity service organisations in the area			Stakeholder participation—Auditing of reports on an annual basis (yes/no)

Source Ilskog and Kjellstrom [52]

different energy sources and several conversion technologies. It captured the supply and demand for energy and agricultural outputs to find an optimal mix for a given rural condition. Ramakumar et al. [85] developed a linear programming model for integrated rural energy systems. The idea is simple here—the system will be designed to minimise the total cost subject to a number of constraints related to energy availability, energy demand, and other technical/system constraints. There were many different methods of optimisation used to analyse rural energy systems namely: Linear programming, Geometric programming, Integer programming, Dynamic programming, Stochastic programming, Quadratic programming, Separable programming, Multi-objective programming, Goal programming and Hybrid methods. The model presented by Ramakumar et al. [85] was suitable for stand-alone systems. Ashenayi and Ramakumar [5] and Ramkumar et al. [84] expanded these models to include a knowledge-based design tool and other factors such as power reliability (loss of power probability) and scenario design.

Sinha and Kandpal [98–100] designed an optimisation model for rural energy supply considering lighting, cooking and irrigation demands. These models were applied to an Indian context to analyse the cooking, lighting and irrigation needs of rural areas and this showed how such a technique can be effectively used as a decision tool. These models considered a number of alternative technologies with different cost characteristics and found the optimal combinations using linear programming.

Iniyan and Jagadeeshan [53] developed an optimal renewable energy model (OREM) which considered 38 different renewable energy options. The model minimised the cost/efficiency ratio and used resource availability, demand, reliability and social acceptance as constraints. Devdas [24–27] presented a linear programming model for analysing rural energy for local-level development. The program optimised the revenue of rural output subject to energy and non-energy constraints. The model was applied to the District of Kanyakumari of Tamil Nadu, India.

Parikh and Ramanathan [77] presented the INGRAM model to analyse the interactions between energy, agriculture and environment in rural India. This program maximised the net revenue of the rural energy system subject to constraints that included crop residue balance, animal feed balance, dung balance, fertiliser nutrients balance, as well as energy balance to ensure adequate supply to meet the demand. The model was calibrated for the year 1990–1991 and applied for the year 2000. Although this is not a rural energy supply model per se, it incorporated elements that are relevant for a sustainable rural energy system development, although it did not consider the use of modern renewable energies in the analysis.

Akella et al. [1] used an optimisation framework to analyse the optimum renewable energy use in a remote area in India. The paper considered solar photovoltaic systems (SPV), micro hydropower (MHP), biomass energy supply (BES) and wind energy supply (WES). The model provides the least-cost combination of different renewable energies that could be used to meet the need. However, the model considers the overall energy use in the village and does not consider the projects that would be used to supply such energies. The model used the following equations (Box 1) where Z is the total cost of providing energy, MHP, SPV, WES and BES represent four renewable resources indicated above. All sources are used to meet the demand subject to availability constraints. The problem was solved using Lindo and Homer. The HOMER analysis produced somewhat higher results because the software takes into account the cost of the local grid, cost of batteries and cost of conversion, while LINDO only considered the renewable system costs.

A very similar study was reported by Kanase-Patil et al. [55] where the case study was performed at a different location in India. This study considered micro-hydro, biomass, biogas, PV and wind. A number of alternative scenarios have been presented, and the least-cost supply option is determined through the optimisation process. The optimisation programme was run using Lingo and HOMER packages.

Box 1: Equations used by Akella et al. [1]

Minimise:	$Z = 1.50\ \mathrm{MHP} + 15.27\ \mathrm{SPV} + 3.50\ \mathrm{WES} + 3.10\ \mathrm{BES}$
Subject to:	$\mathrm{MHP} + \mathrm{SPV} + \mathrm{WES} + \mathrm{BES} = D$ kWh/year
	$\frac{\mathrm{MHP}}{0.9} \leq 12.8.166\ \mathrm{kW\,h\,m^{-2}\,year^{-1}}$
	$\frac{\mathrm{SPV}}{0.9} \leq 22.363\ \mathrm{kW\,h\,m^{-2}\,year^{-1}}$
	$\frac{\mathrm{WES}}{0.80} \leq 15,251\ \mathrm{kW\,h\,m^{-2}\,year^{-1}}$
	$\frac{\mathrm{BES}}{0.85} \leq 641,385\ \mathrm{kW\,h\,m^{-2}\,year^{-1}}$
	$\mathrm{MHP}, \mathrm{SPV}, \mathrm{WES}, \mathrm{BES} \geq 0$

Source Akella et al. [1]

Howells et al. [47] presented a study of a hypothetical, non-electrified, low-income South African village using MARKAL/TIMES—an optimisation model used for deciding the least-cost option for meeting the energy needs of the village. In contrast to other models, this application considered the entire range of end-use energy demand—cooking, lighting, space heating, water heating, refrigeration and other. It also considered electricity, diesel, LPG, solar, wind, candle, paraffin, coal and wood.

The study suggests that such a detailed analysis is feasible. Such a framework can be used to capture multiple objectives—such as cost minimisation, minimisation of environmental effects, etc. It could capture the dynamic aspect of energy transition by considering a long-term perspective. But data availability is a constraint—especially data on appliance stocks, efficiencies, is not readily available. The model complexity increases as more technological options are included and the long-term dynamics is considered.

2.2.5 Multi-Criteria Decision-Making Method

The multi-criteria decision making (MCDM) is a decision support system that is used to capture multiple dimensions of a project or a policy, some of which may be conflicting with each other. There are three schools of thoughts in this area—the American School (or value measurement models), the European School (or outranking models), and the goal, aspiration reference level models [65]. The American school focuses on the Analytical Hierarchy Process and multi-attribute value/utility theory. This assumes that the decision-maker is aware of the preferences and can express and rank them unambiguously. On the other hand, the European school does not assume full knowledge of preferences by the stakeholders and is therefore less restrictive. The third category, on the other hand, tries to find alternative solutions that are closest to achieving a desired goal or aspiration level. These methods compare options relative to an ideal solution and the option closest to the ideal is chosen.

Each of these has been applied to energy and renewable energy issues—Greening and Bernow [42] point out the potential of MCDM in energy and environment studies, while Ref. [110] presents a recent review. Some other studies include Refs. [28, 65, 75, 78]. Some studies have also applied these techniques to decentralised energy systems. A brief review of these approaches and applications to rural energy issues is presented below. Loken [65] insisted that in choosing an appropriate MCDM approach, it is better to avoid 'black-box' models as they are poorly understood by the decision-makers. Transparent approaches generate better acceptability of results and outcomes as decision-makers trust the results.

AHP Method

The analytical hierarchy process is a powerful and flexible decision-making process developed by Saaty [89] that is used to solve complex problems involving interactions of different criteria across different levels. It is a multiple criteria decision-making technique that allows subjective as well as objective factors to be considered in decision-making process. The AHP allows active participation of decision-makers/stakeholders in reaching agreement, and gives managers a rational basis on which to make decisions.

The AHP is a theory of measurement for dealing with quantifiable and intangible criteria that has been applied to numerous areas, such as decision theory and conflict resolution [108]. AHP is a problem-solving framework and a systematic procedure for representing the elements of any problem [91]. AHP is based on the following three principles: Decomposition, comparative judgements, and synthesis of priorities.

Formulating the decision problem in the form of a hierarchical structure is the first step of AHP. In a typical hierarchy, the top level reflects the overall objective (focus) of the decision problem. The elements affecting the decision are represented in intermediate levels. The lowest level comprises the decision options.

Once a hierarchy is constructed, the decision-maker begins a prioritisation procedure to determine the relative importance of the elements in each level of the hierarchy. The elements in each level are compared as pairs with respect to their importance in making the decision under consideration. A verbal scale is used in AHP that enables the decision-maker to incorporate subjectivity, experience, and knowledge in an intuitive and natural way. For pair-wise comparison, a scale proposed by Satty [89] is commonly used (see Table 6). After comparison matrices are created, relative weights are derived for various elements. The relative weights of the elements of each level with respect to an element in the adjacent upper level are computed as the components of the normalised eigenvector associated with the largest eigenvalue of their comparison matrix. Composite weights are then determined by aggregating the weights through the hierarchy. This is done by following a path from the top of the hierarchy to each alternative at the lowest level, and multiplying the weights along each segment of the path. The outcome of this aggregation is a normalised vector of the overall weights of the options. The mathematical basis for determining the weights was established by Saaty [89].

Dyer and Forman [31] describe the advantages of AHP in a group setting as follows: (1) both tangibles and intangibles, individual values and shared values can be included in an AHP-based group decision process, (2) the discussion in a group can be focused on objectives rather than alternatives, (3) the discussion can be structured so that every factor relevant to the discussion is considered in turn and (4) in a structured analysis, the discussion continues until all relevant information from each individual member in a group has been considered and a consensus choice of the decision alternative is achieved. A detailed discussion on conducting AHP-based group decision-making sessions including suggestions for assembling the group, constructing the hierarchy, getting the group to agree, inequalities of power, concealed or distorted preferences, and implementing the results can be found in Saaty [90] and Golden et al. [39].

AHP is the most commonly used MCDM approach. Zangeneh et al. [116] used the AHP method to prioritise distributed energy options using a case study of Iran. The first level sets the prioritisation goal. At the second level, four factors are considered—technical, economic, environmental attributes and regional primary energy resources. At the third level, sub-criteria for each of the factors are introduced. For economic aspects, two factors are considered: Costs and market. For cost, two further factors are considered—investment cost and operating cost. For market, two other factors are considered—potential of making money through supply and potential of ancillary service supply.

For technical issues, three factors are considered—operational issues, structural issues and technical requirements. Six factors are considered under operational issues—power quality, forced outage rate, response speed, efficiency, start-up time, and capacity factor. Under structural issues four factors are considered—footprint, lifetime, modularity and installation lead time. Similarly, three factors are included in the technical requirement category—maintenance, domestic technical knowledge and interconnection equipment.

Table 6 AHP pair-wise comparison scale

Score	Description
1	Equally preferred
3	Weak preference
5	Strong preference
7	Very strong or demonstrated preference
9	Extreme importance
2, 4, 6, 8	Intermediate values

Under the environmental dimension, three factors have been considered: noise emission, pollution emission and aesthetics. While noise and aesthetics did not have any further factors, under pollution emission, five factors are considered—PM10, SO_2, CO_2, NO_x and CO. The case study considered PV, wind, fuel cell, micro-turbine, gas turbine and diesel engines as alternative technologies. The prioritisation was done based on a survey of expert views (51 participated but 37 results were retained). The analysis was performed using Expert Choice software. The paper presented the results of the prioritisation exercise with detailed tabulation of criteria values at each level.

Other studies using AHP for energy analysis include Wang et al. [109], Wang and Feng [111], Limmeechokchai and Chawana [64], and Kablan [54].

Multi-criteria Decision-Making for Renewable Energy Sources (MCDM-RES)

Polatidis and Haralambopolous [80] presented an integrated renewable energy planning and design framework that they applied to a Greek island in the Aegean Sea. The planning activity is considered to be a multi-dimensional activity that takes technical, economic, environmental and social aspects into consideration. The authors highlight the complexity of energy planning process due to the presence of structural aspects, multiplicity of actors and multi-dimensional sphere of interactions. This is captured in Fig. 2. In addition, they are mindful of the fact that technologies and decision-making processes have further temporal and spatial dimensions, and these aspects along with social dynamics have to be taken into account.

Given the presence of multiple objectives and multiple actors, the authors use a multi-criteria decision-making framework. The decision-making process involves the following eight steps:

- Problem identification and initial data collection.
- Institutional analysis and stakeholder identification.
- Creation of alternatives.
- Establishing evaluation criteria.
- Criteria evaluation and preference elicitation.
- Selection of the MCDA technique.
- Model application.
- Stakeholder analysis of the results and feedback.

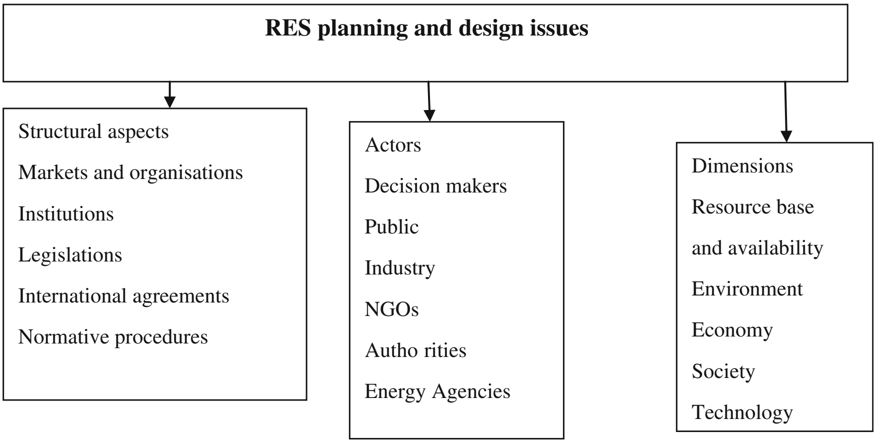


Fig. 2 Renewable energy planning issues. *Source* Polatidis and Haralambopolous [80]

At the last stage, where the results are shared with the stakeholders, if the level of acceptance is found to be low, the process will be repeated to generate a more acceptable outcome and the solution can then be implemented.

The application to the Greek case showed how the above steps were followed. Four alternative options were considered: (1) installing a 2 MW diesel generator, (2) a 4 MW hydro plant in conjunction with 4 wind turbines of 0.6 MW each, (3) a 4 MW hydro plant in conjunction with 8 wind turbines of 0.6 MW each, and (4) a 2 MW diesel generator along with a 4 MW hydro plant and 12 wind turbines of 0.6 MW. The evaluation criteria were initially developed through a literature review. This was then discussed with the stakeholders and finalised. These are presented in Table 7. The analysis was performed using PROMETHEE II package, a widely used program following the European tradition of MCDM analysis. The PROMETHEE suit of packages has been used in energy planning decision-making (see Table 8 for a list of such applications).

Many other studies have been reported in the literature in the field of rural energy or renewable energy supply using the MCDM approach. Such studies have covered a wide range of applications (see Table 9) and have used established software packages or have presented alternative tools. Cherni et al. [18] presented a multi-criteria analytical tool SURE for rural livelihood decision analysis which can be used to decide appropriate rural energy supply options that can be used for enhancing rural livelihood. The package was developed through the support of DfID (Department for International Development, UK) and incorporates technical and non-technical aspects such as financial, social, human and environmental dimensions. The paper reports the application of the model to a Colombian rural community.

Cherni et al. [18] indicate that although MCDM has been used in analysing rural energy issues, the technical aspect received a privileged treatment in the

Table 7 Evaluation criteria used in the Greek analysis

Energy resource criteria	Economic criteria	Environmental criteria	Social	Technological
Amount of imported oil avoided (toe/year)	Payback period (years)	Land used by the project (m^2)	Employment creation	Reliability and safety
Potential for reducing blackouts (% of peak load)	NPV of investments (€)	Compatibility with other activities	Public acceptance	
Amount of electricity produced (kWh/year)	Installation cost (€/kW)	Noise creation		
	Operational costs of electricity generation (€/kW h)	Visual impact		
	Net economic benefit for the community (€/year)	Construction of electricity networks and access roads (km)		
	Entrepreneurial risk (risk of project failure)	CO_2 reduction potential (tons of CO_2 avoided)		

Source Polatidis and Haralambopolous [80]

Table 8 List of applications of PROMETHEE in the area of energy

Application field	References
Comparing CSP (Concentrating solar power) technologies	[14]
Regional energy planning with a focus on renewable energies	[81, 103, 105]
Analysis of national energy scenarios in Greece with a focus on renewable energies	[29, 37]
Designing energy policy instruments	[30], (Madlener and Stagl 2005)
Evaluation of different heat supply options	[38]
Prioritisation of geothermal energy projects	[40, 41, 43]
Participatory analysis of national renewable energy scenarios in Austria	[60, 67]
Evaluation of biomass collection and transportation systems	[61]
Siting of hydropower stations	[68]
Comparing cooking energy alternatives	[78]
Evaluation of residential energy systems	[87]
Comparing energy technologies based on renewable, fossil or nuclear resources	[104]
Evaluation of energy research projects	[107]

Source Oberschmidt et al. [75]

Table 9 Application of MCDM in rural energy issues

Reference	Area of application	Tool/Method
Cherni et al. [18]	Rural energy supply for rural livelihood	SURE
Haurant et al. [44]	PV on farming land in an island	ELECTRE
Georgopoullou et al. [36]	Renewable energy planning in a Greek Island	ELECTRE III
Kablan [54]	Rural energy in Jordan	AHP
Pokharel and Chandrashekar [79]	Rural energy	Goal programming (STEP)
Karger and Hennings [56]	Sustainability of decentralised options	AHP

decision-making process. The issue of sustainable rural energy supply and rural livelihood issues received little attention. SURE they claim have overcome this challenge. Buchholz et al. [12] argue a similar participatory process for wider use of biomass energy in a sustainable energy context.

2.2.6 Systems Analysis Approach

For any analysis of a rural energy system, it is important to understand and capture the complex interrelationships that exist with the society, environment, technologies and governance aspects. One of the main issues related to any decision-making is the failure to incorporate appropriate feedback from various interactions. Also, the analysis has often been carried out at a highly aggregated level, which in turn removes the possibility of capturing important issues or aspects that influence the system performance [101]. Further, additional issues related to conventional modelling include the following [83]:

(a) Inter-temporal interactions and feedback are not modelled explicitly;
(b) The disequilibrium framework for modelling is missing.
(c) Time delays and other distortions of the energy system variables are not explicitly modelled.
(d) Non-linear responses to actions are not explicitly represented.

The systems approach has attempted to remedy this problem by understanding the information feedback structures in systems [20, 35] and by representing such feedbacks through casual loops and analysing them quantitatively. In the area of rural energy and rural electrification, various studies have been reported in the literature. For example, Alam et al. [4] reported a model for rural energy system of Bangladesh. The model considers crop production, biogas production, and rural forest and agro-based industries and analyses how output can be optimised to improve the quality of life. Similarly, Alam et al. [2] have reported an application of their previous model for farming in Bangladesh, while Alam et al. [3] reported the analysis of rural household energy use. The model incorporates feedback loops, non-linearity and time-lag features commonly found in real systems. Xiaohua et al. [115] presented a model to analyse the interaction between the rural energy system and the economy for a Chinese rural community. It considered a basic feedback structure of rural energy- economy and analysed the factors affecting rural energy use.

2.3 Practice-Oriented Literature for Decentralised RE Supply Analysis

The literature is also well developed for this category of studies but we shall review four studies—Cabraal et al. [13], CEEP [15], ESMAP [32] and World Bank [113] as they include some form of frameworks for analysing off-grid energy supply.

2.3.1 Cabraal et al. [13] Study

This study focused on the best practices for household rural electrification using solar PV systems. The study reported a number of case studies and provided a framework for economic/financial comparison of alternative options for household electrification. The cash flow analysis using economic and financial evaluation methods was used as the framework of analysis and was performed in Excel. An annex to the report enlists the following steps for such an analysis:

- Energy demand estimation: As electricity is used for lighting and appliances, the demand for these services has to be considered for decentralised electricity supply;

- Village selection criteria—identifying a set of conditions/parameters for village selection is the second step in the process. The parameters normally considered are number of households to be connected, distance from the grid, size and number of productive loads, and load growth prospects. Each of these factors affects the cost of supply and hence is an important consideration for supply decision.
- Alternative technology options—The third step is to identify alternative technologies that could be used to supply the energy service. The study considered kerosene/battery schemes, solar home schemes, isolated grid and central grid extension. The sizing of the alternative systems to satisfy the needs is also done at this stage.
- Least-cost comparison of options—This step provides the economic and financial cost comparison of alternative options using the cash flow method. The levelised cost of each option is calculated to determine the least-cost option. The break-even analysis is used to identify the range of economic viability of alternative options for villages of different size (household numbers) and household density.

The study also evaluated the experience of a number of case studies by considering the technical, financial and institutional performances using a set of criteria. For technical evaluation, the factors considered were: system size selection, system quality, installation repair quality, training/maintenance, availability of spare parts, and battery recycling. For financial evaluation, the performance was evaluated based on credit supply, financial sustainability, system pricing and tax/subsidy structures. For institutional performance, the institutional structure, marketing strategy, information dissemination and sustainability of institutional structure were considered. The study while focusing on practical applications, has not reported any systematic tool for the distributed off-grid systems.

2.3.2 Worksheet-Based Tool in CEEP [15]

CEEP [15] relied on a worksheet-based package, called rural renewable energy analysis and design tool (RREAD) for RE system analysis for decentralised operations. The model considered—economic, social, technical and environmental aspects. The programme analyses the energy availability, technical viability, economic feasibility and social—environmental value of a PV, wind and PV-Wind hybrid systems (see Fig. 3 for the model structure).

> The input module consists of six sets of data: Resource data, load data, system configuration, capital and operating costs, financial data and policy scenario information (e.g. the existence of tax credits, subsidies, and program initiatives to internalise social benefits/costs, etc.). The resource, load data and system configuration data are used to evaluate the system's overall energy performance, including energy output, resource-load matching capacity and service reliability. Cost, financial and policy data measure the economic, social and environmental values of using renewable energy systems [15].

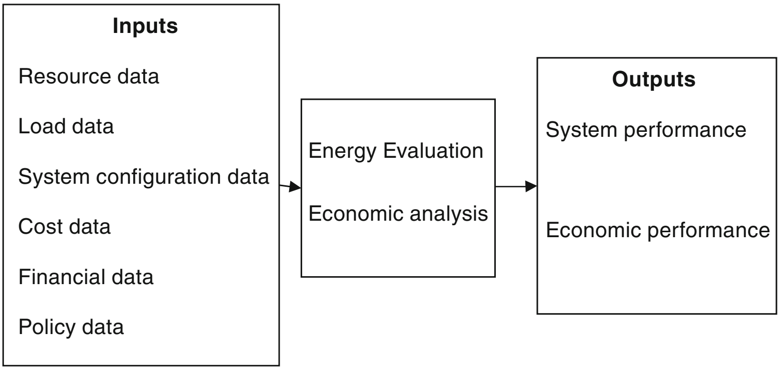


Fig. 3 Structure of RREAD. *Source* CEEP [15]

This method was used to determine the levelised costs of supply for different systems under different conditions in China. The study then conducted a socio-economic analysis using a local survey. The report also used a logistic regression model to analyse the survey results. This study considered all relevant dimensions in a systematic way using a practical tool but it was designed only for PV-based supply. This limited technological choice is a constraint for its generic use.

2.3.3 ESMAP [32] Study

The ESMAP [32] study provided the best practice guidelines for implementing decentralised energy systems for project managers. The decentralised option is an alternative approach to 'production of electricity and the undertaking and management of electrification project that may be grid-connected or not'.

It provides a step-by-step approach to project implementation which focuses on five steps.

- Step 1: Definition of institutional and regulatory environment—This stage will make sure the government commitment to the activity is enlisted and the institutional arrangement for decentralised energy services is established. Key activities thus include assessing government commitment, role and responsibilities of the agency responsible for decentralised energy supply, verification of legal provisions for off-grid supply and public sector involvement, identification of market barriers, assessment of technical capacity, assessment and identification of local financial organisations, identification of local institutions/NGO and their roles/responsibilities and assessment of private sector interest.
- Step 2: Market assessment and identification of project concept: This is the preparatory step for developing the project idea. Key steps include: Collection and review of existing information and/or initiation of a market analysis, collation of market information and completion of market analysis, analysis of competing products or services, identification of cost of service and disposable

income of consumers, and the identification of possible distribution paths. This step provides market information that can be used in the next stage.
- Step 3: Appropriate technology and product choice—This step selects the appropriate technology option to provide a reliable and cost-effective supply to meet the local needs. Key steps include: Identification of available technologies, energy demand estimation in terms of energy use, form, and quantity, determination of the most appropriate technology option, selection of a product delivery option, and product testing and specification preparation. At the end of this step, a tested product option is available for delivery.
- Step 4: Selection of a delivery mechanism—The study focuses mainly on two types of delivery mechanisms—cash and credit system or leasing through a dealer and delivery through an energy service company (ESCO). The key steps involved at this level are: Assessment of credit availability, review of distribution infrastructure, assessment of affordability of decentralised energy options, selection of a product and its delivery channel, and initiation of distribution channel establishment. This step provides a delivery mechanism for an identified technology option and initiates the process for establishing the delivery of the product.
- Step 5: Review and evaluation of financial options—This step evaluates whether the financial sector is geared to meet the financing needs of decentralised supply and identifies appropriate options to meet the local needs. Key steps here include: Identification of financial needs, evaluation of the rural banking system and the availability and cost of credit, mobilisation of the banking sector, identification of local partners, identification of financing options and programmes and determination of the terms of financing.

This study covers the entire set of activities related to a decentralised energy supply and is quite generic in terms of technology choice or country of use. It suggests a sequential framework of analysis with a detailed list of criteria that can be used in each step. Two areas are under-represented—environmental aspects and social dimension of the problem. Also, the potential for conflicts at each stage is not adequately captured.

2.3.4 World Bank [113] Study

World Bank [113] identifies the following critical factors for an off-grid project design:

(a) Comparing technology options—the first task is to determine the suitable technology option or options. The general guidance given is as follows:

    (1) if the consumer size is small and dispersed, and if their main need is lighting, individual systems like SHS works; Other technologies for individual demand are pico-hydro systems where water resources are available while wind home systems are now being piloted.

    (2) Where consumers are concentrated and can be economically inter-connected, a mini or micro grid is commonly used. Diesel, RET (renewable energy technologies) or hybrid options are used.

(b) Social safeguards and environmental considerations—Although off-grid projects are generally environmentally beneficial, some components such as use of batteries can have some environmental effects. These need to be carefully integrated with the national policies on waste recycling and hazardous wastes. Similarly, off-grid projects must adhere to national guidelines or regulations on watershed protection, land use and land acquisition.
(c) Productive and institutional applications—Off-grid communities could engage in many productive activities such as agricultural production and processing, fishing, animal rearing if quality energy is provided. Similarly, institutional or community-level uses such as schools, clinics or community centres could form another main use of off-grid electricity. The project design should take advantage of such 'systematic and pragmatic approaches' [34].
(d) Enhancing affordability—Generally, only 2–3 % of the consumers are found to afford cash purchases of off-grid solutions. The customer base can be expanded to 20–30 % with micro-credit. With leasing, the customer base can be increased to 40–50 %, while long-term fee-for-service options could increase the customer base further. Subsidies, consumer financing, low-cost technology options and support to businesses and commerce can also be considered to improve affordability.
(e) Business models for off-grid solutions—The supply of off-grid solutions could be provided using a number of players—private entities, individuals, community-based organisations, NGOs and state agencies. Appropriate incentives are required to attract players into this business. Various alternatives have been experimented—including dealerships, ESCO, leasing arrangements, medium term service agreements, community-based supply and hybrid forms. The local market condition plays an important role in deciding the appropriate business model.
(f) Regulating the off-grid supply—This is an important aspect of supply where the state has to play an important role to ensure that consumers are not overcharged and that they receive a quality supply. The regulatory framework for traditional grid supply may not be appropriate for such services and needs a special attention.
(g) International co-financing support—For providing access to energy using renewable energies, various co-financing options are available, including funding from the Global Environment Facility (GEF), Global Partnership for Output-based Aid (GPOBA), the climate investment funds and the Clean Development Mechanism (CDM). These sources could be tapped to reduce the financial burden of the national agencies.

The elements of a sustainable off-grid electrification project are presented in Fig. 4.

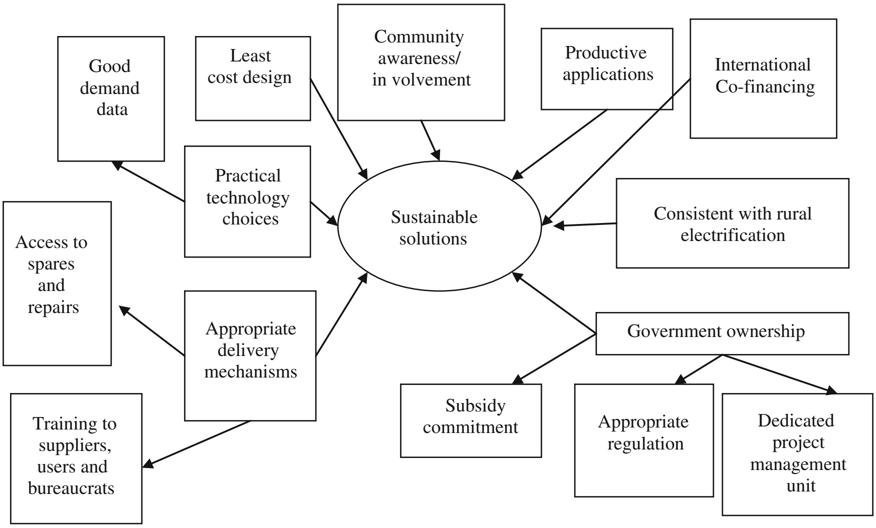


Fig. 4 Elements of a sustainable off-grid electrification project. *Source* World Bank [113]

The alternative analytical frameworks presented above provide ways of analysing the mini-grid system. However, each tool or analytical approach has its own strength and weakness. While the case-based approaches tend to provide practical guidance, they do not always rely on academically rigorous frameworks. On the other hand, academic studies are not always practically oriented, thereby reducing their potential for real-life applications. Thus, there is need for an integrated approach.

However, before such an integrated approach is considered, it is important to take a look at the practical experience at the project level to understand and identify essential factors that may be affecting their performance. With this objective in mind, we present insights from a field-level study in the next section.

3 Insights from the Field

This section goes into the project level evaluation and strives to understand the basic conditions that have largely shaped off-grid project viability. Based on secondary sources, the evaluation covers 74 cases of off-grid/decentralised project interventions from India[3] that include a range of technologies such as biomass,

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[3] The information collection and analysis is carried out under a specific methodological framework. The initial activity was the scoping exercise of case profiles of off grid energy interventions by mining all the possible secondary information. This was followed by selected field visits and a series of expert interviews, both direct and telephonic. In order to gain further insights at a collective level, a participatory workshop was conducted and preliminary findings of this study were presented and discussed with different stakeholder representatives in the workshop.

Table 10 Details of off-grid sites visited

Project name	Technology	Size of the plant (kW)	Ownership	Funding
Rampura	Solar	8.7	Community	Non-govt.
Radhapura	Biomass	10	Community	Govt.
Tamkuha	Biomass	33	Private	Private
Amthagouda	Micro-hydro	20	Community	Non-govt.
Karlapeta	Micro-hydro	25	Community	Non-govt.
BERI	Biomass	1,000[a]	Government	Mixed

[a] Cumulative capacity

solar, micro-hydro, small wind and hybrid systems. There is considerable variation among the projects in terms of geographical locations, use of technology, size of the plants, tariff structures, ownership and management arrangements, among others.

The desktop research on the above off-grid cases was complemented by field visits. We conducted field visits to six project sites and investigated the fundamental conditions shaping the project operation and management. The details of the field sites and key operational attributes of the projects are presented in Table 10.

A statistical profile of the database of selected cases is presented in Table 11 with information related to the type of technology, size of the plant, implementing entity, source of finance and energy applications. A majority (53 %) of the projects are based on biomass gasification technology and mid-sized plants, ranging between 11 and 50 kW, constitute more than 50 % of the cases. There is variety in terms of project implementing entities (e.g. village energy committees (VEC), NGOs, state nodal agencies and in some cases private business entities) but in majority of cases either VEC or NGO is the implementing agency. Though private entrepreneurship is believed to possess a lot of potential in the rural energy business, the database has only 10 % of cases implemented by private entities. We categorise the source of funding into three major groups, i.e. government, non-government and mixed. Nearly half of the cases in the database have funding from non-government sources. On the basis of energy applications, the database has 40 % of the selected cases demonstrating clear income-generating links.

A key challenge in preparing the database for analytical work was to identify each project's current operational status. This was an intensive exercise and we have largely relied on expert information to categorize projects as operational, partially operational and non-operational. The database has 61 % of cases under the operational category, which allows us to take the analysis to the next level of identifying key determinants (see Table 12).

The operational viability of off-grid projects in the Indian context is largely determined by policy support, social acceptance in the form of community participation, linkages with income-generating opportunities, and technological appropriateness. To incorporate the policy dimension to our database, we took the

Table 11 Statistical profile of the selected off-grid projects

Technology	%	Plant size	%	Implementing agency	%
Biomass gasification system	52.7	Less than or equal to 10 kW	24.3	VEC and NGO	66.2
Micro-hydro	24.2	11–50 kW	51.4	State agency	23.0
SPV and others	23.1	Above 50 kW	24.3	Private company	10.8

Source of funding	%	Policy link	%	Income-generating link	%
Government	37.8	States with policy links	62.5	With links	39.2
Non-government	48.6	States without any policy link	37.5	No links	60.8
Mixed	13.5				

Source This study

Table 12 Distribution of selected off-grid projects in terms of operational status

	Case types	Operational (61 %)	Non-operational and partial operational (39 %)
Technology	Biomass	47	79
	Otherwise	53	21
Size	<10 kW	22	28
	>10 kW	78	72
Funding source	Govt.	24	59
	Non-govt. and Mixed	76	41
Community participation	Exists	24	45
	Not exist	76	55
Income-generating linkage	Exist	47	28
	Not exist	53	72
Policy linkage	Exist	67	41
	Not exist	33	59

geographical location of each off-grid case and mapped the project to state-specific decentralised/renewable specific policies (or elements of it).[4] It was found that in 62.5 % of cases, there exists some kind of policy support to promote and develop off-grid energy development in the concerned State. This percentage figure goes up to 67 % if we consider only those projects which are currently operational; more interestingly, nearly 60 % of the projects currently non- or partially operational seem to have suffered because of lack of policy support.

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[4] Even though it is hard to find any specific policy operating at the state level to promote decentralized interventions, policy ‘strings’ can be traced in other provincial policies (mostly state-specific renewable energy policies) specifying the need and importance of decentralized energy development in the state.

The critical role of policy support in determining the success of a project was strongly emphasised in our interactions with project developers during the field visits. The consensus is that macro-economic policy enunciation must be strengthened with local mechanisms for continuous monitoring and accountability frameworks, specifically for government owned and operated projects. Further, the interactions with stakeholders reveal that regulatory uncertainty and vacuum can be stifling the growth of these projects and that the current paradigm of ad hoc and piecemeal dispensation to regulation produces sub-optimal outcomes. Policies at the local level are perceived as major determinants of project outcomes and often developmental policies integrative of off-grid elements form the policy foundation for many of the off-grid energy systems. The flip side of this is that in-congruencies in the local governance structures act as impediments to project development.

It is generally accepted that the success of off-grid/decentralised energy systems largely depends on the ability of such projects to generate local income-generating opportunities. Our case-based analysis supports this proposition and the field visits made it clear that often people prioritise livelihood opportunities over other energy needs. For instance, in Radhapura, energy requirement for irrigation purposes is given high preference over lighting needs. Even in projects run by private initiatives such as Husk Power Systems operating in Uttar Pradesh and Bihar, there is every effort to create additional sources of income through the project intervention.

Another crucial element which has been prominently highlighted in the literature is to community participation in project activities, which in some cases is expected to culminate with community ownership of the project. In the current paradigm of off-grid systems in India, largely dominated by government funded schemes, community participation has been assigned a significant role in project management. Such a premise, however, seems to be challenged in practice by the reality of capacity constraints among communities, local level conflicts, and ‘elite capture’. In our analysis of the 74 case studies, only a fourth of the operational projects are characterised by community participation and the remaining are largely led by private enterprise. Interestingly, the majority (55 %) of the non- and partially operational cases in our database also does not have community participation; hence, it would be erroneous to make any straightforward conclusion regarding the role of communities. From our site visits, we found that in two cases—Radhapura and BERI—there is evidence to suggest that community participation has failed its premise. While in Radhapura societal conflicts have inhibited community participation, the BERI project operational in Karnataka has experienced a shift from community-led management to a professional management body. On the other hand, the success of private initiatives like HPS in Bihar suggests that there are viable alternatives to community participation in off-grid project design.

Unlike community participation, the database gives reason to link more definitively a project’s source of funding with the project’s long-term viability. For operational projects as well as the category of non- and partially operational projects, government funding has clearly not been fortuitous in the majority of cases. The reason may be found in the soft budget syndrome identified in public

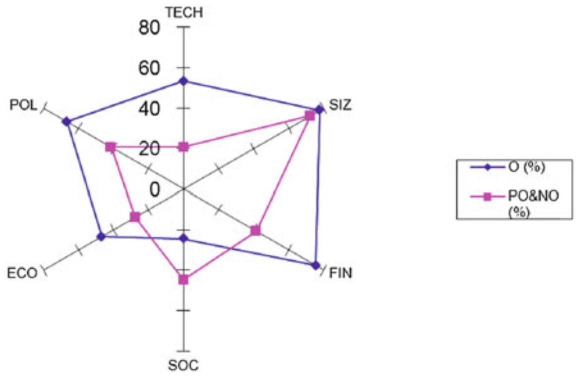

Fig. 5 Comparative analysis of performance of Indian off-grid projects. *Source* this study

finance literature. With guaranteed funding and lax monitoring, government funded projects are said to operate under soft budget constraint conditions, which inevitably leads to weak budgetary discipline by project developers and implementers. Moreover, a majority of public funded projects grossly fail on after sale service and poor maintenance structures.

It can be discerned from Fig. 5 that size of the plant impacts the success of the project. It appears from the analysis that there is a minimum defining size, which can have definite impact on the success of the project. Projects with a mean size more than 20 kW are found to be more viable indicating that very small-sized plants may not be able to fulfil the basic energy needs of a community, especially in a dynamic context when such needs grow and change over time.

Next step in the analysis is to examine the comparative position of both the groups, i.e. operational as well as non- and partially operational in a holistic manner. Figure 5 reveals some interesting insights. Operational projects are found to be dominantly spread across all the variables save community participation. This indicates that projects that are operational are often large sized, with primary source of funding from non-governmental agencies and having strong income-generating and policy links. Comparatively, the performance of non-operational and partially operational cases on the six key variables appears to be skewed with weak policy support, minimal income-generating links and modest community participation.

4 Towards an Integrated Approach for Off-Grid Analysis

The above analysis makes it clear that successful off-grid interventions are based on much more than techno-economic assessment. A meaningful business model would need to factor in the whole set of constituent elements such as choice of technology, scale of the project, type of policy support, role of community, income linkages and funding sources. The integration, moreover, would need to feature in a dynamic framework that is able to account for multiple interacting drivers at different scales of the social, economic and institutional context in which the intervention is planned.

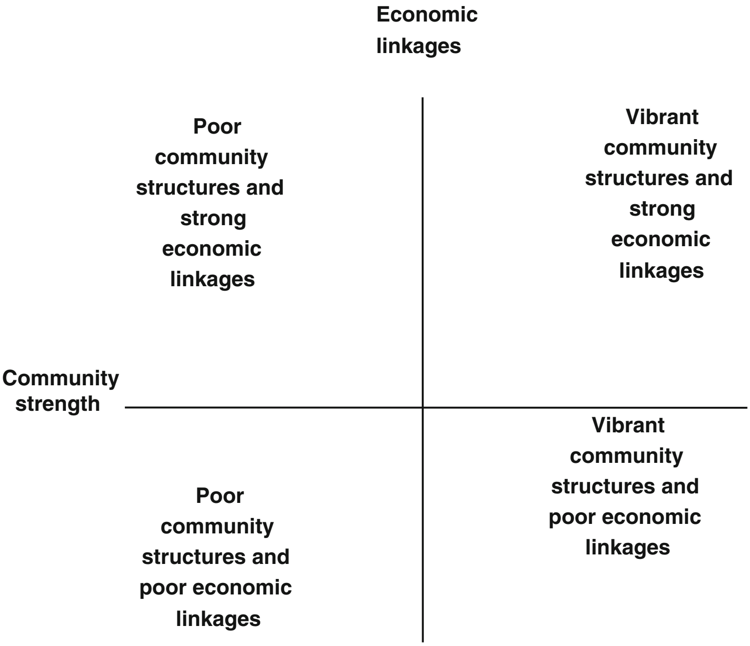

Fig. 6 Possible combinations of community structures and economic linkages

We suggest that the business case for an off-grid intervention should start by looking at the local context. A useful approach may be to distinguish between the set of determinants that are generally context dependent and those which are context neutral. Choice of technology, social acceptance and ownership, and economic linkages are essentially context specific outcomes in the project cycle of an off-grid intervention. At a more macro level and as exogenous influences, we have policy support and institutional financing.

Considering technology choice to be partially neutral and to some extent driven by external determinants, the choice of intervention would primarily be determined by two crucial locally embedded elements, i.e. strength and ability of local community structures and economic linkages. In terms of a conceptual framework, community structures can have two extreme forms, i.e. one deeply cohesive, well organised and having genuine interests to participate in the project operation and management, and the other largely disorganised, fractured, sabotage prone and passive to the project matters. Economic linkages can have similar characterisation with two extreme types: One with easy market access, vibrant local economy, and the other remote and opportunity constrained. Figure 6, with its four quadrants, not only captures the combinations of these extreme varieties of the two context dependent determinants, but also allows us to contextualise in terms of intermediate combinations with varying degrees of heterogeneity. Such contextualisation,

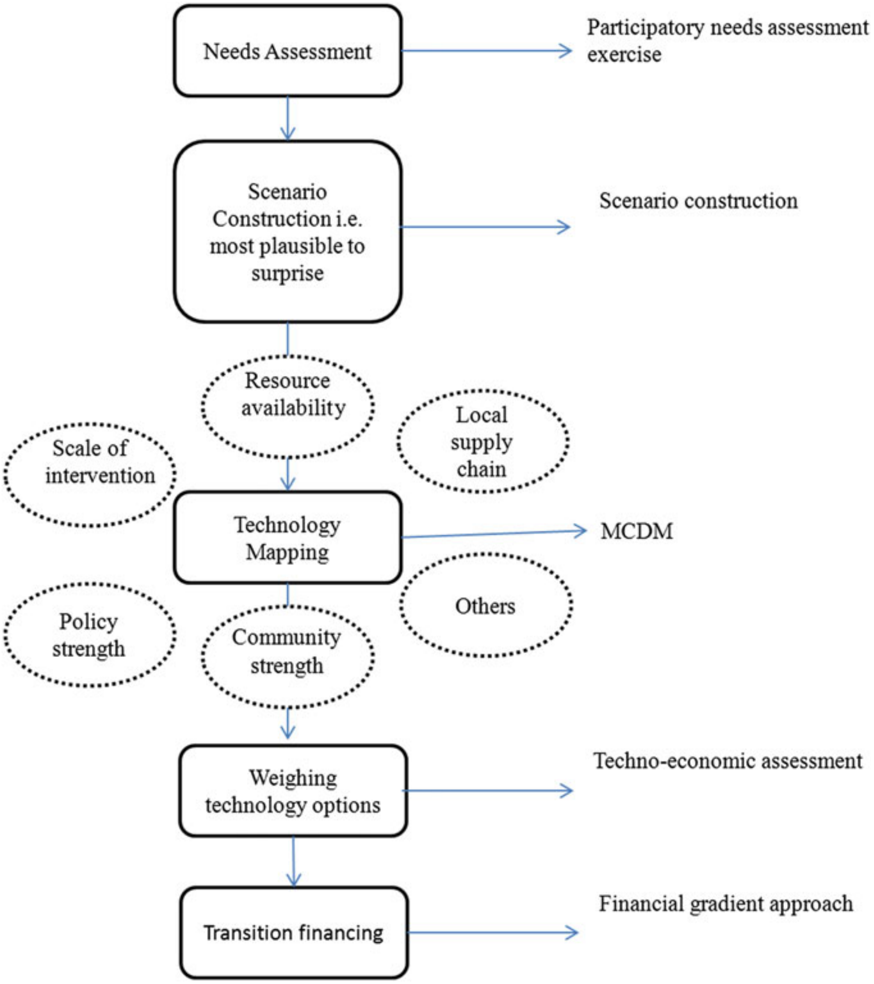

Fig. 7 An integrated approach for off-grid interventions

in turn, establishes the need for a non-uniform and context-relevant approach to decision-making in off-grid energy interventions.

Figure 7 presents a decision hierarchy or 'tree' for sustainable off-grid energy projects. It consists of six essential stages and, importantly, decisions arrived at each stage are fed into the next stage in the process. Given the framework of Fig. 7, one can possibly map the various contextual reference points to a continuum of off-grid energy services ranging from one extreme of that of a 'merit' good to the other extreme of fully marketable services. Once the nature of services is identified, the next step in the hierarchy is about the decision on the scale of project intervention. This can be facilitated through a baseline assessment of the specific context for its energy needs and productive potential; the dynamic character of the context may be introduced through the technique of scenario building and future scenarios may range from the most plausible to a ‘surprise’.

Step three in the decision tree is the evaluation of appropriate technology, which would require the application of a multiple criteria technique. The criteria would include resource availability, local supply chain, community capabilities, policy strength, scale of the intervention, and other supporting factors. An appropriate multi-criteria decision tool considering the above identified factors can decide on the appropriateness and relevance of technology type/s with respect to the context and scale. Following the multi-criteria analysis, alternative technology types can be made subject to cost effectiveness analysis to arrive at a final decision on technology selection.

The final stage of decision-making involves issues related to finance and the choice of an appropriate financing mechanism. Here, we would need to refer back to the mapping done in stage one, in which the context defines the nature of off-grid energy services to be provided. It is hypothesized that the choice of finance would be determined by the characterisation of the off-grid energy service. If the context defines the services to be fully marketable, one would expect private investment to be forthcoming given the appropriate policy support. On the other hand, if the context is such that the off-grid energy services are best viewed as a ‘merit’ good, it would be justified to expect public investment in the project. In between these two extremes, off-grid energy services would require a mixed form of financing which may be linked to varying gradients of transition depending on the dynamism of the context.

5 Conclusions

The review of literature presented in this chapter shows that researchers and practitioners have used various analytical tools and frameworks of different levels of complexity to analyse decentralised mini-grid systems. However, the academic literature often focuses on abstract cases having limited real-life linkages. The practice-oriented literature, on the other hand, relies on financial calculations to a large extent without necessarily taking an integrated perspective.

To overcome such issues, this chapter has presented a field-level analysis that looked into the experience of 74 off-grid electricity projects from India using mini-grids. The desk-based analysis was supplemented by field visits to six project sites. The experience from these projects reveals that operational viability of off-grid projects is largely determined by policy support, social acceptance in the form of community participation, linkages with income-generating opportunities, and technological appropriateness. The key pointers coming out of our analysis are that: (a) macro-economic policy instruments must be aligned with local accountability mechanisms, specifically for government owned and operated projects; (b) at the project level, key choices related to technology selection and scale of intervention need to emerge from an understanding of the context; (c) the context itself is a variable depending on community structure and local economy; and (d) financing of a project may be linked to the nature of energy services defined by the context.

We have proposed an analytical process consisting of six stages to capture the multiple dimensions in the analysis. The framework is quite flexible as it does not prescribe specific tools or choices, and therefore it is suitable for application in a wide range of contexts and for various alternative technologies. Various applications of this integrated approach are also included in the subsequent chapters of the book. Although we are not reporting any tool development based on this framework, this remains an area for further work. Similarly, there is further scope for research to develop real-life case studies using such a framework.

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