Sustainable Energy Handbook

Module 5.2

On-grid Rural Electrification

Published in February 2016

1 What are the general principles of on-grid rural electrification?

As rural electrification projects very rarely support themselves financially, it is of utmost importance to select least-cost solutions. For a least-cost installation, it is generally admitted that the demand forecast is based on 10 years period maximum. The general principles are that:

- The cost per kWh transported and distributed has to be reasonable (not exceeding 0,15USD/kWh)
- In case the loads are only basic uses (lighting, mobile phone charging) with annual consumption of less than 10 kWh, even with the grid being nearby, solar lanterns are the least cost option;
- In case the loads are mainly rural households with small loads of 50-150kWh per year (or even less), that are far away from the grid (above 5-20 km), solar lanterns and solar home systems are generally the least cost option;
- In case small load centres are far away from the grid but the loads are substantial (above 500 kWh per year), these centres can be supplied through mini-grids by solar photovoltaic (PV) systems, small hydro-power plants, biomass-energy plants and backed up by diesel generators, depending on the prevailing conditions and requirements, either in a stand-alone manner or as part of a (hybrid) mini-grid;
- If small load centres are not too far from the existing network (less than 20 km), consumers can also be supplied through the extension of the grid. Several small load centres located within the same area or along the same road shall be combined into a cluster.

A sustainable rural electrification project depends on a number of critical decisions. Important factors in the project planning are the technology, ensuring institutional and economic viability, safeguarding the social and environmental aspects and optimizing productive uses of electricity.

Technical elements relevant for the decision making include:

- Distance to national grid and capacity of supply
- The average cost of connection increases with the distance to the grid and decreases with the capacity of supply
- Population density and number of households
- The average cost of connection decreases with the number of households served and with the population density as well
- Medium/long term electricity demand forecast
- The distribution network must be designed on the basis of a 10 year demand forecast
- Number of productive end uses/industrial uses and forecast growth
- The capacity of the distribution network increases with the ratio of productive uses per household as well as institutional facilities per households
- Long term marginal cost for energy production in grid connected systems

- In sub-Saharan African countries, the long term marginal cost for energy production tends to decrease with a shift of the generation mix from fuel oil to renewable energy. This is a key driver of supply price to the end-user
- Levelized costs for energy production in isolated systems
- The cost of energy production in isolated system decreases with the load factor of the isolated system
- Selection of socially and environmentally appropriate technologies
- Socially and environmentally appropriate technologies brings non monetised benefits that need to be accounted for in the economic analysis
- Vulnerability to extreme weather events and (in certain regions) vandalism Technologies need to be adapted to the severity of the local environment and the social and economic implication of the time to re-establish supply in case of partial destruction of the infrastructure

Economic and miscellaneous elements relevant for the decision making include:

- Total cost per connection (including investment in distribution network, grid strengthening, generation capacity, transmission lines, etc.)
- Operation and maintenance cost, including analysis of electricity losses
- Levelised cost of electricity supply or cost of services supply
- Tariffs, demand forecast and expected revenue from electricity sales
- Market effect and subsequent impact on investments in decentralised solutions[1]

The **main components of an electrical grid** are

- The large scale generators and high voltage transmission line
- The bulk substations that tap in the high voltage transmission line and feed the medium voltage distribution lines
- The medium voltage distribution line
- The MV/LV distribution lines and the LV distribution lines to supply load at a limited distance of the distribution substation
- The service drop line that links the distribution LV line and the meter of the consumer
- The service entrance system including the distribution board with protection and the in-house wiring that connect the appliances.

[1] On grid electrification may convert existing investment in off-grid solutions into stranded costs ; expectation by the consumer of future on grid electrification will hamper the deployment of market based off grid solutions

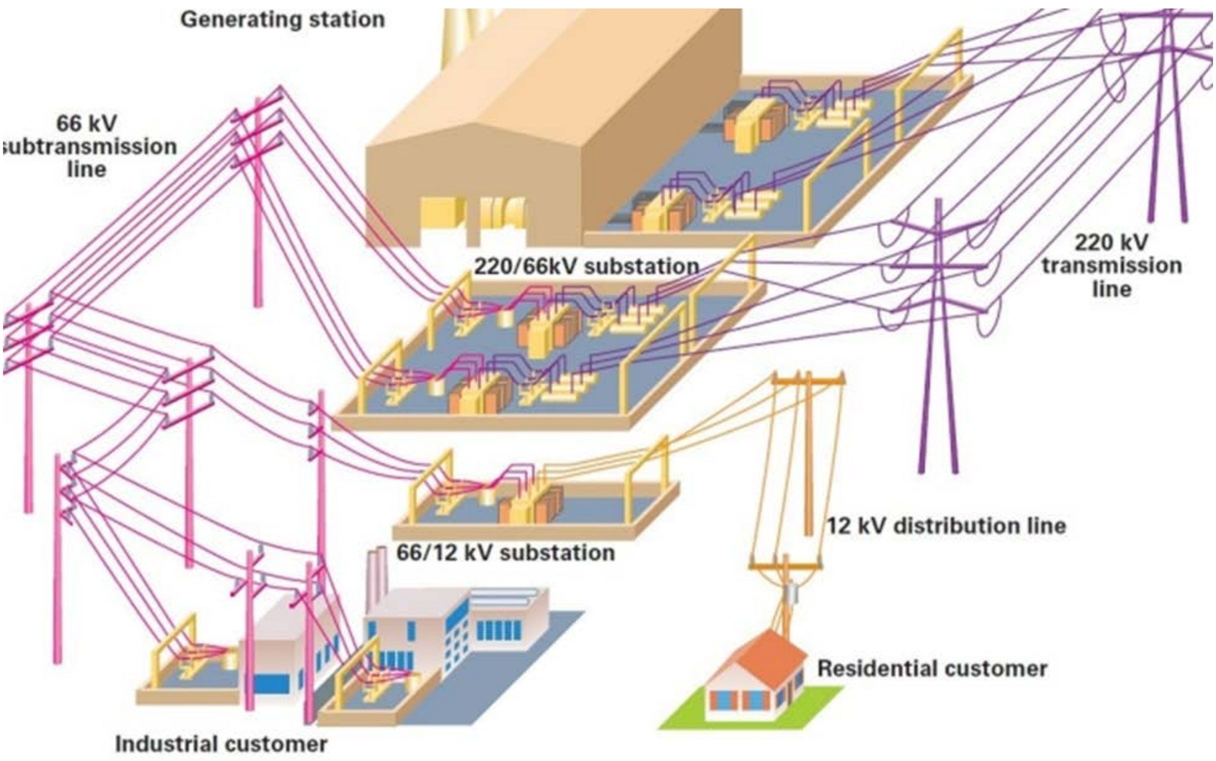


Figure 1: Illustration of a grid system

Principles for sizing the wires and for the technical existing norms (MV and LV)

For rural consumers to benefit from electrification, electricity must be transmitted over distribution lines from the power supply to these consumers. Because the conductor used for these lines is one of the most expensive components, there is an incentive to make electrification more affordable by using a smaller (therefore cheaper) conductor. However in the process of transmitting electricity resistance in the conductor leads to a drop in voltage along the line and to an associated loss of power. Reducing conductor size can result in (1) poor quality of power at the consumer end of the line and (2) loss of power. Low voltage can result in poor service (decreasing the light output of incandescent bulbs, making it difficult to ignite fluorescent tubes, or burning out electric motors). Loss of power along the line means extra power must be generated and paid for, if there is sufficient excess generating capacity; otherwise, fewer consumers would be served by that supply.

Assuming that the power supply is operating to specification, the size and type of conductor used and to a lesser extent the power factor are the sole factors that determine whether an acceptable voltage can be maintained.

Use of 220 or 380 volts, single or triple phase

220 V single phase adequately supplies all appliances and end uses commonly found in a rural home. However, some large commercial and industrial users need 380 V (or higher voltage) three phase to run motors and industrial processes. This suggests that the initial length of a rural LV distribution line is using a three phase distribution line in order to reach the last industrial or commercial customer, often located nearby the main road. Then it divides into individual single phase lines to supply the remainder of the residential customers. When tapping the three phase conductor with 2 phase lines, the load on each phase of the three phase conductor should be balanced

Three phase four wire (wye) is the configuration commonly used for low voltage three phase distribution networks designed by national electric utilities and can be the least expensive. However

for mini grids, three phase three wire (delta) proves to be more flexible with the generator capacity in case of load imbalance.

Electrical Losses calculation

The power loss along a single-phase two-wire line is calculated as follows

$$P_l(kW) = 2I^2rL.10^{-3}$$

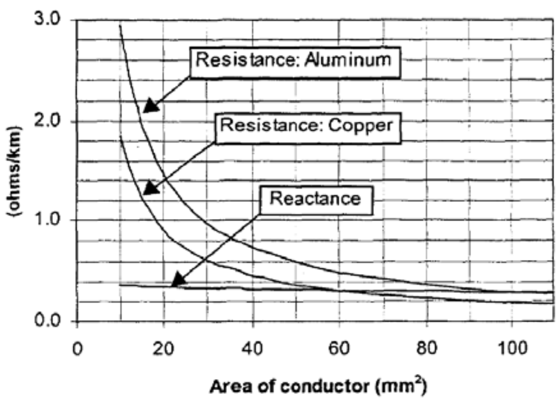
Where

I = current in the lines
r= line resistance (Ohm/km)
L= length of the line (km)

Usually I is derived from the knowledge of the Load to be served (P in kW), voltage (E in V) and phase angle ϕ between the current and the voltage.

$$I = \frac{P\ (kW)}{2E\cos\phi}10^3$$

Resistance and reactance of aluminium and copper conductors is displayed in the figure below. AN equivalent spacing of 0.30 m and a frequency of 50 Hz are assumed.



Source: Minigrid design manual, ESMAP, September 2000

Usually, the industry tolerates 3% of losses for HV lines and 5-8% for MV and LV lines.

2 What are the main technical issues?

Medium voltage vs low voltage distribution lines

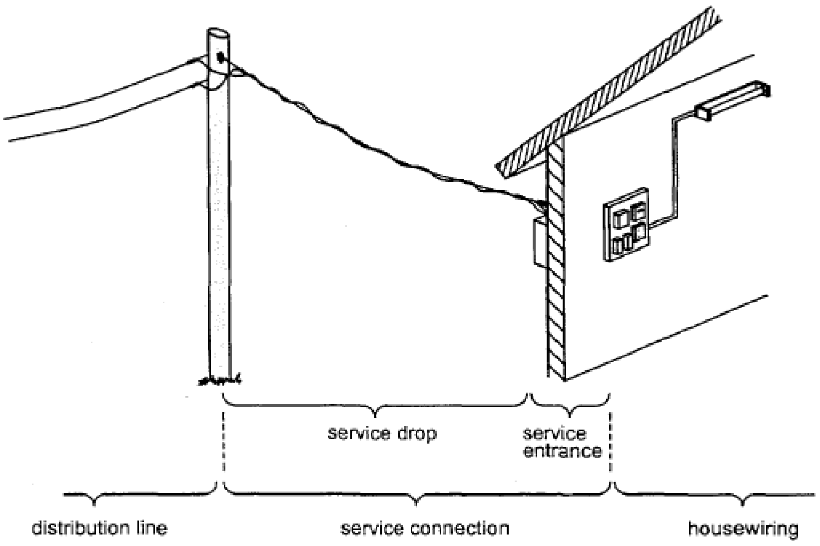
Rural electrification needs to be done through low voltage cables and transformers, preferably by means of insulated overhead cables over poles. When distances are significant (above 700-1000 meters) and when power to be transmitted start becoming appreciable (above 12 MW) it is indispensable to consider medium voltage distribution like (33 kV,20 kV or 11 kV) if imposed by local constraints.

In order to keep costs down and reduce the spare parts management and stock, it is recommended to standardize sizes of all equipment: transformers, cables, insulators, and poles, electrical and mechanical fittings.

Service connections

The service connections consist of three main components:

- Service drop/house connection
- kWh-meter/pre-paid meter/current limiter/flat-rate meter
- Internal house wiring/ready board



Source: Minigrid design manual, ESMAP, September 2000

The design options of the service drop are multifarious and reflect the fact that a proper and sound design always shall consider the particular conditions on site and that it cannot be fully standardised. The **service drop** consists of a conductor from the nearest pole to the house being connected, or in some cases a conductor from one house to the next. The service drop cable shall preferably be one uninterrupted length of cable with no joints, from the nearest pole to the meter. This makes unauthorized connections more difficult and the risk of accidents is minimised.

Concentric neutral cables (1-phase Cu with screen) instead of twisted cables (2xAl) are an attractive alternative for small consumers (up to 5A) since the conductor size is small (4-10 sq mm Cu) compared with (10-16 sq mm Al). The cable is safe and prevents unauthorized connections by its layout. The cable is built up with an insulated core, i.e. the phase conductor, with a concentric neutral/earth wire surrounding the core, and an outer sheet of PVC or PE.

The low voltage line is protected at the distribution transformer through a fuse[2] or a miniature circuit-breaker (MCB)[3]. The use of fuses has proven not being the best solution since fuses often are substituted through a wire or a bolt, mainly caused by lack of spare parts with the maintenance groups. The use of MCB at the source of the low voltage feeder and at the houses is a safer alternative and may be preferable despite higher investment cost.

Fuse or MCB may be used as load limiters, a cheap alternative to metering; if the consumers draws a current higher than the pre-set value, the cut-out will operate and disconnect the supply. Some load

[2] A fuse is a device for opening a circuit by means of a conductor designed to melt when an excessive current flows through it. Two types are commonly used the rewirable fuse and the cartridge fuse

[3] A circuit breaker is an electromechanical device that is designed primarily to automatically open a circuit when current is in excess of its design rating pass through.

limiters have to be reset manually while others reset automatically. The consumer pays a fixed monthly fee according to the rating of the load limiter, irrespective of the kWh consumption.

Metering and related issues

The principal function of the meter is to record the energy consumed to enable the utility to prepare the bill and receive the payment.

kWh meters can be installed as **conventional meters** that require periodical reading in order to achieve correct billing. This requires a lot of manpower related to the reading and issuing of the bills. Further it requires the consumers to go to the nearest billing office and pay for the energy already consumed in the previous period. Another possibility is that the expected consumption is charged and paid one reading period in advance.

kWh meters offer several advantages:

- Meters provide an accurate record of the power consumption
- Meter readings can help with the detection of fraud or meter failures
- Meters encourage energy conservation since the bill is directly determined by the consumption

As an alternative, **prepaid kWh meters** can be installed. This has a major advantage since the energy is paid in advance. It is anticipated that payment in advance encourages the consumer to save energy since the time span between payment and consumption is radically reduced. This form of payment, when the customer can pay for a small amount of energy at one time, fits also better into the peoples' custom to buy rather small amounts of other energy sources for cooking and lighting.

The disadvantage of both kWh meter types is the costly procurement. The prepaid meter is the most costly alternative:

- Around 30 USD for basic in-house prepaid meter
- Around 60 USD for split prepaid meter hard wired (meter mounted at the top of the pole hardwired to in house interface panel)
- Around 120 USD for split prepaid meter PLC communication (meter mounted at the top of the pole, house interface panel connected to meter RS 232 through Power Line Carrier - PLC), panel can be mounted anywhere near electrical wire

In addition, it has also been shown in South Africa that the prepaid meters have a significantly shorter lifetime than the traditional electromechanical kWh meters.

Another alternative is the introduction of so-called **flat rate meters** used in some countries. This device limits the consumed energy per hour and will cut the power when the paid energy is consumed, and the customer must wait for the next metering hour to reconnect the supply. The meter is available in a range of sizes for consumed energy and can be easily changed from one tariff to the next. Unused energy over one hour is credited for the next hour, and so on. The tariff could be introduced as a monthly prepaid scheme.

House connection fee

The house connection fee of above 200 USD is not affordable for many rural households. Widespread connection to the distribution system in rural areas can be achieved only through reducing the connection fee to a much lower amount. In developing countries with a high electrification rate, the connection fee is either a token fee or consists of the deposit for the kWh-meter only.

The main investment for the electrification concerns the cost for the construction of the medium voltage line (16000 to 18000 Euro per km) and to a lesser extent the distribution transformers (from 700 Euro per kVA – 25 kVA - to 300 Euro per kVA – 200 kVA) and the low voltage distribution line (from 4500 Euro per km – 2 wires same pole - to 9000 Euro per km – 4 wires new poles). This investment has to be done anyway, regardless whether only a few households that can afford a high connection fee are being connected or also the majority of the households which do not have the funds for it.

An amount acceptable for the utility and affordable for the majority of the rural households needs to be agreed based on more detailed connection policy studies. However, even high connection fees can be workable if specific financial arrangements are put in place (such as subsidies, credit through micro-finance etc).

When planning grid extensions and electricity meters for new areas, the type of meter should be considered, to be dual metering if the user in future will install PV and will be selling excess energy to grid.

3 What is the typical benchmark?

In order to provide a benchmark for on-grid rural electrification, the table below display the average connection cost per customer as a function of 4 categories (A-B-C-D) characterised by the supply capacity, the length of MV line, the average length of LV line per customer, the maximum number of customers and the rate of connection (number of actual customers connected / maximum number of customers).

In general, the benchmark depends on the country, but the figures are expected to be similar in several Sub-Saharan African countries. However, for reasons of social development and population stability, Governments may also instruct utility companies to provide electricity even when costs exceed 1,000 USD/connection.

The table below shows that for a locality at 10 km from the grid, connecting only 10 customers (average yearly consumption of 1440 kWh per customer) with a 25 KVA transformer (i.e. 20% of maximum number of customers for this transformer) will cost more than 4000 $ per connection (including financial costs) and an unaffordable distribution cost of around 30 USct/kWh, while connecting 200 customers with a 200 kVA transformer (i.e. 50% of maximum number of customers for this transformer) will cost around 400 $ per customer with an affordable distribution cost of 3.0 USct/kWh.

		A	B	C	D
MV line length (km)		10	10	10	10
MV/LV transformer capacity (kVA)		25	50	100	200
Maximum number of customers		56	111	223	444
of which households		40	85	178	366
LV Line Length per customer (meter/cust.)		48	47	47	47
Unit economic cost (US$/customer)					
Connection rate,,,,,,,,,,,,	20%	4211	2315	1308	760
Connection rate,,,,,,,,,,,,	50%	1752	993	590	371
Connection rate,,,,,,,,,,,,	100%	932	553	351	242
Unit economic cost (US$/customer) with connection fee					
Connection rate,,,,,,,,,,,,	20%	4144	2248	1241	693
Connection rate,,,,,,,,,,,,	50%	1685	926	523	304
Connection rate,,,,,,,,,,,,	100%	866	486	284	175

Should the locality be at 30 km from the main grid, then the cost for connecting 10 customers with a 25 KVA transformer would jump to above 10000 $ per customer (Levelised cost of 80 USct/kWh), while the cost for connecting 200 customers with a 200 KVA transformer would raise to nearly 800 $ per customer (Levelised cost of 5.5 USct/kWh) as illustrated in the table below.

The tables above suggests that for a very small locality (10 to 60 customers with an average yearly consumption of 1440 kWh per customer) at a distance of 30 km from the grid, an off grid solution (at around 3000 $ per household) would definitely have a lower investment cost. However the cost of the electricity service would be much higher than the grid tariff and the quality of supply would be degraded compared to on grid supply.

4 What are the organisational models?

Different approaches to operation exist depending on local socio-economic conditions and on the regulatory situation of each country. Ownership of the system (generation and distribution grid) and responsibility for O&M[4] are the two key factors. There are four main business models for on-grid electrification:

4.1. National utility/central planning model

In the national utility/central planning model approach, the mini grid is scheduled in the rural electrification master plan, approved by the Ministry of Energy and with technical inputs of the rural electrification agency. Engineering, procurement of equipment and construction is ensured by a Rural Electrification Agency tapping in a rural electrification fund set-up from a levy on the national tariff and long term loans / grants provided by donors. At commissioning, the newly built grid in rural areas is handed over to the utility[5] for technical operation, sale of electricity and billing of customer according to the national tariff. The economic loss (difference between revenue collection based on national tariff and operating cost of the rural grid) is financed by the utility from its regulated revenue. Such losses are factored by the regulator in the revenue requirement for the tariff calculation.

4.2. End-user initiative (cooperative, village or community) model

In this business model the initiative is taken directly by the local population who feel ignored (or un-prioritized) by the tenants of the utility business model. The end-users can group themselves under a cooperative (non-profit organisation under the cooperative act) or under the authority of the local community or village with an empowered decision committee and capacity to raise funds and secure partnership with private sector.

4.3. Private sector model

4.3.1. **Private O&M6 contractor of a rural electrification system:** In this model, the investment is fully financed by the public sector and donors. The construction works are done by contractors which are selected based on a bidding process by the public authority in charge of renewable energy. The private company operates the system

4 Operating and Maintenance

5 The utility has a public service supply obligation over the territory where the grid is extended; it may be public or private

6 Operating and Maintenance

once it has been set up. Private companies usually bid for such contracts. Their offer includes a formula of how they are being paid for their services. If things go well, the private company recovers its costs and makes a (small) profit. The tasks of the private company comprise power production and distribution, maintenance of the system and administrative tasks (meter reading, billing, collection, etc.).

4.3.2. **Private concessionaire of a rural electrification area:** This model assumes that the private company is granted the electricity supply monopoly in the concession region during a certain period, typically 15 – 25 years (concession contract). The company has the responsibility to implement incremental investments mentioned in the concession contract (such as grid extension on small distances) and to operate the grid. A large portion - typically between 60% and 80% - of the initial investments costs of the grid is financed by the public sector and donors in the form of subsidies. Only a small portion has to be financed by the private company. Depending on the size of the concession, the amount can be substantial, however. The private companies who invest or contribute to investment will try to maximize the return on equity and to minimise the risks of running grids in rural areas (dispersed population, weak capacity to pay).

4.3.3. **Private electricity producer in rural area:** The private investors interested by rural electrification business are more attracted to become a power producer only (IPP) and to sell power to one customer (utility or mini-grid operator / off-taker) with suitable and guaranteed feed-in-tariff. The off-grid power generation is generally well supported by regulatory framework through a long term power purchase agreement with a creditworthy off-taker entity. The tariff of the power purchase agreement should enable a full recovery of the annuitized CAPEX[7] cost and all incurred OPEX[8] cost. For volatile OPEX cost like fuel oil, a pass-through cost arrangement is recommended in order to avoid a mismatch between the revenue and the cost of fuel oil. In those conditions, private developers of a rural power generation plant can more easily invest and safely recover their stakes.

4.3.4. **Private distributor in a rural area:** The power distribution business model in a rural area is less-demanding technically than in urban area but is much riskier as the revenue is strongly dependent on the electricity sales to rural customers. The worse revenue scenario is determined by:

- A lower number of customers
- A lower average electricity consumption by customer
- A capped tariff should the local grid be interconnected with the national grid a few years after commissioning

Private developers prefer having reliable anchor customer(s), if investing in distribution and becoming a rural distributor.

4.3.5. **The A-B-C business model:** The private sector is interested to finance and distribute power through a rural mini-grid to customers if they can have one or more stable and reliable anchor and business loads (industrial or institutional). This is the purpose of the so-called A-B-C model where:

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7 Capital expenditure

8 Operation expenditure

- Anchor customers as tea factories, telecom or pumping ensure continuous and predictable load improving the bankability of the mini-grid,
- Businesses as rice mills, shops, crafts ensures large loads which increases the amount of sold electricity and reduces the unit cost of supply
- Community which requires affordable electricity at lowest prices.

4.4. Hybrid model (often Public Private Partnerships)

Hybrid business models typically try to integrate success factors of the above mentioned models while eliminating risks. To do this the ownership and operation structure is subdivided into power production (national utility), power distribution and power sales and assigned to the different private and public partners. The ownership structure is often linked to the operational structure. This process is known as "legal unbundling" in the world of large utilities.

Summary of business models for on grid electrification

Business Models	Borrower	Owner Asset	Remark
1°) Utility based	1 Existing Utility	Utility	Known by most FIs
2°)Community based	1 New Community	N civilians	Weak creditor base - unproven
3.1°) Private O&M Contractor	1 New Energy Service Company	N civilians	Weak creditor base - unproven
3.2°) Private Concessionaire	1 New Private utility	Concessionaire	Contract-based. Ongoing investment obligations
3.3°) Private Generator – IPP Model	1 New Generator	IPP	Contract-based
3.4°)Private Rural Distributor	1 New Distributor	Distributor	Weak creditor base – unproven
3.5°) A-B-C Business Model with Anchor Loads	1 New Private Utility	A-B-C Company	Anchor-load based

5 What is the environmental and social impact?

The environmental impact of rural electrification is minimal, however certain precautions need to be observed especially for the transformers, which should all be dry-type and not oil-filled.

Rural electrification provides undeniable benefits to the population and undoubtedly contributes to enhancing productivity and living standards.

Households that have access to on-grid electricity benefit of additional comfort, including the possibility to educate their children during the night and improved access to water.

However, customers of on-grid electrification may face a number of risks in dealing with their in-house wiring that may cause people electrocution or other incidents to the grid due to damages to the utility equipment (transformers, lines etc.).

6 What are the major studies required?

Typically, for a rural electrification project, the technical studies to be undertaken include:

Consumer/demand assessment

Geographical survey of household locations

Appraisal of proximity to nearest medium voltage substations and wholesale price of electricity

Appraisal of local renewable energy resources and fossil fuel market for least cost off-grid/ on grid decision

Topographical appraisal

Network reticulation study

Design drawings drafting

Materials/equipment bill estimating

Materials/equipment specification drafting

7 What are the key questions?

Institutional, Policy and Regulation Analysis

Is the targeted location within the service territory of the electric utility? Is there a connexion application procedure? How long does it take to get a response to the application?

Is the targeted location scheduled for electrification in the rural electrification master plan?

Are permits required for electricity generation, distribution, sale of electricity?

What is the procedure for way leave for electricity lines?

Is there a feed-in tariff for off grid / on grid renewable energy generators?

Financial analysis

Are the costs per connection acceptable?

Are the financial indicators (pay-back period, Internal Rate of Return (IRR), cost per kWh transported, distributed) acceptable?

What impact will have this grid extension on the public finances?

What will be the running costs of the grid including the maintenance?

Economic analysis

What is the impact of the project on the economic and incomes generating activities?

What is the expected social impact on the beneficiary population (education, health,)?

What impact will have this grid extension on the public finances?

Organisations and business models

Ownership by the local community/beneficiaries?

How will the grid be managed?

What type of organisations is the most appropriate to manage the grid?

What activities are currently authorised to the private sector and private individuals and what needs to be reviewed in the energy law, regulation, to allow the setting-up of new business models?

Technology

To whose standards/norms the grid will comply?

What are the main physical constraints for this grid extension?

Key technical benchmarks (average length per connection, length of the MV line,….)

Has the national grid the capacity to supply electricity to the planned grid extension?

Tariff

Is the connection fee (installation, regular connection charge,…) affordable?

Tariff of the electricity sold (flat fee, prepaid meter,…)?

Willingness to pay of the various stakeholders?

Operation and maintenance

How and who will operate and maintain the grid?

What type of organisation will be set-up?

Who has the know-how to run the distribution grid?

Business plan

Is a market analysis available (demand forecast, expected consumption, willingness to pay of the beneficiaries,…)?

Is a business plan available and realistic?

If needed, what will be the amount of subsidy during the construction and the operating phases?

8 Useful references

http://www.club-er.org/index.php/en/ressources-et-forum/ressources-documentaires.html: booklets on

- Public private partnership in rural electrification programmes
- Financing rural electrification programmes
- Planning tools and methodologies for rural electrification
- Potential reductions in rural electrification distribution costs
- Multi-sectoral coordination and rural electrification in Africa

https://openknowledge.worldbank.org/bitstream/handle/10986/15871/WPS6511.pdf?sequence=1 (connection charges in sub Saharan countries 2013)

http://www.ruralelec.org/fileadmin/DATA/Documents/06_Publications/ARE_Best_Practises_2013_FINAL.pdf

http://www.ruralelec.org/(internet site of alliance for rural electrification)

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IEA PVPS report Task 9

Rural Electrification with PV Hybrid Systems Overview and Recommendations for Further Deployment 2013 http://www.iea-pvps.org/index.php?id=task9&no_cache=1&sword_list[]=hybrid

Operational Guidance for World Bank Group Staff, Designing Sustainable Off-Grid Rural Electrification Projects: Principles and Practices, 2008 basic reliable guide, even a little bit old PV economics have changed. http://siteresources.worldbank.org/EXTENERGY2/Resources/OffgridGuidelines.pdf

ASEAN Guideline on Off-grid Rural Electrification Approaches http://aseanenergy.org/media/documents/2013/04/11/a/s/asean_guideline_on_off-grid_rural_electrification_final_1.pdf