Rural electrification: the options

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1. Introduction

A key factor in improving the lot of the rural poor is to provide access to an economic and reliable supply of electricity because, as Figure 1 shows, there is a very strong relationship between electricity use and the Human Development Index.

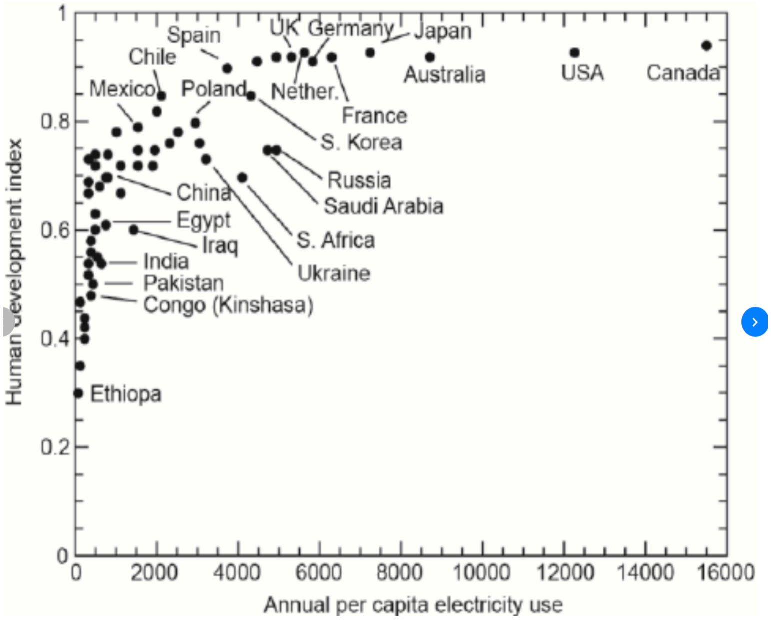

Fig1 HDI and Electricity use

Worldwide, 1 billion people lack an electricity supply. 600 million of them are in sub-Saharan Africa. In addition, nearly 2.7 billion people lack access to clean cooking facilities relying instead on biomass, coal or kerosene as their primary cooking fuel[1]. It has been estimated that $300 billion ($20-$25 billion per year) is needed to provide universal access to electricity by 2030[2].

This paper will show that the cost of connecting them to a grid or a mini grid can be more than halved if appropriate distribution technology is used.

According to Figure 2 from the World Bank[3], Africa is the continent with the greatest need for rural electrification.

For rural electrification, the key problem is minimising the cost of bringing electricity to houses and villages in sparsely settled areas.

2. Options

The options available for rural electrification are:

- solar or wind power supplemented by batteries;
- small diesel generators;
- connection to the grid;
- connection to a mini grid based on small hydropower;
- connection to a mini grid supplied by large diesel generators.

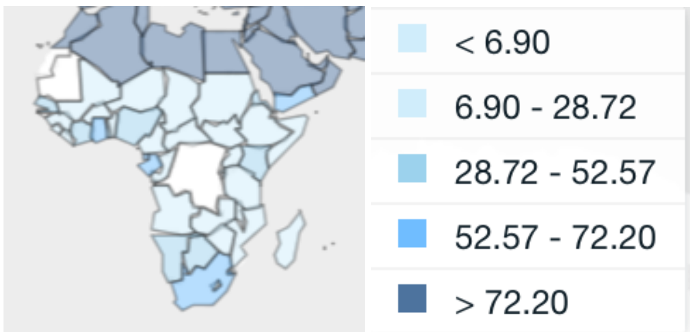

Fig 2 Electrification %

Solar power is a very popular option but it is limited to lighting, radio, TV and charging cell phones. The high cost of solar cells, inverters and batteries rules out supplying larger loads like a cooker, motive power or air conditioning. The battery capacity needed to supply a 10 kW load for 15 hours per day with sufficient in reserve for 5 cloudy days is about 500 kWh. The installed cost of the battery plus 30 kW of solar cells and the inverter would be about $150,000 – $15,000 per kW of load! By contrast, a 10 kW diesel costs less than $2000. Even though diesel generators have problems of their own, the difference will buy a lot of diesel fuel!

Wind power also has many problems especially in countries where periods of low wind speed can the last for longer than a few days.

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1 https://www.iea.org/newsroom/news/2018/october/population-without-access-to-electricity-falls-below-1-billion.html
2 https://www.weforum.org/agenda/2018/06/1-billion-people-lack-electricity-solution-mini-grid-iea/
3 https://data.worldbank.org/indicator/EG.ELC.ACCS.RU.ZS?view=map

Nevertheless, starting with solar power is an excellent way of introducing a rural population to the advantages of electricity. Experience in Bhutan showed that after a few years with solar power rural populations are very keen on a more substantial supply that will allow them to make wider use of electricity and further improve their standard of living.

The economics of the last three options are heavily dependent on the cost of rural distribution. If the costs can be reduced by a factor of three – which is usually quite easy – then the area that can be served from a grid substation or a mini grid is enormously expanded. If the economic distance limit from a mini grid with conventional distribution is 10 km, increasing this to 30 km will increase the area that can be economically supplied from 300 km² to 3000 km². There can be no doubt that reducing the distribution cost is the key factor in rural electrification.

3. Conventional systems

The most common technology for rural distribution is extending the three-phase 11 kV or 22 kV systems used for reticulating small towns further and further into rural areas. Many of these systems are based on obsolete practices that massively increase the cost of supplying power to a lightly loaded rural system (Fig 3).

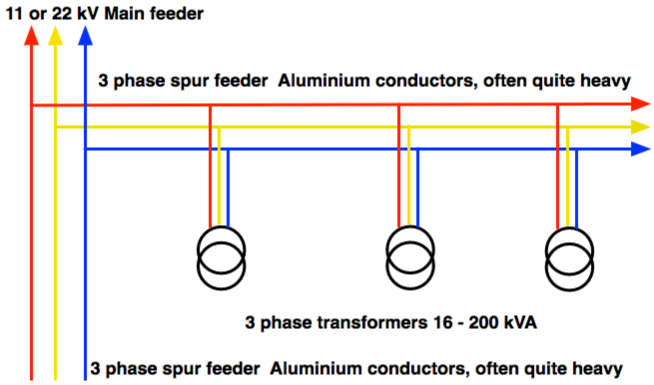

Fig 3 Conventional system

Fig 4 Typical conventional 15 kVA tf

Typical examples are:

- installing small (15 - 50 kVA) three phase transformers complete with LV switchgear or fuses that were designed for much larger transformers on two pole transformer structures (Fig 4)
- the use of "standard" 50 mm² or even 100 mm² conductors when much smaller conductors would be quite adequate
- using HV isolators instead of dropout fuses
- having much shorter spans than are needed in a rural area. .

4. Low-cost systems

All low-cost systems are single phase because the low loads involved in rural electrification cannot justify using three conductors when one or two will do. In Australia, steel conductors are widely used for spur lines to small individual loads.

Some engineers are concerned that single phase systems cannot supply three phase motors and the like and hence should be avoided. This problem no longer exists. 10 kW single phase motors are commonly available and it is possible to purchase single phase motors larger than 50 kW[4]. Electronic converters are that convert single phase to three-phase are also available. A 10 kW converter costs about $400.[5]

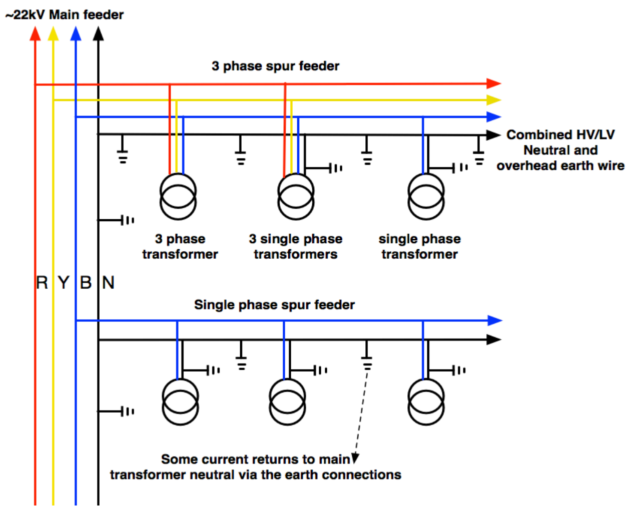

Fig 5 US Rural system

[4] https://singlephasepowersolutions.com/casestudies/
[5] http://www.southern-converters.com/phase-converter-panels.html

The two commonly used low-cost systems are the US REA system (Figs 5 & 6) using a phase and neutral conductor and the Single Wire Earth Return (SWER) system (Fig 8) invented by Lloyd Mandeno in New Zealand in the 1920s. It is widely used in Australia and other countries. Figure 8 shows a typical 10 kVA transformer station and Fig9 shows a schematic diagram.

As can be seen from the map of Queensland (Fig7), Australian SWER systems extend for hundreds of kilometres. Some carry loads of 600 kW. The cost savings over conventional systems have been enormous.

The main difference between the two is that the US system uses a neutral return conductor while the SWER system uses the earth to carry the return current.

Fig 6 Typical US 15 kVA tf

If a neutral wire breaks the US system operates using earth return until the break is detected and fixed. I have discussed this with a US distribution engineer and he has assured me that operating with a broken neutral is not unusual and, in his experience, has not caused problems. The difference between the two systems is less than it might seem and the conclusion is that the US HV neutral wire is often redundant.

5. Selection of voltage

Countries that follow UK practice usually extend existing 11kV systems into sparsely settled areas. Now that 20/22 kV switchgear and insulators cost about the same as 11 kV the cost difference between 11 kV and 22 kV is quite small. Where long distances are involved, the higher-voltage can be cheaper overall because smaller conductors can be used. In Bhutan inexperienced consultants selected 33 kV 3 phase for rural electrification. They used 15 kVA three-phase transformers to supply small loads that were expensive, needed three insulators instead of one or two and had serious problems under lightning conditions because the primary winding is made of very fine wire. Single phase 19.3 kV (33/1.732) or 22 kV would have been much better.

Fig 8 SWER 10 kVA tf

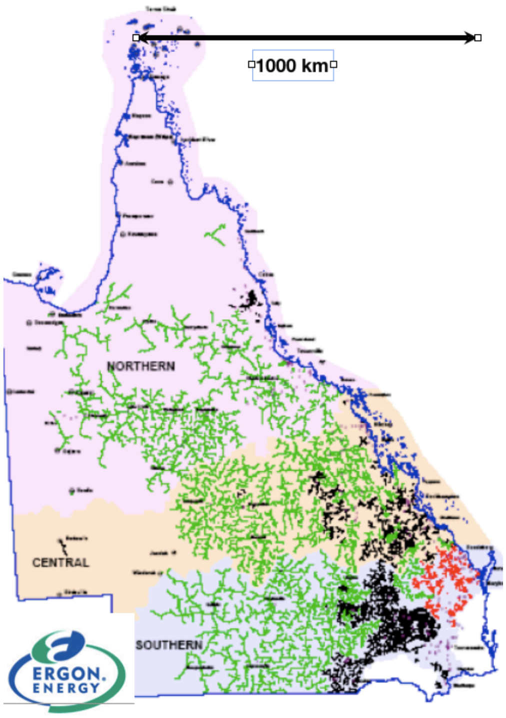

Fig 7 SWER in Queensland, Australia

6. Isolating transformers

When SWER was being developed in the 1920s, earth return telephones with a single conductor made of fencing wire strung on locally grown poles were in common use in rural areas. It was found that the return current from the distribution transformers was causing serious telephone interference. Installing 11kV/11kV isolating transformers between the three phase system and the single wire system reduced the telephone interference to acceptable levels and, as a bonus, allowed the use of 11 kV to earth on the spur line which provided increased transmission capacity and also allowed the use of standard two phase transformers. Now that earth return telephone lines have been totally supplanted by mobile phones telephone interference is no longer a real consideration.

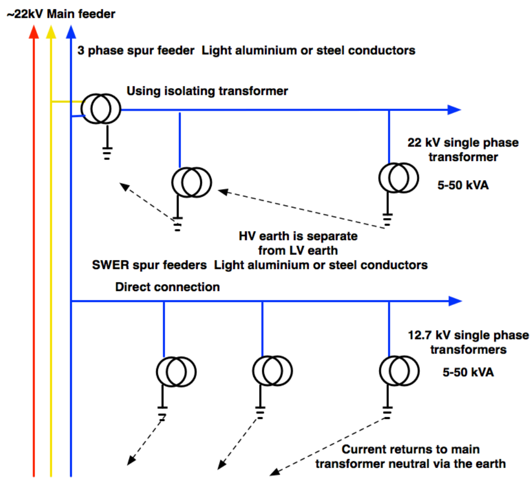

Fig 9 SWER systems

If rural electrification system is being fed from a 33 kV system then 19.3 kV or, alternatively, 22 kV from a 33/22 kV transformer can be equally satisfactory. If it is fed from a 22 kV system then 12.7 kV can be compared with the probably better option of a 22/22 kV isolating transformer. If it is fed from an 11 kV system, an 11/11 kV isolating transformer can be used but 11/22 kV will often be a better option.

If large-scale electrification is being considered involving hundreds of transformers then transformers with a single HV bushing should be considered instead of using standard two phase transformers.

7. LV system

Most SWER systems have a 230/460 V three wire LV system because it has about 25% of the losses of a 230 V system and the transmission distance is much greater. For flexibility each transformer has two identical 230 V windings brought out to 4 bushings to simplify supplying a single phase 230 V load.

Experience has shown that ground mounted LV switchgear should be avoided as it adds to cost and is a maintenance burden. Some systems have LV fuses adjacent to the transformer but experience has shown that they give more trouble than they are worth.

The supply to individual households should include an earth leakage circuit breaker that will switch off the supply if an earth fault occurs or somebody touches a live conductor. Such a device almost completely rules out the possibility of death by electric shock. It can be argued that this device eliminates the need for wiring regulations or standards within a house. If the wiring is dangerous then the system cannot be energised until the electrician has made it safe. If the lights are on, the system is safe. If somebody touches a live metal he/she will receive a nasty but non-fatal shock and the lights will go out.

8. Earth connection

With SWER the HV earth connection is critical to the safe operation of the system. If the earth connections break above ground the broken wires immediately carry dangerous voltages. If the earth resistance is too high, then dangerous step and touch voltages can appear in the vicinity of the HV earth. In reality, this only occurs if the earth resistance is remarkably high. For instance, the full load current of a 16 kVA single phase transformer operating at 19.3 kV will be less than one amp so the earth resistance needs to be greater than 50 ohms or so to create any danger. In Australia, regulations limit the potential rise while others insist on the same resistance regardless of size. This is not a sensible option because it means that small transformers are required to have the same earth resistance as much larger ones.

Normal SWER practice has two separate connections from the HV earth to the HV neutral, the tank and any surge diverters. A separate earthing electrode and connection are used for the 230/460 V system. The need to have separate earth electrodes increases the cost. As US experience seems to indicate, that it has little – if any – advantage over the US practice of connecting all neutrals and earths together to give a single combined HV/LV earth and neutral wire.

As there are often problems in getting a sufficiently low resistance with a single electrode adjacent to the transformer there are significant advantages in the combined neutral/earth system because, if earthing conditions are critical, the main earth electrode can often be located in an area where the earth resistance is lower.

9. Earth fault protection

At the substation the three-phase outgoing lines will be equipped with earth fault relays usually set to trip the feeder if the earth fault current exceeds 20% of the feeder rating. If the distribution system does not include isolating transformers, care will need to be taken to make sure that the single phase spur lines are balanced across the three phases. If isolating transformers are used, the three-phase line currents will always be balanced.

10. Poles

With a single conductor, span length is dictated by ground clearance, pole length and wind loading.

On undulating or hilly country, very long spans are possible by locating poles on high ground. Spans in excess of 500 m are achievable if steel or steel reinforced conductors are used. An example is "Quince"[6] with an aluminium area of 7.2 mm², a diameter of 5.3 mm, a breaking load of 12.7 kN and a resistance of 4 ohms/km. At 22 kV it will supply about 10 kW over a distance of 50 km with a voltage drop of 1000 V. Sag for a 200 m span will be about 1 m, 2.2 m for 300 m. On level ground, spans of 300 m should be possible. If the topography is suitable, spans of 1000 m with a sag of 25 m should be possible.

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[6] Australian Standard 3607

With two conductors, the possibility of conductor clashing and doubling the wind loading on the poles limits the span to 100 - 150 m and so increases the number and cost of poles.

It is important to use poles that are sufficiently strong for the maximum loading conditions – but no stronger.

11. A hybrid option

As already pointed out, UK/European/Australian practice of separating the HV and LV earths adds expense and complication and, in reality, is little different from the US system because the two separate earth electrodes are connected via the ground. Thus any earth potential rise from the HV system inevitably appears – perhaps with a small reduction – in the LV earthing system.

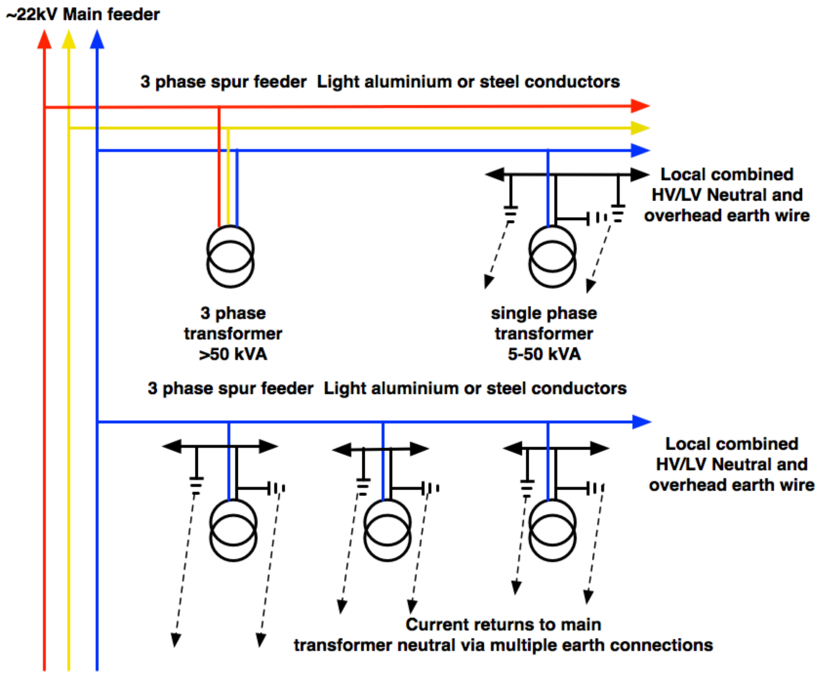

Fig 10 Hybrid system

It can also be argued that with the US system the cost of neutral conductor in long sections of line between transformer stations is not justified because, as I have been able to establish, the system works perfectly well without it. It is important to remember that the resistance of the body of earth is about 0.06 ohms per kilometre – much lower than the 1.2 ohms/km of a 25 mm² conductor or the 4 ohms/km of a 7 mm² conductor. The high resistance will drive a considerable proportion of the return current into the ground so eliminating the neutral conductor is not likely lead to a major increase in the current already being carried through the earth.

Transformer connections and the LV system follows US practice with pole mounted sealed transformers and the HV and LV neutrals all connected to the same earth. The HV/LV neutral/earth wire is earthed regularly at poles and at houses. This provides a multitude of earth connections so the risk of losing the connection between the high-voltage neutral and earth is much reduced and any earth potential rise is widely distributed. Where steel or reinforced poles are used each pole can be used provide a multitude of earth connection points.

In a village with several transformers, the neutral/earth wire should be continuous between transformers.

With the hybrid system (Fig 10), cost savings are made by eliminating the neutral/earth conductor and also by allowing the use of fewer and lighter poles because the wind loading is halved and there is no need to have intermediate poles purely to maintain conductor spacing. In addition, reliability is increased and O&M costs reduced. If there are hundreds of kilometres of line the savings can be large.

Compared with SWER, the saving would be less but safety will be improved and O&M costs are likely to be even less.

To sum up, all three systems are quite satisfactory: the US system is the most expensive and SWER is a more expensive and a little less safe than the hybrid system. All three systems are hugely cheaper than commonly used three-phase systems.

12. Relative costs

The following costs are based on cost estimates made 30 years ago for a rural line 10 km long serving three villages. The costs have been trebled to allow for inflation so are likely to give a reasonably accurate estimate of the relative costs. Conductor costs are for an individual conductor.

(a) Conventional 11kV system

Item	**Cost**
200 Poles, erected @ $500	$100,000
30 km of 100 mm2 3 phase HV conductor @ $3/m	$270,000
HV Conductor stringing @ $2400/km	$24,000
600 HV pin insulators @ $15	$9,000
100 HV tension insulator strings @ $60	$6,000

3 - 100 kVA transformers	$30,000
3 - 2 pole transformer structures @ $10,000	$30,000
3 km of four wire 150 mm2 LV conductor @ $5/m	$60,000
LV insulators etc @ $2500/km	$7,500
LV Conductor stringing @ $3500/km	$10,500
Misc fittings, stays etc @ $3000/km	$10,000
Engineering, surveying, drawings etc	$50,000
Total	**$580,000**
Total per km (rounded)	**$58,000**

(b) Low Cost 20/22kV Three Phase system

Item	**Cost**
100 Poles, erected @ $500	$50,000
10 km of 16 mm2 3 wire HV conductor @ $1.5/m	$45,000
HV Conductor stringing @ $2000/km	$20,000
300 HV pin insulators @ $15	$4,500
60 HV tension insulator strings @ $60	$3,600
6 - 16 kVA transformers	$20,000
6 - 1 pole transformer structures @ $3000	$18,000
3 km of four wire 100/50 mm2 LV cond @ $3/m	$36,000
LV insulators etc @ $2500/km	$7,500
LV Conductor stringing @ $3000/km	$9,000
Misc fittings, stays etc @ $2500/km	$25,000
Engineering, surveying drawings etc	$45,000
Total	**$333,600**
Total per km (rounded)	**$33,000**

(C) SWER 22kV or 19.3 kV

Item	**Cost**
80 Poles, erected @ $300	$24,000
10 km of 3/12 steel HV conductor @ $0.5/m	$5,000
HV Conductor stringing @ $300/km	$3,000
80 HV pin insulators @ $15	$1,200
20 HV tension insulator strings @ $60	$1,200
6 - 16 kVA transformers	$20,000
6 - 1 pole transformer structures @ $3000	$18,000
3 km of three wire 100/50 mm2 LV conductor @ $3/m	$27,000
LV insulators etc @ $2000/km	$6,000
LV Conductor stringing @ $1500/km	$4,500
Misc fittings, stays etc @ $2000/km	$6,000
Engineering, surveying drawings etc	$30,000
Total	**$155,900**
Total per km (rounded)	**$16,000**

There is reasonable confidence that SWER will reduce the cost of conventional rural electrification by more than 60%. Compared to the best three-phase distribution costs are reduced by about 50%. If there are long distances between consumers, SWER could be more than 10% cheaper and more reliable than the US phase/neutral system.

13. Implementation

To be successful, the government of the country needs to make a long-term commitment to rural electrification with or without solar power as an intermediate step.

The distribution authority should then set up a task force to investigate the various options and produce standard designs that will provide the most reliable and economic supply. This may involve trips to countries like Australia to learn from their experiences and to get advice on how their system could be improved in a greenfield situation. Ensuring that the designs are optimised in terms of capital cost and operation and maintenance costs is a prime objective and, wherever necessary, existing standard practices (such as transformer standards specifying conservator tanks and expensive LV switchgear) that would stop this happening, must be abandoned.

NRECA have produced a guide for rural electrification[7] that will assist planning and implementation. It is based on American practice but it does mention SWER built to Australian standards – which, for historical reasons, are not the same as the guidelines in this paper.

Some trial lines should then be built based on the new standards to see what problems arise and how improvements can be made. Once this is done, the standard can be modified as needed and the program can get underway.

As far as possible, financing from development banks should be avoided because, very often, they are more interested in lending money and imposing outside consultants than they are in providing a reliable low cost system matched to the needs of the country and making sure that local engineers acquire the expertise they need going forward..

14. Conclusion

The cost of the distribution system is a major factor in the economics of rural electrification. Adopting the best available system will massively reduce the capital and operating and maintenance costs of rural electrification.

Three phase supply is seldom needed now that solid-state converters from single phase to three-phase are available.

Any organisation contemplating a large-scale development of rural electrification should not be bound by existing distribution standards but, instead, develop appropriate standards focused on minimising the capital and operating and maintenance costs.

The Author

Bryan Leyland has been involved in the power industry for nearly 50 years. He is an electrical and mechanical engineer and Fellow of three Institutions. He managed his own consulting business specialising in hydropower for 25 years. Since his 1962 paper on SWER, h has had an active interest in low-cost rural electrification and written a number of papers on the subject.

Bryan has also acted as a specialist adviser on rural electrification for the Asian Development Bank.
He has attended many overseas conferences and written papers on a wide variety of subjects on most aspects of hydropower. A few years ago he was named by "Waterpower and Dam Construction" as one of the 60 most influential people in the hydropower industry worldwide.

You[7] http://www.nrecainternational.coop/wp-content/uploads/2016/11/Module7DistributionLineDesignandCostEstimationforRuralElectrificationProjects.pdf