

A Generic Techno-Economic Model for Analyzing Electricity Distribution Networks

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Abstract-- The authors have created a techno-economic model of an idealized electricity distribution network in order to carry out analysis for strategic network planning and regulatory pricing. The model assumes a homogeneous load area supplied by a single zone substation. The model is capable of simulating any size load area, both underground and overhead networks and many combinations of voltage. Individual consumer loads may be allowed to vary over as wide a range as observed in practice. The model is not restricted to distribution practices in any particular country.

Index Terms—Power distribution economics, power distribution faults, power distribution maintenance, power distribution planning, power distribution protection, power distribution reliability.

I. INTRODUCTION

THE model takes as its base a portion of territory that has been uniformly subdivided into lots of equal size but not all of which have been taken up. It further assumes a homogeneous consumer base with identical maximum demands and load profiles. It proceeds to reticulate these lots in accordance with accepted best engineering practice, utilizing only two basic laws, Kelvin's Law and Ohm's Law. The reticulation takes the form of a number of high voltage feeders emanating from a zone substation. Each feeder comprises a main radial backbone line with a number of lateral lines branching off either side (see Fig.1). The backbone line continues until the extremities of the supply zone are reached and each successive lateral line is extended to the point where the last consumer can be reached. In a rural situation where every consumer is supplied from their own distribution substation, this is to the last lot boundary. In an urban situation, where many consumers are supplied from the one distribution substation, the high voltage lateral continues to the point where the last consumer can be reached by low voltage reticulation from the last substation while still maintaining voltage within acceptable limits.

Where voltage conditions on the high voltage system cause recognized voltage limits at the consumers point of attachment to be exceeded, automatic regulating transformers are inserted

as needed. At the extremities of the laterals, where it may no longer be possible to protect the system against short circuits, automatic circuit reclosers are inserted to ensure adequate protection. Wires are sized in accordance with Kelvin's Law by allowing so many square millimeters of cross sectional area per ampere. Voltage levels are calculated using Ohm's Law.

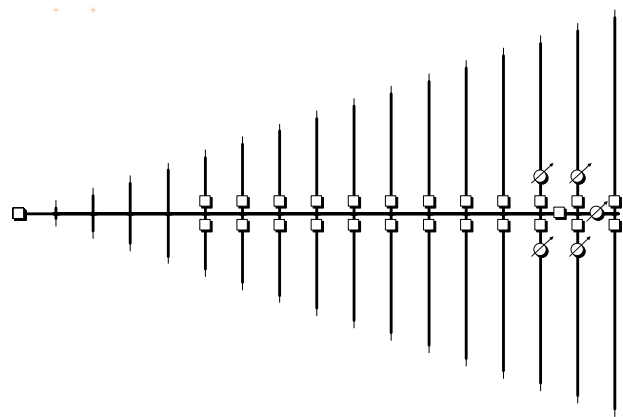


Fig. 1. Computer generated feeder model showing backbones and laterals, together with all necessary reclosers and regulators to satisfy protection and voltage regulation requirements.

For regulatory pricing the system is then costed out using standard unit rates. Distribution costs are then allocated to each consumer as fixed charges. These fixed charges are also expressed on the basis of cents per kWh or \$ per kVA for comparison purposes. The model also calculates the cost of losses and the cost of lost load per consumer.

II. MODEL INPUTS

The model accepts a wide range of inputs of various kinds, cadastral, financial and electrical etc and produces both technical and financial outputs. These are summarized below.

A. Spatial Information

Lot frontage	Occupancy Rate
Lot depth	Total Lots
Lot Area	Multiple Occupancy
Road width	Total Consumers

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B. Electrical Loads

Consumption	Low Load/Full Load
ADMD	Design ADMD
Load Factor	Undiversified Demand
Power Factor	Consumption
Diversity Factor	

C. Financial Assumptions

Capital contributions	Asset Value
Remaining life	Depreciation
Rate of Return	Rate of Return
Sub-transmission losses	Distribution Losses
Value of Lost Load (VOLL)	

D. Sub-transmission

Sub-transmission Voltage	Permanent Faults pa
Distance to transmission	Temporary Faults pa
Sub-transmission length	Response Time
Conductor area per Amp	Basic Insulation Level

E. Zone Substations

Secondary Voltage	Permissible Overload
No of Transformers	Total Load
Name Plate Rating	No of Feeders
Protection Factor of Safety (FOS)	

F. Backbone Lines

System voltage	Response Time
Number of feeders	Basic Insulation Level
Total length of all backbones	Laterals per Section
Conductor area per Amp	Urban Design Span
Permanent faults	Design Voltage Regulation
Temporary faults	

G. Lateral Lines

System voltage	Temporary Faults
Number of laterals	Response Time
Total length of laterals	Basic Insulation Level
Conductor area per Amp	Urban Design Span
Permanent faults	

H. Distribution Substations

Secondary Voltage	Permanent Faults
Number	Temporary Faults
Name Plate Rating	Response Time
Permissible overload	Consumers per Sub
Calculated Loading	

I. LV Distribution

Voltage	Temporary Faults
Number	Response Time
Total length	Urban Design Span
Aluminum Area	Design Voltage Regulation
Permanent faults	

III. MODEL OUTPUTS

The model produces a range of financial and technical outputs to allow evaluation and comparison of many supply scenarios.

A. General

Consumers / Zone	kW / Consumer
HV Route km	kVA / Consumer
Total Route km	kWh / Consumer
Consumers / Circuit km	
Consumers / Route km	

B. Financial

The following outputs are available expressed per km, per consumer/consumer, per kWh and per kVA.

- Optimized Replacement Cost (ORC)
- Optimized Depreciated Replacement Cost (ODRC)
- Operations and Maintenance costs (O&M)
- Depreciation allowance (Dep)
- Return on Assets (RoA)
- Distribution Use of System charge (DUOS)
- Cost of Losses
- Customer Outage Cost
- Total Customer Cost (including losses and outages)

The following figures are also available in fully cost reflective terms

- Lowest price
- Average price
- Highest price

C. Reliability & Losses

The following indices are also available as averages and also worst case

- Interruption Frequency Index (SAIFI)
- Interruption Duration Index (SAIDI)
- Response Time (CAIDI)
- Distribution Loss Factor (DLF)

Quantity	\$/ km	\$/ Cons	\$/ kVA	c / kWh
Replacement Cost (RC)	\$ 190,080	\$ 3,699	\$ 1,232	
Optimised RC (ORC)	\$ 142,560	\$ 2,774	\$ 924	
Depreciated ORC (DORC)	\$ 71,280	\$ 1,387	\$ 462	
Operation & Maintenance	\$ 5,587	\$ 9.06	\$ 3.02	1.36
Depreciation	\$ 2,851	\$ 4.62	\$ 1.54	0.69
Return on Assets	\$ 5,346	\$ 8.67	\$ 2.89	1.30
Use of System Charge	\$ 13,785	\$ 22.36	\$ 7.44	3.36
Losses	\$ 384	\$ 1.12	\$ 0.37	0.17
Outage	\$ 193	\$ 0.57	\$ 0.19	0.08
Total	\$ 14,362	\$ 24.05	\$ 8.00	3.61

Table 1 – Sample output for an urban distribution system.

IV. MODEL RESULTS

Over the past two years, literally thousands of scenarios have been modeled and their most salient features noted. It should be particularly noted that the comments below are made in respect of homogeneous load areas.

A. Output Measures

Of all the available output measures, the most consistently reliable indicator of performance in the area of distribution was found to be the total cost per consumer, which rises only gently with consumption, even with a tenfold increase in consumption.

Other measures such as cost per kWh and cost per kVA were found to be derivatives of total cost and subject to considerable volatility depending on the energy consumption patterns of the consumer.

The explanation of the stability of costs per consumer in the face of rising consumption lies in the consumer related operating expenditures, the costs of having to place a pole on every second lot boundary regardless of consumption level and the largely fixed costs associated with any zone substation regardless of capacity

B. Cost Drivers

The principal driver of costs was found to be customer density (customers/km) represented in the model by lot frontage. This finding was consistent for urban, semi-urban, rural and sparse rural subdivisions. The corollary of this finding is, that within homogeneous load areas, distribution charges should perhaps be levied on the basis of lot frontage.

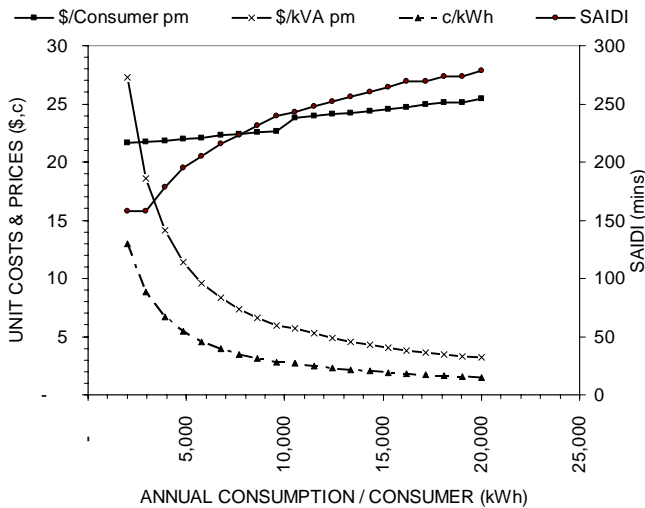


Fig. 2. Unit Costs, Unit Prices and Unreliability as a function of Annual Consumption

Average energy consumption was found to be only a marginal driver of total costs measured as \$/kVA, (Fig.2). However, average consumption does have a notable impact on average unit costs (c/kWh), reflecting the benefits of economies of scale. Higher levels of energy consumption for any given level of network capacity investment cause the largely fixed costs to be spread over a much larger throughput. This can give the illusion of greater operational efficiency but is really just a reflection of the scale efficiency of higher energy density.

Average maximum demand was also found to be not a particularly significant cost driver.

1) Lot Frontage - Urban

Fig.3 shows that costs per consumer are a linear function of lot frontage, with a heavy fixed component which represents the fixed costs. Unreliability measured by SAIDI also increases. Costs per kVA and per kWh simply follow the costs per consumer.

2) Lot Frontage – Semi-urban

Fig.4 shows the same relationship of costs and unreliability with lot frontage. SAIDI eventually becomes stable but erratic as reclosers come into effect.

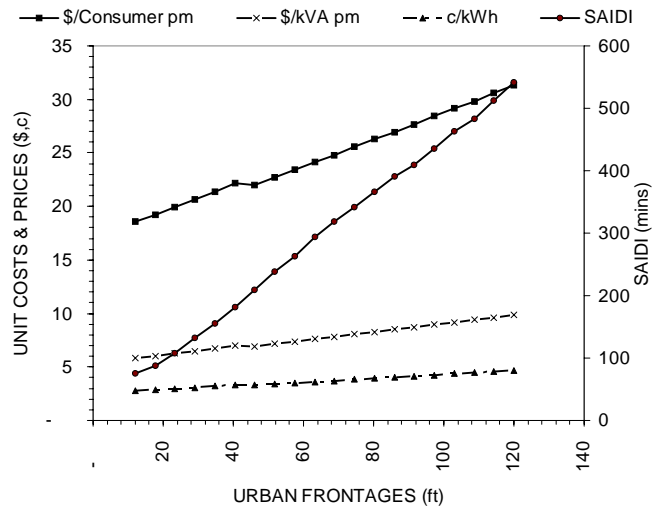


Fig. 3. Unit Costs, Unit Prices and Unreliability as a function of Urban Lot Frontage

3) Lot Frontage – Rural

Fig.5 continues the same story with costs increasing and SAIDI stable but erratic.

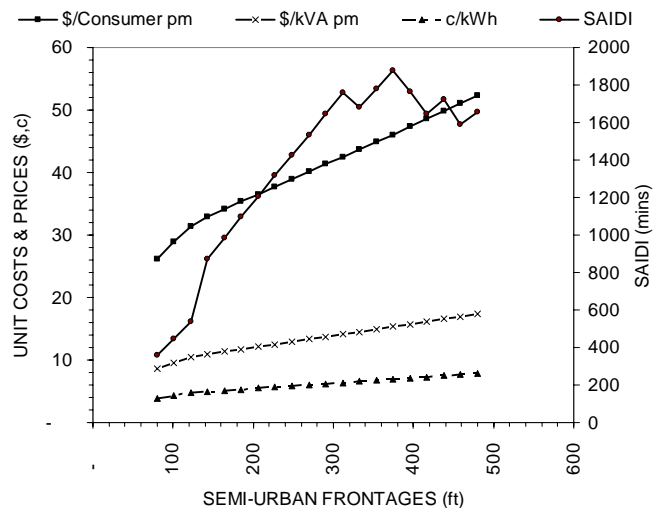


Fig. 4 Unit Costs, Unit Prices and Unreliability as a function of Semi-urban Lot Frontage

4) Number of Consumers - Urban

Fig. 6 shows the cost reduction associated with the increase in total number of consumers served within a given load area. Reflecting the strong impact of customer density on network costs, the decline is sharp in the first instance, but declines more gradually as the number of customers connected rises. There is, however, an increase in unreliability with growing length of high voltage feeders, demonstrating the trade-off between price and reliability.

In rural towns, the town population limit may be reached well before all the desired economies of scale are realized. This

has the effect of leaving regions with well spaced small towns at a cost disadvantage compared with regions having either larger towns or very closely spaced small towns. However, all other things being equal, smaller towns with their own zone substation should have higher reliability than larger ones.

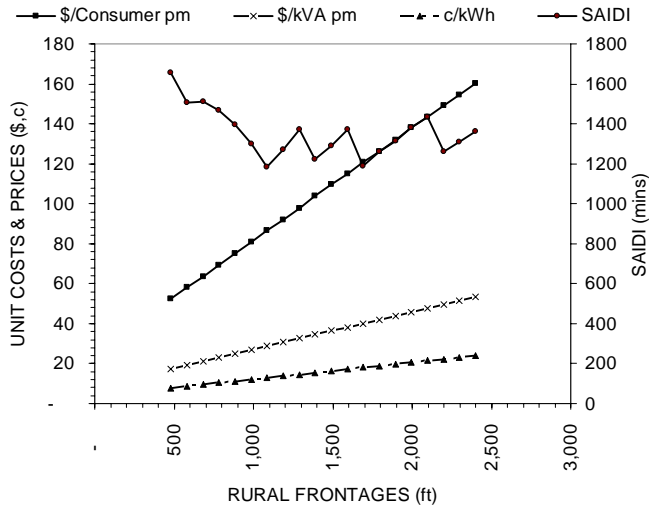


Fig. 5. Unit Costs, Unit Prices and Unreliability as a function of Rural Lot Frontage

In metropolitan areas, though, economies of scale will not be constrained by population limits and the choice is available to planners to optimize costs and reliability by selecting a maximum number of consumers to be served by an individual zone substation.

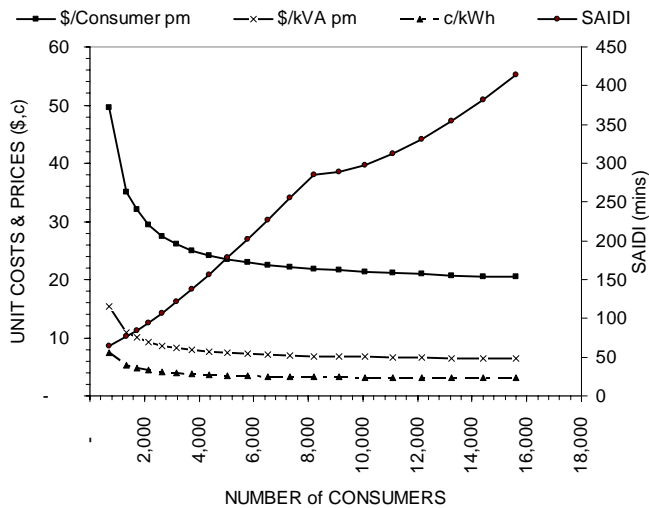


Fig. 6. Unit Costs, Unit Prices and Unreliability as a function of Total Number of Consumers.

5) Number of Consumers - Rural

The tendency noted above for unreliability to increase with the total number of consumers served is far more pronounced in rural situations where dramatic decreases in price per kWh are accompanied by equally dramatic increases in unreliability.

6) Load Factor

Fig. 7 demonstrates that poor load factors tend to drive unit costs up but also that there is a limit to the reductions that may be achieved by improving load factors

7) Power Factor

The model can also demonstrate that poor power factor has a tendency to drive unit costs up, but also that there are decreasing returns on investment in power factor correction and at around 0.8PF.

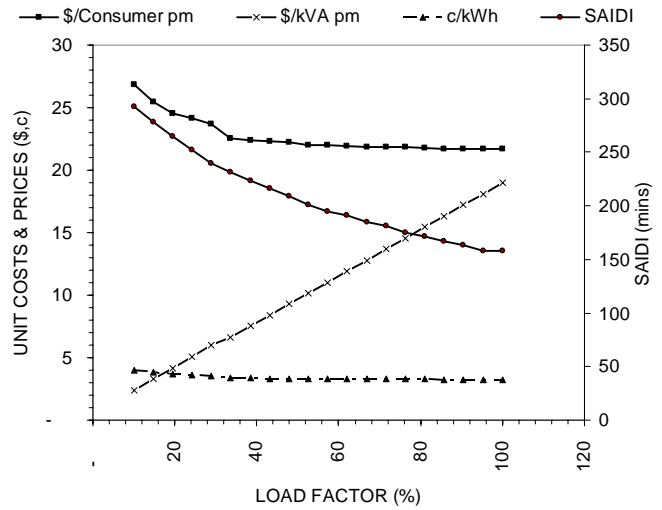


Fig. 7. Unit Costs, Unit Prices and Unreliability as a function of Annual Load Factor

V. DISPERSION OF RESULTS

In the above analysis the results are system averages. In both costs and unreliability there will always be greater or lesser degrees of variation between consumers, depending on whether they are connected close to or far away from the source of supply.

A. Costs

To produce Fig. 8, consumers were allocated only their share of upstream costs. As can be seen, the de-averaged costs can be very widely dispersed in many cases. If consumers were to be priced cost reflectively then some very strong signals for installation of distributed generation would result.

B. Unreliability

Fig. 9 shows how average values of SAIDI can considerably understate the worst case reliability situation. The model can demonstrate that sectionalizing will indeed reduce average figures for SAIDI but will have no affect at all on the worst case situation. It can be demonstrated that the solution for improving worst case figures lies in providing back-feeds from adjacent feeders or substations or even distributed generation.

VI. CONCLUSIONS

A. Economies of Scale

Economies of scale are demonstrated by the model but they are of a special kind. The bigger the load area served by an individual zone substation, the lower the costs per consumer, as the largely fixed costs of the zone substation are distributed over more and more consumers. Such economies of scale, though, may be constrained by town size.

B. Unreliabilities of Scale

As load areas increase, reliability decreases on account of the greater length of individual feeders. This decrease is reflected in SAIFI as well as SAIDI.

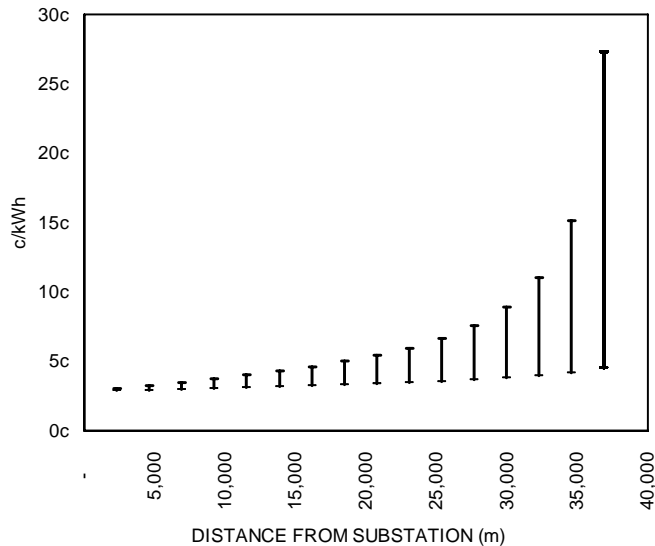


Fig. 8. Range of Unit Costs as a function of Distance from Main Substation

It has been noted in the past that changes to higher voltages have often been accompanied by decreases in reliability as systems become stretched. This is a function of feeder length, however, not voltage per se.

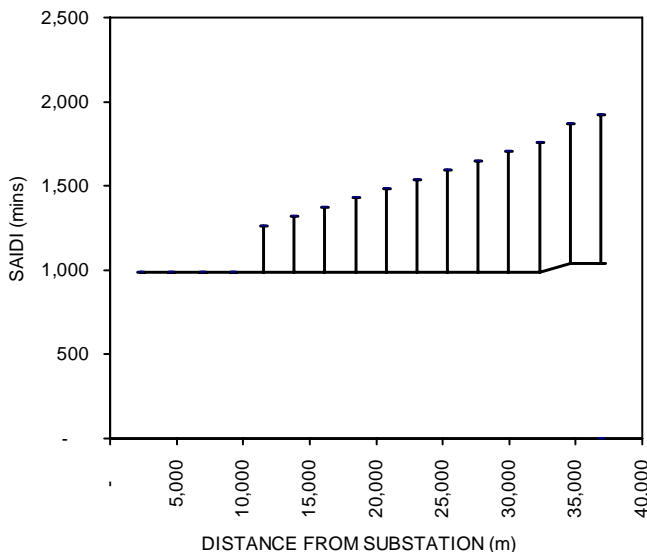


Fig. 9. Range of Reliabilities as a function of Distance from Main Substation.

The model has been used to show that the most cost effective way of improving reliability is by the use of back feeds.

C. Dispersion of Performance

Because of the very nature of electricity distribution systems, which take energy from a central source and distribute it over

a broad area, costs and unreliability will vary with distance from the source.

VII. REFERENCES

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VIII. BIOGRAPHIES

Leith Elder was born in Melbourne, Australia, on October 25, 1943. He graduated from the Albury High School, Albury NSW, and studied at the University of Sydney.

His employment experience includes the Australian Government, The Sydney County Council Sydney NSW, The Southern Tablelands County Council, Goulburn NSW, Great Southern Energy, Queanbeyan NSW, Country Energy Queanbeyan NSW. His special fields of interest include system protection and overhead line design. He has served on several Australian standards committees.

He received his degree in Electrical Engineering from the University of Sydney in 1965 and is a regular presenter of papers to the Electric Engineering Society of Australia.

Margaret Beardow is Principal of Benchmark Economics an energy economics consultancy she established in 1997. Studying at Macquarie University Sydney she graduated with a BA (Honors) degree, majoring in economics and geography (minerals).

Margaret has 25 years experience in the energy sector; including coal, oil, gas, and electricity. More recently she has specialized in network pricing regulation, providing analysis and advice to most Australian distribution and transmission businesses. In conjunction with a number of colleagues (including Leith Elder) she has developed an economic cost model for distribution networks that identifies key network cost drivers and quantifies the likely impacts on regulated financial indicators.

She is Visiting Fellow in the Faculty of Engineering at the University of Technology Sydney and a Fellow of the Australian Institute of Energy. Margaret writes regularly on electricity markets and regulation and has presented at International Conferences.