TECHNICAL AND ECONOMIC REVIEW OF DISTRIBUTION VOLTAGE IN KATHMANDU VALLEY

A. Objective of this Review

1. This review of the voltage level of the medium voltage distribution network in Kathmandu Valley has been prepared at the request of Nepal Electricity Authority (NEA).[1] It evaluates whether the existing 11 kilovolt (kV) distribution system voltage level in the valley should (i) be retained and the network rehabilitated, replaced or reinforced as required to meet the projected load growth; or (ii) be replaced by either a 22 kV network or a 33 kV network, in both cases fed directly from the transmission system.

B. Suitability of Existing 11 kV System

2. From the onset of electrification in Nepal, voltage levels and designs of the transmission and distribution system have been based on British practice, as reflected in the following three-phase voltage levels:

(i) low voltage distribution: 400/230 V;
(ii) medium voltage distribution: 11 kV;
(iii) medium voltage sub-transmission: 33 kV;
(iv) high voltage transmission: 66 kV, 115 kV and 220 kV; and
(v) extra high voltage transmission: 400 kV.

3. A summary of NEA's key statistics, including number of customers, peak demand and energy sales, for Kathmandu Valley is provided in Annex 1.

4. Kathmandu Valley is currently served by a total of 14 grid substations (132/11 kV and 66/11 kV) as shown in Table A2 in Annex 1.

5. The existing 11 kV medium voltage distribution system in Kathmandu Valley is derived from these grid substations, with each substation having typically ten 11 kV feeders. The 11 kV medium voltage system then supplies 11/0.4 kV distribution transformers; standard three phase ratings used in Nepal are 50, 100, 200 kilovolt-ampere (kVA). Some areas derive supply from single phase 15 kVA and 25 kVA pole mounted units.

6. Overhead distribution 11 kV lines are generally three phase using aluminium conductor steel reinforced (ACSR) 100 mm^2 (Code Dog) with some lines 50 mm^2 (Code Rabbit) and 30 mm^2 (Code Weasel). Existing line losses in the 11 kV system are reported to be >10%.

7. Demand in the Kathmandu Valley is expected to increase by as much as 10% per year for the foreseeable future, increasing from about 400 megawatt (MW) now to 2,500 MW by 2025-2030.[2] Overall power supply should improve dramatically in the next few years due to new generating capacity, especially the 456 MW Upper Tamakoshi project (scheduled to come online in 2019), operation of the first 400 kV cross-border line at full capacity (~ 1000 MW), and operation of a second 400 kV cross-border line by 2020 (another ~ 1000 MW).

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[1] Prepared by project preparatory technical assistance consultants Mike Breckon and Paul White in September 2016.

[2] Current demand is likely to be significantly higher than 400 MW, however the level of suppressed demand and the extent of load shedding throughout the year (but particularly in winter) make it difficult to estimate the true level of demand.

8. This expected load growth will require the number of grid substations (132 kV or 66 kV) and 11 kV feeders to double or triple within the next 20 years. One option to adding more feeders is to enhance the feeder capacities by increasing the conductor sizes. This option though would require an upgrade of the poles and cross arms in order to support the additional weight.

9. Continuation and expansion of the 11 kV network will be challenging because of the need to increase the number of 11 kV feeders and the inherent difficulties in positioning these new feeders in heavily built up urban areas, particularly as they egress from the grid substations. Securing land to build primary substations to supply the medium voltage network will become increasingly challenging in Kathmandu Valley. Selecting a distribution voltage higher than 11 kV will reduce the number of grid substations required and thus reduce (but not eliminate) this problem.

10. Another consideration is that, based on discussions with NEA and confirmed by initial observations in the field, a significant amount of the existing 11 kV system is in poor physical condition and needs to be replaced, possibly within the next 5 years or so. The estimated extent of this includes:

(i) 80% of overhead circuits;
(ii) 50% of distribution substations (11/0.4 kV) owned by NEA and 10% of distribution substations owned by customers; and
(iii) 50% of pole-top switches.

C. Options for Replacement of 11 kV System

11. As noted in para 8, the expected load growth will require the number of 11 kV feeders to increase significantly. An obvious alternate to this is to increase the voltage of the feeders, to either 22 kV or 33 kV. The power transfer capacity of any given power system is a function of voltage level and current; therefore, a 22 kV system can deliver twice the capacity of an 11 kV system over the same conductor size. The key benefits of a higher distribution voltage include:

(I) lesser number of distribution feeders needed to supply the load in any area;
(II) reduced distribution losses as feeder currents will be less; and
(III) capital investment will be less with not as many feeders and fewer primary substations.

12. The choice of a higher voltage is guided by international standards and availability of electrical equipment in these standard voltage ratings. The preferred standard voltages are listed in Annex 1. Of these, 22 kV or 33 kV could be considered as alternative distribution voltages to 11 kV.

13. The 33 kV option is used in many countries as a sub-transmission voltage to supply 11 kV system through 33/11 kV area substations. However, it is not commonly used as a distribution voltage to directly supply the low voltage network. One exception is in Sri Lanka; in the 1980’s Lanka Electricity installed a 33/0.4 kV distribution system in their supply area in various townships outside the Colombo city area. The objective was to reduce supply costs by eliminating the need for 33/11 kV area substations. Their 33 kV distribution system is still in service but has not been replicated outside their supply area.

14. The 22 kV option is a common distribution voltage used in numerous countries around the world (examples are shown in Section C in Annex 1).

15. Despite the advantages of higher distribution voltages, examples of conversion from a lower to a higher voltage are limited; optimization of the existing voltage is usually the preferred option for reasons of cost and practicality. However, there are a few past examples of other countries embarking on voltage conversion programs in urban areas:

- **Thailand.** In metropolitan Bangkok, the distribution of electricity is the responsibility of the Metropolitan Electricity Authority. Sub-transmission in this area was previously mostly at 69 kV. However, rapid growth in load in the 1980s necessitated the introduction of a 230 kV sub-transmission ring around the city. The configuration of the 69 kV system became somewhat complicated but the configuration of the replacement 230 kV sub-transmission is radial. The standard grid substation transformer configuration is 2x50 megavolt ampere (MVA). Medium voltage distribution is now standardized at 20 kV, with 12 kV in the older parts of the city mostly replaced.

- **Cambodia.** In the city of Phnom Penh, the original electrical network became very run down after a lengthy period of civil disorder. Between 1993 and 1998, the entire medium voltage distribution system was overhauled, and a standardized medium voltage distribution voltage of 20 kV introduced to replace the older 15 kV network and pockets of other voltages such as 3.3 kV, 6.6 kV and 11 kV. At the same time, a new 115 kV sub-transmission ring was installed around the city to supply the new 20 kV network.

D. Technical Considerations Associated with A New 22 kV System[3]

16. A new 22 kV system could be supplied directly from new power transformers at the existing 132 kV grid substations, through a star winding with the neutral point earthed. Some utilities include a low-resistance earth to reduce earth fault currents and voltage depression during faults to promote system reliability and safety. The type of earthing would need to be studied separately and is outside the scope of this paper.

17. The 22 kV medium voltage distribution system would then supply new 22/0.4 kV distribution transformers; international typical three phase ratings are 100, 150, 160, 200, 250, 300, 315, 400, 500, 600, 630, 750, 800, 1,000 kVA which covers the existing capacities of distribution transformers used by NEA. Equipment rated at 22 kV, including distribution transformers, conductors, insulators and switchgear, is readily sourced internationally, with the nearest manufacturing sources including China, Indonesia, Thailand, and Vietnam.

18. In general, the design of 22 kV overhead lines is very similar to that of 11 kV lines, the key difference being the need for increased safety clearances as shown in Table A.4 in Annex 1. Consequently, a new 22 kV construction would require taller poles and wider cross arms than currently used for 11 kV.

19. Consideration would need to be given to the vector grouping of the 22 kV voltage source at grid substations to ensure that the low voltage systems from 22 kV and 11 kV in adjoining

[3] Most of this section applies equally to 33 kV. However, 33 kV is unequivocally higher cost than 22 kV (as demonstrated in Section E) and for simplicity is not discussed in this section.

supply areas can be paralleled. As with the type of earthing needed for a new medium voltage system, this would need to be studied separately and is outside the scope of this paper.

20. Adoption of a new distribution voltage will require the implementation of a carefully planned conversion program, designed to effect the changeover in the quickest possible time with minimal disruption in supply to the consumer, and with a target date to remove all 11 kV distribution at the same time. This program would need to be planned and implemented to phase out the 11 kV system over a finite period (e.g. 50% replaced in 5 years and 100% within 10 years).

21. It is envisaged that conversion would be done on a feeder-by-feeder basis, starting at the grid substation end once the new 22 kV source is installed and available. Each feeder would need to be back fed by 11 kV so as to maintain supply to the customers on the low voltage side. One section of the feeder would be isolated and made safe for work; then the 11 kV transformers removed and replaced by a 22 kV equivalent transformers. Once ready, the feeder section would then be livened at 22 kV and then the process repeated for the next section of the 11 kV feeder, until the complete feeder is changed over to 22 kV. In some situations, particularly in new feeder areas, dual voltage 22/11/0.4 kV transformers could be utilized so that the transformer could initially be energized at 11 kV, then when the feeder is ready for conversion the internal taps in the de-energized transformer changed to the 22 kV setting.

22. In summary, from a technical viewpoint a 22kV medium voltage distribution would reflect international practice and would not require significant design and construction changes for NEA.

E. Comparison of Options 11kV With Higher Voltages

1. Capital Costs and Ratings

23. The change from 11 kV to 22 kV could be achieved at a relatively small premium in capital cost, as the marginal additional cost of 22 kV equipment compared with 11 kV manufactured in the United Kingdom and Europe is small, noting also that the majority, if not all, 11 kV switchgear currently is rated at 24 kV for sale into the European market. The premium is not expected to be more than 10%–15% in the case of 22 kV and around 20%–25% in the case of 33 kV.

2. Economic

24. The main economic benefits arising from a change to a higher distribution voltage would be:

(i) A reduction in capital and running costs through the reduced number of substations required to inject power into the distribution network and the reduced number of distribution feeders required (given the higher load-carrying capacity of 22 kV and 33 kV circuits);

(ii) A reduction in line losses (doubling the voltage reduces losses by 75%, all other things held constant); and

(iii) In the case of existing networks, the justification for a voltage conversion usually rests on the rate of demand growth and the run-down condition of the existing network, as argued to be the case here.

25. A least-cost evaluation in economic terms has been adopted, comparing the present value of capital and operating costs for each of 11 kV, 22 kV and 33 kV networks in Kathmandu Valley. Indicative capital costs for substations and medium voltage equipment for each of the three voltages examined were as noted in Table 1 below. Low voltage costs (and the cost of transformation losses in distribution transformers) were omitted, as they will be common to all the alternatives. An estimate was made of the need to substantially refurbish or replace the existing 11 kV network in the medium term for reasons of capacity or cost and the cost of that work was estimated.

Table 1: Indicative Average Unit Costs and Equipment Ratings

Voltage Level	132 kV Grid Substations	Overhead Circuits	Underground Circuits	Distribution Substations
Unit Cost ($000) [a]				
11 kV	9,900	18	45	31
22 kV	10,900	20	56	36
33 kV	12,200	22	72	41
Average Rating (MVA) [b]				
11 kV	45	6	9	0.2
22 kV	80	12	18	0.2
33 kV	120	18	27	0.2

kV = kilovolt, MVA = megavolt-ampere.

[a] Unit costs (per circuit-km and per substation) are averages for typical sizes and include installation and commissioning (but exclude taxes and duties).

[b] Ratings are for installed capacity in the case of substations and thermal limits in case of circuits. Circuit ratings are discussed further in the appendices.

Sources: Nepal Electricity Authority, Electricity Viet Nam and consultant's estimates.

26. The main assumptions were as follows:

(i) Peak electricity demand is currently around 400 MW and will grow at 9% per annum for the first years of the 25-year period, reducing to 6% per annum thereafter. At these growth rates, demand would increase to 1,500 MW in 15 years and to 2,700 MW in 25 years. For simplicity, demand (and demand growth) was assumed evenly distributed around Kathmandu Valley;

(ii) Peak coincidence factors (to 132 kV and 66 kV primary substations) of 0.75 for medium voltage feeders and 0.65 for distribution substations;

(iii) Approximately 75% of the replacement circuits will be underground and new distribution substations will be of the enclosed, ground-mounted type, with compact, metal-clad switchgear;

(iv) The assumed unit costs and equipment ratings as shown in Table 1 above;

(v) Average line resistance of approximately 0.5 Ω/km, reducing to around 0.33 Ω/km as larger diameter overhead and underground conductors are employed;

(vi) Transformer losses are assumed substantially the same in all options and were thus excluded;

(vii) The cost of power losses is assumed to be $105 per kilowatt (kW) per annum and the cost of energy losses I assumed to be $0.06 per kilowatt-hour (kWh);

(viii) The existing medium voltage network topography and planning philosophies would be retained, irrespective of the voltage used; and

(ix) An economic discount rate of 10% per annum in real terms has been assumed, reflecting the rationing of scarce public resources.

27. The results of the analysis are shown in Table 2, Table 3, and Table 4.

Table 2: Indicative Physical Outcomes

Statistics		Distribution Voltage 11kV	22kV	33kV
Year 1 demand	(MW)		400	
Average compound demand growth	(%)		8.5%	
Year 20 demand	(MW)		2044	
Year 20 statistics:				
No of 132 kV substations	(no.)	51	29	20
No of MV feeders	(no.)	428	212	137
MV losses				
Peak	(MW)	21	14	11
Energy	(GWh)	54	36	30

GWh = gigawatt-hour, kV = kilovolt,MW = megawatt, no = number
Source: Asian Development Bank estimates.

Table 3: Least-Cost Comparison - Present Value of Economic Costs (25 years)
($ million)

Economic Costs	Distribution Voltage 11 kV	22 kV	33 kV
Capital (years 0-5)	112	196	238
Capital (years 6-25)	315	241	235
Operations and maintenance	37	29	30
MV losses	35	17	10
Total	**500**	**483**	**514**

Source: Asian Development Bank estimates.

Table 4: Sensitivity Analysis - Present Value of Economic Costs
($ million)

Sensitivity Parameter	Base Case (%)	Sensitivity (%)	Distribution Voltage 11 kV	22 kV	33 kV
Base Case			*500*	*483*	*514*
1. Annual demand growth	9	6	332	342	377
		12	739	687	716
2. 11 kV lines requiring immediate replacement	80	25	490	483	514
		100	503	483	514
3. Economic discount rate	10	8	605	575	604
		12	420	414	445

Source: Asian Development Bank estimates.

28. The following conclusions can be drawn:

(i) The 22 kV option has slightly lower cost than the 11 kV over the 25-year analysis period;

(ii) As expected, the 33 kV option is less economic than either of the other alternatives;

(iii) Table 3 shows that the 11 kV option has a lower capital cost during the first 5 years but the condition and capacity of the existing network is critical to the analysis. If it is found on detailed examination that the need for replacement of the existing network is greater than that assumed above, then the case for conversion to 22 kV is strengthened. Conversely, the reverse is true;

(iv) The analysis is particularly sensitive to the rate of demand growth: lower rates favor retention of 11 kV and higher rates favor voltage conversion; and
(v) The choice of a lower discount rate would strengthen the case for conversion to 22 kV.

29. Irrespective of voltage conversion (but more so if it were to proceed), the opportunity exists for NEA to reassess its medium voltage network planning approach in order to optimize the future network, adopting best practice in terms of layout, flexibility and modern technology to improve network performance and to lower operating costs in the future.

3. Financial

30. The analysis above is an economic assessment, not a financial one—that is, it considers what is best for Nepal as a whole—and that is the correct approach in planning studies of this type. From a financial standpoint, NEA's capital investment requirements and debt service obligations would be higher if voltage conversion were undertaken. A separate analysis would be required to consider the financial aspects of the work but that was beyond the scope of our present assessment. NEA needs to be mindful of the likely capital cost of the conversion ($250 million–$300 million).

F. Conclusion and Next Steps

31. The analysis shows that there is a marginal economic case for conversion to 22 kV based on the assumptions that we have made. The analysis demonstrates that retention of 11 kV and conversion to 22 kV are preferred to conversion to 33 kV.

32. The option to upgrade the distribution voltage system reflects the findings of other studies, including those of CIRED-Cigré working groups, which have found that the justification for voltage conversion programs is generally reliant on a high rate of projected growth in the network concerned and a run-down state of the existing assets.[4] The extent to which the latter is the case in the Kathmandu Valley should therefore be the subject of a detailed engineering assessment, following which the economic analysis of a conversion program should be reassessed.

33. It is strongly recommended that NEA undertakes a comprehensive assessment of all risks (including operational, funding, political, public relations, technical and procurement risks) associated with a change in distribution voltage and then decides whether to retain existing 11 kV or convert to a higher voltage.

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[4] Cigré/CIRED Working Group CC 01. *Interaction between Transmission and Distribution System Planning – Final Report and Technical Papers.*

SUPPORTING INFORMATION

A. Existing NEA System in Kathmandu Valley

1. NEA's statistics for Kathmandu Valley are shown in Table A1.

Table A1: Key Nepal Electricity Authority Statistics

Statistic		Kathmandu Valley	Total
Total number of Customers	Nº	0.579 m domestic	2.797 m domestic
Peak Demand	MW, GW	~ 400 MW; predicted to increase to 2.500 GW	1.385 GW; predicted to increase to 4,281 GW by 2030
NEA Generation	GWh		5.100
NEA Annual Sales	GWh	0.625 domestic	1,793 domestic
Average Monthly Sales	GWh	total demand for FY 14-15 was 1,300 GWh, so ~ 100 GWh . month, increasing at 10% per year	
Existing 132 kV network	km		2,417
Existing 11 kV network	km	1,200 km of 11 kV lines slated for replacement / repair / expansion]	
Existing LV network	km	600 km of 400 V lines slated for replacement / repair / expansion	
Distribution transformers	Nº, MVA	3,000 transformers 11/0.4 kV, 100, 200, 300, 500 kVA transformers are included in draft procurement package]	
Grid substations	Nº, MVA	748.9	
Transmission Losses	%		4.82%
MV/LV Losses	%	11.24%	19.80%

Source: Nepal Electricity Authority 2015–2016 Annual Report.

2. Kathmandu Valley is currently served by 14 grid substations as shown in Table A2.

Table A2: Kathmandu Valley Grid Substations

No.º	Substation	Voltage kV	Capacity MVA	Remarks
1.	Balaju	132/66	45.0	3x15 MVA autotransformer
		66/11	22.5	
		66/11	22.5	
2.	Siuchatar	132/66	37.8	3x12.6 MVA
		132/66	37.8	3x12.6 MVA
		132/66	37.8	3x12.6 MVA
		66/11	18.0	3x6 MVA
		66/11	18.0	3x6 MVA
3.	New Chabel	66/11	22.5	
		66/11	22.5	
		66/11	22.5	
4.	Lainchour	66/11	22.5	
		66/11	22.5	
5.	New Patan	66/11	18.0	3x6 MVA
		66/11	18.0	3x6 MVA
		66/11	18.0	
6.	Teku	66/11	22.5	
		66/11	22.5	
7.	K3	66/11	22.5	
		66/11	22.5	
8.	Baneswor	66/11	18.0	3x6 MVA
		66/11	18.0	3x6 MVA

No.º	Substation	Voltage kV	Capacity MVA	Remarks
9.	Bhaktapur	132/66 132/11 132/11	49.5 22.5 22.5	
10.	Banepa	66/11 66/11	12.5 10.0	Outside Kathmandu Valley
11.	Panchkhal	66/11	10.0	Outside Kathmandu Valley
12.	Lamosanghu	132/33	30.0	Outside Kathmandu Valley
13.	Matatirtha	132/33 132/11	30.0 22.5	3x 10 MVA
14.	Indrawati	66/11	7.5	Outside Kathmandu Valley
	Total		**748.9**	

Source: Nepal Electricity Authority.

B. International Standard Voltages

3. In terms of international standards, IEC 60038:2009 specifies preferred values for the nominal voltages of electrical supply systems and values for equipment and system design. The standard states that the voltages for an AC three-phase system should be selected from the values given in Table A3, Series A and Series B being alternatives: that is, voltages should be selected from either A or B, not from a mixture of both.

4. Nepal has adopted Series A, with 11 kV and 33 kV in use at the sub transmission and distribution level.

Table A3: IEC Preferred Standard Voltages

Highest Voltage for Equipment (kV)	Nominal System Voltage (kV)	
	Series A	Series B
12	11	10
24	22	20
36	33	30
40.5	-	35

Notes:
1. It is recommended that in any one country, the ratio between nominal voltages should be not less than two.
2. In a normal system of Series I, the highest and lowest voltages do not differ by more than approximately ±10 % from the nominal voltage of the system.

Source: IEC 60038:2009, Table 3, Series I.[5]

5. Note 1 of Table A3 implies that 11 kV and 33 kV can be used together; but if 22 kV were to be adopted then it should replace both 11 kV and 33 kV - in other words the three voltage levels should not be used together.

C. International Use of 22 kV

6. Distribution systems insulated to 24 kV is currently used in the following countries:

(i) Asia: (nominally 22 kV unless indicated otherwise)
   a. Cambodia
   b. Hong Kong
   c. Indonesia (20 kV)
   d. Lao PDR
   e. Philippines (23 kV)

[5] Series II in IEC 60038:2009, Table 3 is for 60 Hz North American practice only and not applicable for Nepal.

f. Singapore
g. Thailand (20 kV)
h. Vietnam

(ii) Europe: (nominally 20 kV unless indicated otherwise)
a. Belgium
b. Czechoslovakia (22 kV)
c. Denmark
d. France
e. Finland
f. Italy
g. Netherlands
h. Spain
i. Norway

(iii) South Africa

7. Other countries such as Australia and New Zealand use 22 kV as a non-standard voltage in certain areas (e.g. sub-transmission in the City of Auckland) and as a standard voltage in other parts of the city where a conversion is being made from a 110/33/11 kV system to a 110/22 kV system. A few electricity distributors in India also report limited use of 22 kV (although expanded use of 22 kV has been suggested for India's "smart cities").

D. MV Safety Clearances

8. In general, the design of 22 kV overhead lines is very similar to that of 11 kV lines, the key difference being the need for increased safety clearances as shown in Table A4. Consequently, a new 22 kV construction would require taller poles and wider cross arms than currently used for 11 kV.

Table A4: Comparison of Safety Clearances

Statistic	11 kV	33 kV	22 kV [a]	35 kV
Minimum clearance above ground (m)				
Roads	5.8	6.1	8.0	8.0
Footpaths	5.5	5.8	7.0	7.0
Other places	4.6	5.2	5.5	5.5
Separation between phases (m)				
Horizontal	0.55	1	0.75	0.75
Vertical		1.25	1.5	1.5
Separation between circuits (m)	1.25	1.5	1.0[b], 2.0[c]	2.5[b], 3.0[c]
Safe working clearance (m)	1.25	3	4.0	4.0

[a] Some 22 kV values are same as the 35 kV values as advised by EVN.
[b] Bare wire.
[c] Covered wire.
Sources: 11 kV, 33 kV Nepal Electricity Authority; 22 kV, 35 kV EVN.

E. Conductor Ratings

9. Overhead line ratings shown in Table A5 were calculated at a conductor temperature of 65^{o}C and an ambient temperature of 25^{o}C.

10. Underground cable ratings assume three-core XLPE cables with aluminium conductors installed in ducts.

Table A5: Conductor Thermal Ratings

Conductor		11 kV	22 kV	33 kV
Underground Cables				
300 mm^2	*(A)*	365.0	370.0	370.0
	(MVA)	7.0	14.1	21.1
400 mm^2	*(A)*	420	425.0	440.0
	(MVA)	8.0	16.2	25.1
500 mm^2	*(A)*	475.0	495.0	500.0
	(MVA)	9.0	18.9	28.6
Overhead Lines				
31.6 mm^2 (Weasel)	*(A)*	164.0	164.0	164.0
	(MVA)	3.1	6.2	9.4
52.9 mm^2 (Rabbit)	*(A)*	225.0	225	225.0
	(MVA)	4.3	8.6	12.9
105 mm^2 (Dog)	*(A)*	345.0	345.0	345.0
	(MVA)	6.6	13.1	19.7

Source: CTC Global’s Conductor Comparison Program (CCP) version 2.5.0; Nexan Olex.