Analysis of Indian Electricity Distribution Systems for the Integration of High Shares of Rooftop PV

Final report

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

On behalf of:

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of the Federal Republic of Germany

Project

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Abbreviations

Abbreviation	Full term	Explanation
A/C	Air conditioning	
ACSR	Aluminium conductor steel reinforced	Most widely used conductor type for overhead lines
BRPL	BSES Rajdhani Power Limited	Distribution company in Delhi
BSES	Bombay Suburban Electric Supply	Mother company of distribution companies in Delhi and Uttar Pradesh
CEA	Central Electricity Authority	
CERC	Central Electricity Regulatory Commission	
CPUC	California Public Utilities Commission	Californian regulator
DERC	Delhi Electricity Regulatory Commission	Delhi SERC
DISCOM	Distribution company	Company acting as distribution grid operator and retailer in India
DSM	Demand Side Management	
DSO	Distribution system operator	In India, there are usually no separate DSOs, DISCOMs act as both DSO and retailer
DT	Distribution transformer	Indian terminology: 11/0.4 kV transformer
DT-SS	DT substation	Indian terminology: 11/0.4 kV substation
EHT	Extra high tension	Indian terminology: $V \geq 33$ kV
EHT-SS	EHT substation	Indian terminology: 66/11 kV or 33/11 kV
EHV	Extra high voltage	European terminology: $V > 300$ kV
FIT	feed-in tariff	
HAT	High tension	Indian terminology: $V < 33$ kV
HV	High voltage	European terminology: 50 kV $\leq V <$ 300 kV
IEA	Internantional Energy Agency	
IRENA	International Renewable Energy Agency	
LCOE	Levelized Cost of Electricity	Average per unit cost of generated energy over the lifetime of the generation uint
LT	Low tension	Indian terminology: $V < 250$ V (also used for 0.4 kV feeders)
LV	Low voltage	European terminology: $V < 1000$ V
MNRE	Ministry of New and Renewable Energy	

MPERC	Madhya Pradesh Electricity Regulatory Commission	Madhya Pradesh SERC
MPMKVVCL	Madhya Pradesh Madhya Kshetra Vidyut Vitaran Company Limited	Distribution company in Bhopal
MPPT	Madhya Pradesh Power Transmission Co. Ltd	Subtransmission grid operator in Madhya Pradesh
MT	Medium tension	Indian terminology: V < 650 V
MV	Medium voltage	European terminology: 1000 V ≤ V < 50 kV
NIWE	National Institute of Wind Energy	
NLDC	National Load Dispatch Center	
OHL	overhead line	
OLTC	on-load tap changing	OLTC transformers can change their ration without being switched off
PGCIL	Power Grid Corporation of India, Ltd.	National transmission grid operator
POSOCO	Power System Operation Corporation	Power system and dispatch operator, subsidiary of PGCIL
PPA	Power Purchase Agreement	Contract between utility and generator owner
PT	Power transformer	Indian terminology: Transformer above 11 kV level
PV	photovoltaic	
RLDC	Regional Load Dispatch Center	
RPO	Renewable Purchase Obligation	Obligation for a DISCOM to purchase a certain amount of renewable energy
SCADA	Supervisory Control and Data Acquisition	
SERC	State Electricity Regulatory Commission	
SLDC	State Load Dispatch Center	
SLDC	single line diagram	
TN	Terre neutre	Low voltage / low tension grid with earthed transformer neutral
TSO	Transmission system operator	
UPS	uninterruptible power supply	fast reacting battery unit used by the customer to supply himself during outages
XLPE	cross-linked polyethylene	Material used for cable insulation

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1. Introduction

Under the current national target based on National Solar Mission, 40 GW of rooftop PV shall be connected in India by 2022. To reach this target, a good understanding of the Indian power system, its regulatory frameworks, and the similarities and differences with other countries that have already deployed a large share of rooftop PV has to be developed by all stakeholders involved in the process.

Under the Indo-German technical cooperation, Government of Germany is cooperating with India and has commissioned a project "Integration of Renewable Energies in the Indian Electricity System (I-RE)" through the International Climate Initiative of the German Government. The project is financed by Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) and implemented by Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ) in partnership with Ministry of New and Renewable Energy (MNRE). Considering the need for extensive capacity building in India, GIZ has commissioned Energynautics to conduct this study on the integration of rooftop solar PV into Indian distribution grids at the voltage levels of 33, 11 and 0.4 kV. Starting out with a desktop study on the characteristics and peculiarities of the Indian power system and its regulatory framework, and a comparison to other countries where PV integration has already progressed further, the scope of the study also includes detailed modelling and simulation of four different distribution grid feeders in Delhi and Bhopal. Data for the simulations were kindly provided by the local distribution companies, BSES Rajdhani Power Limited (BRPL), Delhi and Madhya Pradesh Madhya Kshetra Vidyut Vitaran Company Limited (MPMKVVCL), Bhopal.

The study intends to provide an overview of the characteristics of the Indian power system and its problems with regard to a large scale rooftop PV rollout, as well as a template for distribution companies on how to deal with rising PV shares, which studies to conduct and which technology options to select.

2. Characteristics of Indian distribution systems

2.1 Indian Distribution grids

2.1.1 Ownership and operation

The Indian power system has been unbundled since the Electricity Act of 2003 was signed into force. The Act was intended to grant fair and equal access to grids, market and infrastructure to all stakeholders and separated ownership and operation of transmission, distribution and generation [1]. More than 95 % of the Indian transmission and distribution sector still remain publicly owned as of 2016 [2][3], while more than 40 % of generation capacity belongs to independent power producers.[4]

Distribution grids (66 kV and below) in India are owned by the State Electricity Boards. Distribution companies (DISCOMs) are licensed to act as grid operators and retailers at the same time. These companies are in many cases owned by the State Electricity Board themselves, however, some are in private hand, or owned by the municipality, or owned by public-private joint ventures [3].

The DISCOMs are required to develop and maintain an efficient, coordinated and economical distribution system in their area of supply and to supply electricity in accordance with the provisions of the Electricity Act 2003 and its amendments. Hence, DISCOMs are responsible to approve connections to the distribution grid and metered generation and consumption. DISCOMs handle applications for new projects and will approve them based on the technical details of the installation. They are also in charge of the enforcement of compliance with legislation, technical and regulatory frameworks of generators feeding into the distribution grid.

Distribution companies are separate from the transmission companies, which exist both at state and regional level (for the majority of the 132 kV sub-transmission grids and some 220 kV and 400 kV grid sections) and national level (Power Grid Corporation of India Ltd, for inter-state transmission at 132 kV and above). Power Grid Corporation of India Limited (PGCIL), which is the central transmission utility, is responsible for the interstate transmission system and coordinates its planning with the different state transmission utilities. PGCIL operates the system via its subsidiary Power System Operation Corporation (POSOCO, system operation and monitoring), with the National Load Dispatch Centre (NLDC), Regional Load Dispatch Centres (RLDC) and the State Load Dispatch Centres (SLDC).

2.1.2 Topology

Distribution grid structures vary significantly across India, as to be expected due to the sheer size of the country. However, the most common distribution grid topologies are described in the following.

Primary distribution is typically handled at 66 kV and/or 33 kV level or both, referred to as extra high tension (EHT) level by the DISCOMs[1]. The primary distribution system is supplied by an on-load tap changing transformer that steps voltage down from the 220 kV transmission, or more often, the 132 kV sub-transmission level. This is the last active instance of voltage control. The distribution grid company takes over operations from the secondary side of the transformers and has no own means of controlling the voltage dynamically. This means that Indian distribution grids are, similar to the structures found in most countries before the introduction of distributed generation, generally designed as unidirectional grids. Voltage at

1 Indian terminology is different from the terminology used in European power systems, where extra high voltage would refer to voltages above 300 kV.

the secondary winding of the power transformer is set to a value above 1.0 p.u. to account for voltage drops across the distribution system. The primary distribution grid is usually set up with radial or open ring topology, while meshed grids are rare. Large industrial customers may be connected directly to 33 kV or above in some cases.

Secondary distribution takes place mainly at 11 kV, referred to as high tension (HT). Connected to the higher voltage level via transformers with manual tap changers (if at all), the only means of voltage control at this level may be reactive compensation in the form of condenser banks in areas with voltage drop issues. Power transformers supplying the 11 kV grid are rated with up to 20 MVA (if coming from a 66 kV grid), usually supplying several radial feeders or open rings. 11 kV feeders may only be 1 – 3 km long in the cities, but range up to more than 20 km in rural areas, often requiring reactive compensation in the latter case.

66 kV, 33 kV and 11 kV grids consist of overhead lines in most areas, but cabled sections, especially 11 kV, are also not uncommon in larger cities.

Residential customers are supplied either with 400 V three phase or 230 V single phase systems, referred to as low tension grids (LT.) 400 / 230 V feeders are usually a few hundred meters long at maximum to avoid overly high voltage drops and losses. Distribution transformers supplying multiple LT feeders at once exist in various sizes, as they do in most countries. Rural distribution transformers (DT) may be rated at less than 100 kVA, while the largest urban substations are rated at 1250 kVA and above and equipped with multiple transformers in parallel.

Large customers (industrial, commercial or institutional) may have to be connected directly to the 11 kV grid if their peak load exceeds a certain value. 100 kVA is a typical limit (used for example in Delhi and Gujarat), while other states set the limit at 75 kVA (Madhya Pradesh), 63 kVA (Uttar Pradesh) or 50 kVA (Rajasthan.) The limit is defined in each state's supply code as published by the SERC.

Table 1: Distribution grid voltage levels in India.

Level	Transformer	Rating	Cable/OHL	Topology
66 kV	132/66 kV OLTC	20-100 MVA	OHL	Radial, ring, meshed
33 kV	132/33 kV OLTC	20-60 MVA	OHL	Radial, ring
11 kV	66/33/11 kV off or on load tap changer	5-20 MVA	OHL, cable	Radial, ring
1.1 – 6.6 kV	Various voltage levels between 1.1 and 11 kV are occasionally / rarely used			
400 V	11/0.4 kV off-load tap changer	< 1.5 MVA	Cable, OHL	Radial
230 V		< 100 kVA	Cable, OHL	Radial

2.1.3 Losses

Transmission and distribution losses in the Indian power system have been notoriously high, reaching a peak of 28 % of total generated energy in the early 2000s and being reduced to still high values of around 18 – 19 % by 2015 (see Figure 1.) Losses vary by state (see Table 2), with some being below 10 %, while some more politically and economically unstable areas have regularly exceeded 50 % of losses in the last years.

Technical losses are high due to aging equipment, long lines and bad design in places, but the majority of losses are non-technical. Non-technical losses are caused by various forms of electricity theft, such as tapping lines, tampering with meters, bribing the inspectors that read out the meters, or by neglect on the part of the distribution company, such as connecting customers without metering, installing broken or low-quality meters, or failing to regularly read out the meters. Both causes are widely spread in India, with theft being the cause for the majority of non-technical losses.

Figure 1: Total transmission and distribution losses in India in per cent of total generated electricity from 1971 to 2015.[2]

Table 2: Losses (in %) by utility, 2012-15. [5]

Details of state-wise and Utility-wise AT&C losses for 2012-13 to 2014-15					
Region	State	Utility	2012-13	2013-14	2014-15
Eastern	Bihar	BSEB	59.40		
		NBPDCL	50.85	41.93	41.76
		SBPDCL	45.77	48.70	45.28
	Bihar Total		54.64	46.33	43.99
	Jharkhand	JSEB	47.49	26.30	
		JBVNL			47.01
	Jharkhand Total		47.49	26.30	47.01
	Sikkim	Sikkim PD	53.51	71.23	42.37
	Sikkim Total		53.51	71.23	42.37
	West Bengal	WBSEDCL	34.43	32.05	35.35
	West Bengal Total		34.43	32.05	35.35
	Odisha	NESCO	39.61	36.47	38.36
		SESCO	49.36	41.18	42.57
		WESCO	41.87	41.24	41.03
		CESU	43.43	38.48	37.08
	Odisha Total		42.88	39.19	39.28
Eastern Total			42.04	36.24	39.64
North Eastern	Arunachal Pradesh	Arunachal PD	60.26	68.20	67.83
	Arunachal Pradesh Total		60.26	68.20	67.83
	Assam	APDCL	31.85	30.25	26.00
	Assam Total		31.85	30.25	26.00
	Manipur	Manipur PD	85.49	43.55	
		MSPDCL			49.62
	Manipur Total		85.49	43.55	49.62
	Meghalaya	MePDCL	41.71	39.77	34.69
	Meghalaya Total		41.71	39.77	34.69
	Mizoram	Mizoram PD	27.55	32.53	33.51
	Mizoram Total		27.55	32.53	33.51
	Nagaland	Nagaland PD	75.30	38.37	78.48
	Nagaland Total		75.30	38.37	78.48
	Tripura	TSECL	34.45	41.81	38.02
	Tripura Total		34.45	41.81	38.02
North Eastern Total			39.97	35.92	35.29
Northern	Delhi	BSES Rajdhani	15.16	16.19	10.76
		BSES Yamuna	17.94	15.51	19.68
		TPDDL	13.12	9.75	10.31
	Delhi Total		15.22	14.09	12.90
	Haryana	DHBVNL	28.31	30.89	30.71
		UHBVNL	36.97	38.61	34.83
	Haryana Total		32.55	34.33	32.52
	Himachal Pradesh	HPSEB Ltd.	11.90	14.82	15.21
	Himachal Pradesh Total		11.90	14.82	15.21
	Jammu & Kashmir	J&K PDD	60.87	49.14	59.04
	Jammu & Kashmir Total		60.87	49.14	59.04
	Punjab	PSPCL	17.52	17.87	17.56
	Punjab Total		17.52	17.87	17.56
	Rajasthan	AVVNL	19.90	22.06	28.13
		JDVVNL	18.97	25.71	26.99
		JVVNL	20.91	31.08	32.00
	Rajasthan Total		20.00	26.77	29.28

2 Data taken from IEA Statistics (http://www.iea.org/statistics/statisticssearch/), graphic by World Bank.

	Uttar Pradesh	DVVN	45.69	36.47	40.18
		KESCO	37.61	34.29	32.02
		MVVN	45.83	14.43	35.18
		Pash VVN	33.39	23.49	22.19
		Poorv VVN	52.37	20.09	42.91
	Uttar Pradesh Total		42.85	24.67	33.82
	Uttarakhand	Ut PCL	23.18	19.01	18.82
	Uttarakhand Total		23.18	19.01	18.82
Northern Total			28.89	24.86	28.06
Southern	Andhra Pradesh	APCPDCL	15.64	17.54	
		APEPDCL	10.15	6.57	7.67
		APNPDCL	13.09	20.80	
		APSPDCL	12.74	11.77	12.01
	Andhra Pradesh Total		13.70	14.77	10.55
	Karnataka	BESCOM	20.45	18.93	17.59
		CHESCOM	30.42	33.92	21.64
		GESCOM	18.28	30.45	21.25
		HESCOM	20.44	20.42	19.49
		MESCOM	14.57	14.83	15.72
	Karnataka Total		20.78	22.02	18.71
	Kerala	KSEB	12.32	11.45	
		KSEBL		22.99	17.64
	Kerala Total		12.32	16.48	17.64
	Puducherry	Puducherry PD	9.13	16.18	16.64
	Puducherry Total		9.13	16.18	16.64
	Tamil Nadu	TANGEDCO	20.71	22.35	24.74
	Tamil Nadu Total		20.71	22.35	24.74
	Telangana	TSNPDCL			16.49
		TSSPDCL			11.91
	Telangana Total				13.23
Southern Total			17.40	19.08	18.22
Western	Chhattisgarh	CSPDCL	25.12	23.17	27.84
	Chhattisgarh Total		25.12	23.17	27.84
	Goa	Goa PD	14.14	10.72	13.31
	Goa Total		14.14	10.72	13.31
	Gujarat	DGVCL	10.40	10.83	10.81
		MGVCL	14.94	14.77	11.47
		PGVCL	30.41	24.12	25.18
		UGVCL	14.37	9.10	10.21
	Gujarat Total		19.87	15.93	16.06
	Madhya Pradesh	MP Madhya Kshetra VVCL	29.97	29.60	32.47
		MP Paschim Kshetra VVCL	28.16	21.15	30.79
		MP Purv Kshetra VVCL	36.40	34.83	27.09
	Madhya Pradesh Total		31.15	28.03	30.26
	Maharashtra	MSEDCL	21.95	14.39	19.75
	Maharashtra Total		21.95	14.39	19.75
Western Total			23.36	18.37	21.59
Grand Total			25.48	22.58	24.62

2.1.4 Tariff system and philosophy

Consumer tariffs in India are a somewhat complex issue, as they are subject to state regulation and include different types of subsidies and exemptions for consumers that live below the poverty line, rural consumers, farmers and others. However, almost all states charge higher tariffs from large industrial or commercial consumers than from small consumers to allow access to cheap electricity for residents.

For the electricity distribution segment, the SERCs are currently entrusted with the responsibility of fixing the retail tariffs in accordance with the National Tariff Policy 2006 and as per the provisions of the Electricity Act 2003. The tariff is set based on the estimated Annual Revenue Requirement (ARR) of the DISCOMs in a financial year. The ARR comprises the sum total of power purchase cost (or cost of generation in case of licensee-owned power station), cost of capital, operational and maintenance cost, depreciation, interest on working capital, provision for tax, etc., followed by adjustment with preceding year's unaccounted expenses or revenue gaps.

Electricity prices are comprised of a fixed charge (power price) that is determined by the monthly maximum demand, and an energy charge for each used kWh[3]. The consumers are also loaded with electricity tax and adjustment tariff. Moreover, the varying fuel cost adjustment (FCA) charges is another burden for customers. Typically, prices will go up as consumption and load rise, both for the fixed charge and the energy charge. Tariffs for residential customers in Delhi are given in Table 3. The tariffs charged from non-residential customers are substantially higher, starting from a fixed charge of 80 Rs/kW/month and an energy charge of 845 Paisa/kWh for small sanctioned load and demand and rising from there.

Table 3: Electricity tariff structure for residential customers in Delhi 2015-16.[4]

	CATEGORY	FIXED CHARGES[1]	ENERGY CHARGES[2]
1	DOMESTIC		
1.1	INDIVIDUAL CONNECTIONS		
A	Up to 2 kW Sanctioned Load		
	0-200 units	40 Rs/month	400 Paisa/kWh
	201-400 units	40 Rs/month	595 Paisa/kWh
	401 – 800 units	40 Rs/month	730 Paisa/kWh
	801-1200 Units	40 Rs/month	810 Paisa/kWh
	Above 1200 Units	40 Rs/month	875 Paisa/kWh
B	Between 2kW and 5 kW Sanctioned Load		
	0-200 units	100 Rs/month	400 Paisa/kWh
	201-400 units	100 Rs/month	595 Paisa/kWh
	401-800 units	100 Rs/month	730 Paisa/kWh
	801-1200 Units	100 Rs/month	810 Paisa/kWh
	Above 1200 Units	100 Rs/month	875 Paisa/kWh
C	Above 5 kW Sanctioned Load		
	0-200 units	25 Rs /kW/month	400 Paisa/kWh
	201-400 units	25 Rs /kW/month	595 Paisa/kWh
	401-800 units	25 Rs /kW/month	730 Paisa/kWh
	801-1200 Units	25 Rs /kW/month	810 Paisa/kWh
	Above 1200 Units	25 Rs /kW/month	875 Paisa/kWh

This structure may in the long run lead to economic issues with PV integration. The DISCOMs draw most of their revenue from large customers, and industry and commerce implicitly subsidize resident customers that pay lower prices. The high tariffs incentivize industrial and commercial customers to connect PV systems under net metering schemes, as power from such units will be cheaper than the power bought from the grid. Development is picking up quickly, as these types of customers typically have the cash available for the upfront investment needed to install a PV unit. This is favorable for India's PV targets, but may turn out to be very challenging for the DISCOMs, as demand from highly charged customers shrinks while demand from residents paying low tariffs is expected to grow. A restructuring and rationalization of tariffing regimes may be necessary to accommodate the changes in the system. Especially with DISCOMs often purchasing power via long term contracts with time frames up to 20 years, this may be a significant barrier to PV integration and the improvement of supply quality in general.

2.2 Regulatory framework

2.2.1 Federal and state governance and regulation

Electricity is a concurrent subject of the seventh Schedule of the Constitution of India. The Indian power system is governed by various government agencies both at federal and state level.

3 Energy is typically measured in "units", one unit being equivalent to one kWh.
4 Tariff schedule of Delhi DISCOMs BRPL, BYPL & TPDDL, as published for the fiscal year 2015-16.

The Ministry of Power is in charge of the overall institutional setup. It is primarily responsible for perspective planning, development of strategies, policy formulation and enactment of legislation with regards to thermal and hydropower generation, and transmission and distribution.

The Ministry of New and Renewable Energy (MNRE) is the nodal ministry responsible for all matters relating to new and renewable energy. The ministry was established with the goal of developing and deploying new and renewable energy for supplementing the energy requirements of the country. MNRE has set the target of installing a PV capacity of 100 GW (40 GW of which will be distributed rooftop) by 2022.

The Central Electricity Authority (CEA) formulates the National Electricity Plan every five years in accordance with the National Electricity Policy, and conducts regular revisions of the document. CEA also specifies the technical standards and safety requirements for power systems.

The Central Electricity Regulatory Commission (CERC) is the federal regulator. There are state regulatory commissions working in tandem with central regulator. The CERC regulates the tariffs of generating companies owned by government entities and private sector. For this, the commission is required to notify regulations, grant licenses and formulate a tariff setting mechanism. As entrusted by the Electricity Act, 2003, CERC has the responsibility to regulate the tariff of generating companies, regulate and determine the tariff for inter-state transmission, issue licenses for transmission and electricity trading, specify Grid Code with regard to Grid Standards and specify and enforce standards with respect to quality, continuity and reliability of service. CERC also advises on the formulation of National Electricity Policy and Tariff Policy with the intention to promote competition in the power market to boost economic efficiency, improve quality of supply, promote least cost investments and thus foster the interests of consumers.

The State Electricity Regulatory Commissions (SERC) have full autonomy in drafting their own regulations, but mostly stick to adding local context to CERC regulations. SERCs are primarily responsible for regulating state generation, transmission and distribution tariffs, provide directions for system planning, enabling necessary conditions for development of a market, adjunction of disputes and improving access of electricity at the state level.

In case of rooftop solar systems the SERCs in each state lays down the detailed guidelines and procedure for grid connectivity and metering with the provision of net metering arrangement and/or feed-in-tariff mechanism. This includes the detailed technical grid code requirements. These directions have to be followed by the respective DISCOM.

A summary the governance level, relevant institutions and their respective regulatory orders with respect to governing distributed grid connected PV systems are summarized in Table 4.

Table 4: Governing regulatory frameworks

Governance Level	Governing Bodies	Regulatory Order
Federal	Forum of Regulators	· Draft Model Regulations for grid tied rooftop solar based on Net Metering, (August 2013) · Model Regulations on Forecasting, Scheduling and Deviation Settlement of Wind and Solar Generating Stations at the State level
	Central Electricity Authority (CEA)	· Technical Standards for connectivity of Distributed Generating Resources, Regulations, 2013 · Installation and Operation of Meters, Regulation 2006 (2nd amendment 2014) · Measures of Safety and Electricity Supply, Regulations, 2010
	CERC	· REC regulations and RE Tariff Regulations for renewable energy
State	State Electricity Regulatory Commission (SERC)	· Net Metering regulations, Solar tariff order, RPO regulations, State Metering Regulations, State Supply Code, Grid code (Over the past one year around 16 SERCs have issued regulations for solar rooftop in their jurisdiction.)

2.2.2 Policies and regulations specific to developing solar generation capacity in India

The Indian Government has announced a series of policy measures to promote solar energy and develop a self-sustaining market. There have been direct and indirect tax benefits, excise duty exemptions and custom duty exceptions provided to renewable energy including solar energy. This includes income tax deferments from all earnings in the first 10 years of operation of a PV unit and accelerated depreciation up to 80% of the project cost for solar energy in the first year itself.

2.2.3 Metering and incentives for rooftop solar PV

A. Metering

For rooftop solar two different types of metering arrangements are possible: gross and net metering. Whereas a net metering mechanism includes a compensation for the electricity generated by the PV system by definition, gross metering is just a way of measuring the generated energy which is usually used when PV electricity is compensated for on a feed-in tariff basis. In a gross metering mechanism, the entire energy generated by rooftop solar PV system is fed directly into the electrical grid and the system owner is benefited based on the sale of power. Typically, this includes priority dispatch and a purchase obligation by the utility, meaning that each generated unit of energy has to be compensated for. The regulatory framework in India for the gross-metering based renewable projects (including solar) has been evolving over the years. Some very early rooftop PV units were connected under gross metering / feed-in tariff agreements, but today, the mechanism is used only for free field utility scale PV installations.

Under a net metering mechanism, the rooftop PV unit is connected to the network of the distribution licensee through a bi-directional metering setup either consisting of a single bidirectional meters or two different meters for consumption and generation. If load exceeds generation, the meter records demand, charging the customer for the electricity drawn from the grid. If generation exceeds load, however, the meter "spins backwards", deducting the excess generation from the recorded value. At the end of a charging period, the customer is charged for the net value of total consumption minus total generation, hence the term net metering. The customer can thus "store" generated energy in the grid for later consumption.

It is important to understand that a grid connected net-metering arrangement requires a well-defined regulatory and commercial framework. As per the present scenario, almost all 30 Indian states and Union Territories have net metering policy and other support mechanism to promote grid connected distributed PV systems. Policy and support mechanism vary in detail from state to state.

B. Incentives

Not necessarily obvious at the first glance, net metering presents an incentive for solar PV in itself. If connected under a net metering agreement, the unit owner is granted to always receive the same price for each generated unit he would pay for one drawn from the grid. As retail prices are considerably higher than wholesale prices, net metered PV is thus given an advantage over other generators that have to compete in the wholesale power market. However, net metering will only incentivize investments if the levelized cost of electricity (LCOE) of a unit generated by PV is lower than the current retail electricity price.

In context of India it has been understood that additional fiscal benefits like capital subsidy, tax credits, and generation based incentives can be provided to net-metering projects with an objective to bridge the gap between the cost of energy generated from rooftop solar system and retail tariff applicable on distribution utility consumer. For an adequate selection of such incentives, decision factors like the impact on project viability and financing, ease of disbursement and a robust monitoring framework to assess operational success have to be evaluated.

Net-metering based arrangements in India are primarily aimed at encouraging self-consumption by the consumer, albeit allowing the customer to store excess energy in the grid, or sell it to the DISCOM. The choice of incentive is thus dependent on the extent to which surplus energy is permitted to be exchanged with the grid and the price at which surplus over a settlement period is to be exchanged. Net-metering arrangement for a consumer primarily offsets power consumption from the grid and therefore compensates the owner of the rooftop system for solar energy consumption at the applicable retail tariff for the consumer category. The net meter arrangement may have a single, double or a three meter system. For multiple (2 or 3) meter systems, DISCOM has to recognize all the installed meters for commercial settlements.

When tariffs in a consumer category are lower than tariffs typically expected by rooftop solar system developers, some additional incentive has to be provided to promote rooftop PV. Such incentives for net metered based arrangements will need to vary across consumer categories and from state to state, as retail tariffs are different across categories and across states.

2.2.4 Regulation dealing with technical and safety aspects of distributed generation

Interconnection frameworks for net-metering based rooftop solar PV need to address minimum technical standards for interconnection and capacity of the system that can be connected to the grid. The cumulative capacity to be allowed by a distribution utility under the net metering arrangement also needs to be specified. There are three regulations by which CEA outlines the technical and safety requirements for distributed generation to be adhered to by DISCOMs and owners of distributed generation system.

- The CEA's Technical Standards for Connectivity of the Distributed Generation Resources [6][7] are applicable to any generating station feeding electricity in to the electricity system at voltage level below 33 kV. The CEA regulations cover the roles and responsibilities of the developer/ system owner and of the Distribution Company, the equipment standards and codes of practice, and the system requirements for safe voltage, frequency, harmonics, etc.
- The CEA's Installation and Operation of Meters regulation from 2006 (amendment in November 2014 includes distributed solar generation) [8] regulates metering standards.
- The CEA's Measures of Safety and Electricity Supply, 2010 [9] govern safety for generators. The CEA regulation 'Technical Standards for Connectivity of the Distributed Generation Resources' Regulation 2013 mentions that safety standards should be in accordance to this code. However, these safety codes are aligned more towards large scale thermal power plants as opposed to small distributed solar PV installations. In addition, states in India have also prescribed some technical requirements for distributed solar PV through government policies, and regulations brought out by the SERCs.

CEA follows standard IEEE 519 which addresses the limitations for current and voltage harmonic contaminations through Individual Harmonic Limits and Total Harmonic Distortion (THD) limits. The voltage distortion limit established by the standard for general systems is 5 % THD. In this standard, the Total Demand Distortion (TDD), determined by the ratio of available short circuit current to the demand current (I_{SC}/I_L), is used as the base number to which the limits are applied. There are specific limits mentioned for various harmonics for different TDD values. The actual measurement that are taken using a harmonic analyzer is a snapshot and provides an instantaneous measurement that is referred to as THD.

India also adopts IEEE 519 on similar lines of Australia and the USA (see Table 5). The present harmonics standard in India is adequate and in line with the best global practices. Additionally, the adoption of IEEE 519 is not a major economic or technical hurdle for the inverter manufacturers to incorporate into their systems.

Table 5: Limits for harmonic distortion as set by IEEE 519 (2014.)

Bus voltage V at PCC	Individual Harmonic (%)	Total Harmonic Distortion THD (%)
V ≤ 1.0kV	5.0	8.0
1kV < V ≤ 69kV	3.0	5.0
69kV < V ≤ 161kV	1.5	2.5
161kV < V	1.0	1.5

As per the CEA (Technical Standards for Connectivity to the Grid) Amendment Regulations, 2013 (Part II, Connectivity Standard applicable to the generating stations, clause B1, sub-clause 2), the following further requirements are applicable to distributed PV:

- The generating station shall not inject DC current greater than 0.5% of the full rated output at the interconnection point.
- The generating units shall be capable of operating in the frequency range of 47.5Hz to 52Hz and shall be able to deliver rated output in the frequency range of 49.5Hz to 50.5Hz.
- Provided that above performance shall be achieved with voltage variation of up to ±5%.

Moreover, DISCOMs like Delhi and Madhya Pradesh are designing and operating the distribution system in conjunction with the Transmission system. The electricity supply codes of Delhi and Madhya Pradesh clearly states the permissible voltage variation for different voltage levels. These are:

- ± 10 % for low tension (0.4 kV) grids;
- + 6 % and - 9 % for high tension grids (below 33 kV);
- ± 10 % for extra high tension grids (33 kV – 220 kV);
- + 5 % and - 10 % for 400 kV grids and above.

2.3 Comparison with other country study cases

2.3.1 Overview of country study cases

The purpose of this section is the comparison of the Indian case to four study cases of countries that display similar system characteristics, high shares of distributed PV, or both. The study cases and the reasons for their consideration are the following:

- Germany: As one of the first countries to roll out a large scale PV integration scheme, the case of Germany should always be studied when discussing PV. While both the incentive scheme and the system structure differ from India, valuable lessons can be learned from the issues that have arisen in the German system in the past decade.
- California: Currently being the leading state in PV integration in the US with the majority of PV being roof mounted, California is an interesting case for different reasons. The diversity of distribution grid structures in California resembles the Indian case more closely than the German case. Unusual for an early adopter of PV, California employs a feed-in tariff system as the main incentive, with other subsidies supporting it.
- Australia: Australia has experienced a rapid growth in rooftop PV installations in the last few years. The general structures of the distribution grid topology are similar to those found in India, however, the incentive structure for PV is much different and worth studying.

- Brazil: Like India, Brazil is a rapidly developing large country with quickly growing electricity demand, experiencing similar issues with weak grids and high technical and non-technical losses. The country does not have a large share of rooftop PV yet, but aims to increase the installed capacity to diversify the generation fleet, however, the target for 2024 is much lower than that of India.

Table 6: Power system overview for each country study case.

	India	Germany	California	Australia	Brazil
Peak load [GW]	148 (2016)	81.7 (2014)	47.3 (2015)	32.9 (2015)	60 (2015)
Minimum load [GW]	Ca. 80 (2016)	36.7 (2014)	16 (2015)	14.9 (2014)	unavailable
Yearly demand [TWh]	1090 (2016)	505 (2014)	259.5 (2015)	197.6 (2015)	463.3 (2015)
Conventional[1] generating capacity [GW]	264 (2016)[2]	108 (2014)	80 (2015)	47.25 (2015)	133.9 (2015)
Dominating primary energy (conventional)	Coal, hydro	Coal, nuclear	Natural gas	Coal, natural gas	Hydro, natural gas
Total PV capacity [GW]	9 (2016)	41.3 (2016)	5.5 (2015)	5.5 (2015)	0.021 (2015)
Rooftop PV capacity [GW]	Ca. 1 (2016)	Ca. 24 (2016)	Ca. 4 (2016)	Ca. 5 (2015)	0.016 (2015)
Targets for rooftop PV	40 GW by 2020	+2.5 GW annually, 52 GW total[3]	1 million units by 2017	33 TWh p.a. total ren. generation by 2020	7 GW by 2024

2.3.2 National renewable energy targets

Renewable energy policies and targets form the basis on which incentives are set and development of renewable energy is promoted in a country. There are different approaches to setting renewable energy targets. Some countries set a certain amount or percentage of electricity that has to be generated from renewable energy annually for a certain date, and leave the exact specifics up to economic development and incentives. Others have much more specific goals, with individual targets set for each technology. As renewable energy policy is a publically much discussed topic, governments may have different ways of communicating renewable energy targets depending on what they believe can gather the most public support. This may take on the form of the targets being communicated in the form of installed capacity in countries like India where a shortage of generation capacity is prominent, or in the form of a certain number of installations for rooftop PV intended to gather support from private citizens (current targets in Australia, or the 1000 (later 100,000) roof program in Germany in the 1990s.) However, there are always some underlying assumptions on installation size and capacity factor. If these and the expected demand development are known, renewable energy targets can always be expressed in a percentage of yearly generated energy.

The role of large scale hydropower in renewable energy legislation is somewhat controversial. Hydroelectric power plants are of course a form of renewable generation, but their environmental impact (including the emissions of methane, a greenhouse gas more potent than carbon dioxide, from hydro reservoirs especially in tropical regions), their long history and their economic comparability with conventional generation sometimes lead to them not being included in national renewable energy targets. As some countries, like Brazil, have huge hydro potential, and others, like Germany, have absolutely none, it may make sense to look at the targets for "new" renewable energy such as PV, wind, biomass and small hydro only for a better comparison.

Germany has vowed to generate at least 50 % of electricity from renewable energy by 2030 and 80 % by 2050 [10], California originally intended to reach a 33 % share by 2030 but has revised it to 50 % [11]. Australia wants to generate 33 TWh p.a. from renewable energy by 2020, meaning a 16.5 % share [12], Brazil is shooting for 89 % by 2030, of which 66 % are expected to be hydro [13][14]. India has committed to raise its current renewable electricity share of 15 % to 60 % of installed capacity by 2030 [15]. This includes large hydropower projects, but also a large share of wind and PV power. Targets are expected to boost the share of new renewable energy (excluding large hydro) from around 7 % today to 19-22 % in 2022, depending on load development. Around 8 % will come from the PV part only.

In comparison to other countries, India's renewable energy targets in total are ambitious, but not overly so. However, what is different from the other study case countries is the projected speed of development. While Germany is approaching its 50 % target for 2030 with a 30 % share already – that took 20 years to implement – India is looking at a huge capacity increase within a very short time frame without much experience in the sector. That does not mean that the targets are unrealistic, as installation cost has dropped, there is considerable investor interest, and India is a very large country. It simply indicates that development (including revisions of regulations and incentives) and the studies that go with it has to be kick-started very quickly to reach the official targets.

2.3.3 Incentives

As of 2017, small scale PV power is still slightly more expensive than the wholesale market prices commanded by large conventional generation [16], requiring some type of incentive to draw investments. These can take the shape of investment subsidies by the government, a granted feed-in tariff (FIT) over a certain period of time, a premium on the wholesale market price, or a net or gross metering scheme. The incentives used in the study case countries are given in Table 7.

Investment subsidies were given by most countries with ambitious PV targets at some point, but have expired or been reduced in the meanwhile in some cases as prices for PV installations dropped. Typical early adopter strategies in Europe involved high feed-in tariffs granted for a period of 15 to 25 years, granting a return on interest for the owner of the unit, while net metering schemes were and are more common outside of Europe. The FIT model proved to be very successful, with large capacities of PV eventually being installed especially in Germany, Italy and Spain. The same is true for Australia, which also has a FIT-based incentive model. This eventually brought down PV installation prices, which played a role in metering schemes picking up pace as well. Feed-in tariffs in most countries that use them have been reduced over time to reflect the dropping PV cost – a new PV unit in Germany would get around 0.50 €/kWh (ca. INR 34/kWh) in the early 2000s, while the tariff for one installed in 2016 is around 0.10 €/kWh (ca. INR 7/kWh) [17].

A net metering scheme will only be an incentive to install PV if grid parity is reached – it is then cheaper to produce the electricity with PV panels than to draw it from the grid.[5] Until about 2012, this was not the case in any major country[6], resulting in very slow development in countries with only a metering scheme. Some countries tried to compensate this with investment subsidies, but usually with limited success. However, as of 2016, where rooftop PV has either reached grid parity or is close to it, investment subsidies turn out to be a good incentive. California currently offers the choice between a granted feed-in tariff (the European model)[7] or an investment subsidy and a net metering scheme[8] (which is what is currently offered in India as well), with the latter becoming more popular with dropping PV prices[9].

5 It must be noted that a net metering scheme will still be an implicit subsidy, as PV generation does not have to compete with wholesale prices which are much lower, but with retail prices, which include the grid fees etc.

6 Grid parity may have been reached earlier in small island systems with extremely high power prices caused by a dependence on imported petroleum.

7 http://fit.powerauthority.on.ca/

8 http://www.gosolarcalifornia.ca.gov/solar_basics/net_metering.php

9 For example, Clean Energy Authority actually recommends customers with small systems to opt for net metering with investment subsidy instead of the FIT: http://www.cleanenergyauthority.com/solar-rebates-and-incentives/california/california-feed-in-tariff/

Table 7: Incentive structure for rooftop PV for each country study case.

	India	Germany	California	Australia	Brazil
Investment subsidy	Residential, social and institutional sectors	Expired	Only with net metering	Residential only	-
Feed-in tariff (gross metering)	Large centr. PV only	yes	optional	yes	-
Net metering	Most states	-	optional	-	yes
Premium on market price	-	optional[4]	-	yes	-

It should be noted that the initial investment for a PV unit may be a significant hurdle especially for customers in developing countries, even if the investment is granted to pay back. This is evident in the Brazilian case, where a net metering scheme has been introduced in 2013[10] and grid parity has been reached in many parts of the country, but a great uptake in PV installations has not taken place. Capital subsidies, which have just been re-introduced for residential, social and institutional customers in India, are expected to mitigate this issue.

2.3.4 Tariff systems

As indicated in the previous sections, in India, large customers have to pay higher electricity charges than small customers. This is a typical structure for developing countries where electricity retailers cross-subsidize potentially poor residential customers through financially stable commercial and industrial customers.

This is fundamentally different from the tariff structures found in wealthy, heavily industrialized countries such as the California [18], Germany [19] and Australia. [20] In all three, commercial and industrial customers pay lower rates than residential. In Germany, a large percentage of industrial customers is also exempt from the renewable energy charge which is used to pay the feed-in tariff for wind and PV.[21] There are several reasons for this type of structure, the primary one is that large customers with a steady baseload demand are able to negotiate better deals for their electricity supply. Lower tariffs for industry are often also state supported – for example through the exemption from the renewable energy charge – to stay competitive in a globalized economy.

Brazil, being a developing country as well, comes in in between. Industrial customers are charged less than urban residential customers, but rural areas with low income are heavily subsidized and charged even less.[11]

Especially if a net metering scheme is used to support PV, different tariffing philosophies will have an impact on PV development. Typically, those customer groups paying the highest rates will reach grid parity for PV first and start investing. In California, this was the residential sector, while rooftop PV development in India was primarily focused on commercial and industrial customers paying high electricity rates in the last years. This is currently being offset by the 30 % capital subsidy for PV granted to residential customers, possibly shifting PV development towards that sector.

Notably, California will introduce variable pricing for residential customers by 2019, where rates are lower during times of high supply and low demand, and vice versa. Similar strategies have been employed in Germany and France since the 1960s: The use of electric storage heating was encouraged, and heaters got a special low tariff to charge during the night, to shift heating demand from the day to the night, smoothening the load curve and making it easier to deal with for a baseload optimized generator fleet based on coal and nuclear. Australia still employs a

10 http://www.enelsolucoes.com.br/blog/2016/06/entenda-o-sistema-de-compensacao-de-energia-eletrica/
11 Agência Nacional de Energia Elétrica (Brazilian Electricity Regulatory Agency) ANEEL http://www2.aneel.gov.br

similar scheme with lower off-peak prices for nightly water heating and storage heating demand. [20] Reacting to the rising PV shares, California has exactly reversed this scheme, with electricity being cheaper during the day to encourage using electricity during the PV peak, and price hitting a peak during the evening load peak.[22]

2.3.5 PV development

The development of installed PV capacity over the years looks roughly similar in Germany, California and Australia (see Figure 2 through Figure 5 - figures include centralized PV as well, but information on rooftop share is provided), all three countries being early adopters of feed-in tariff based incentive schemes. All three experienced a strong uptake between 2008 and 2012 – with the difference being that the trend continues in California and Australia, while PV development in Germany has slowed down significantly.

It should be noted that Germany set world records with almost 8 GW of PV being installed in one year in 2010, and the slowed growth of currently around 1.5 GW p.a. is still strong, however, it falls short of the 2.5 GW p.a. set as targets in the German renewable energy law. The rooftop PV targets set for India with an increase of 39 GW within 5 years (2017 – 2022) require the annual installation of a capacity of 7.8 GW – which is similar to the best years in German development. Considering the lower PV prices today and the fact that India's population is 14 times that of Germany, this target does not look unrealistic. However, there are some issues that need to be addressed:

- India's per capita income is significantly lower than that of German, California or Australia, reducing the number of customers that can actually afford the investment for a PV unit – even with a 30 % investment subsidy and cheap loans available.
- India is just kick-starting the development of rooftop PV and setting incentives. Germany and California had their incentives in place up to 10 years before the boom hit, and had a slow, but steady development of PV before that, allowing for customers, operators and industry to adapt and learn.
- India is trying to achieve the same development without a feed-in tariff. Net metering schemes combined with capital subsidies and cheap loans seem to work in California, where PV development has not slowed down in the last years, when this scheme started largely replacing the dropping feed-in tariffs. However, development speed in California is and has always been slower than in Germany (or Italy or Greece), and no development similar to that planned in India has been realized using a net metering scheme so far.

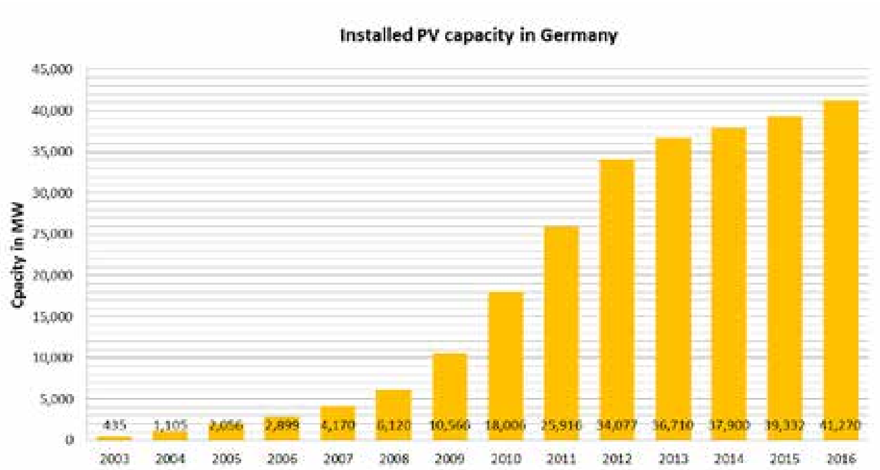


Figure 2: Development of installed PV capacity in Germany. [23][24]

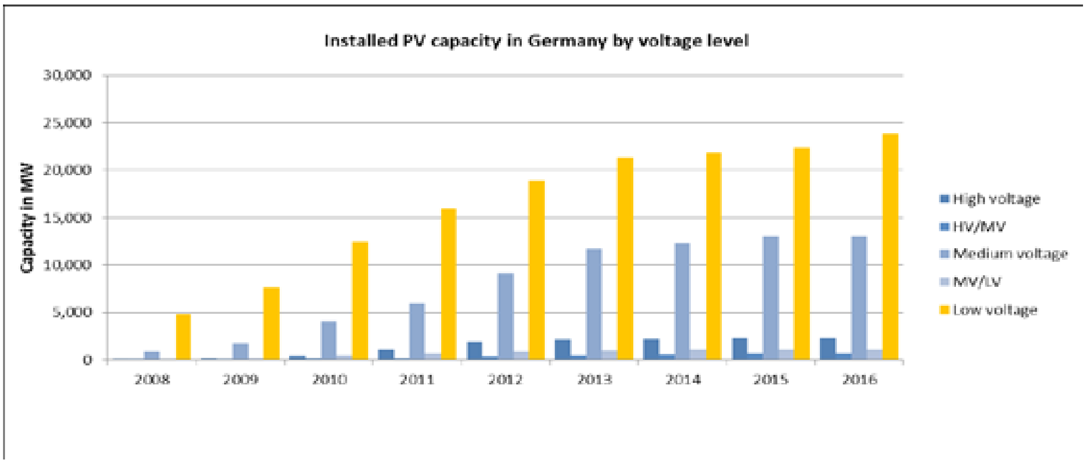


Figure 3: Development of installed PV capacity in Germany by voltage level of connection. [23][24]

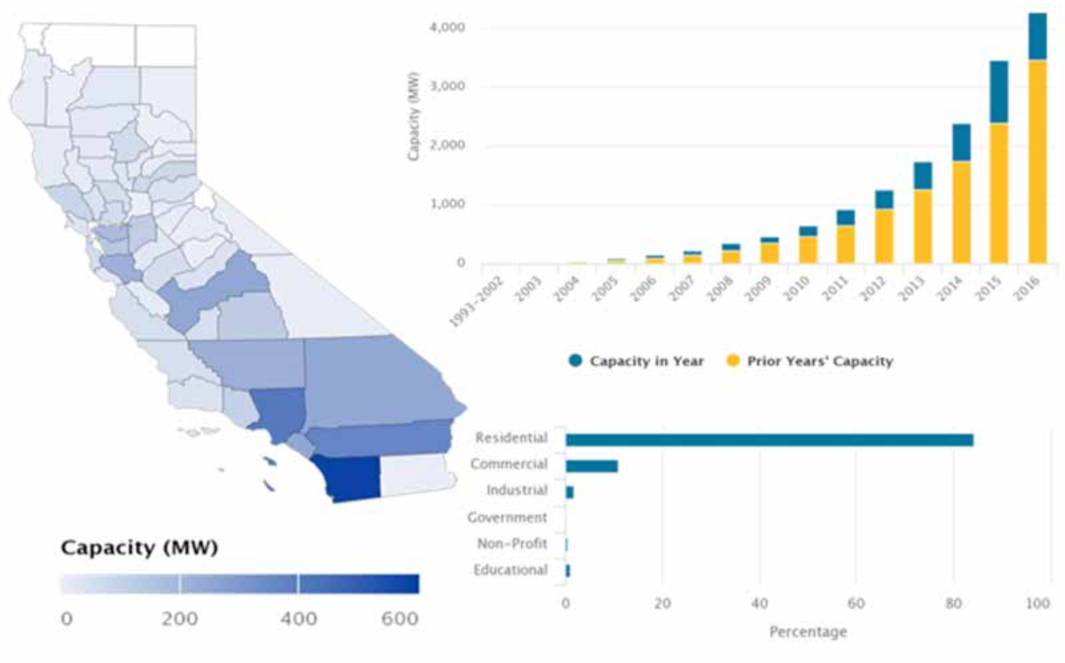


Figure 4: Development of installed PV capacity in California. [25]

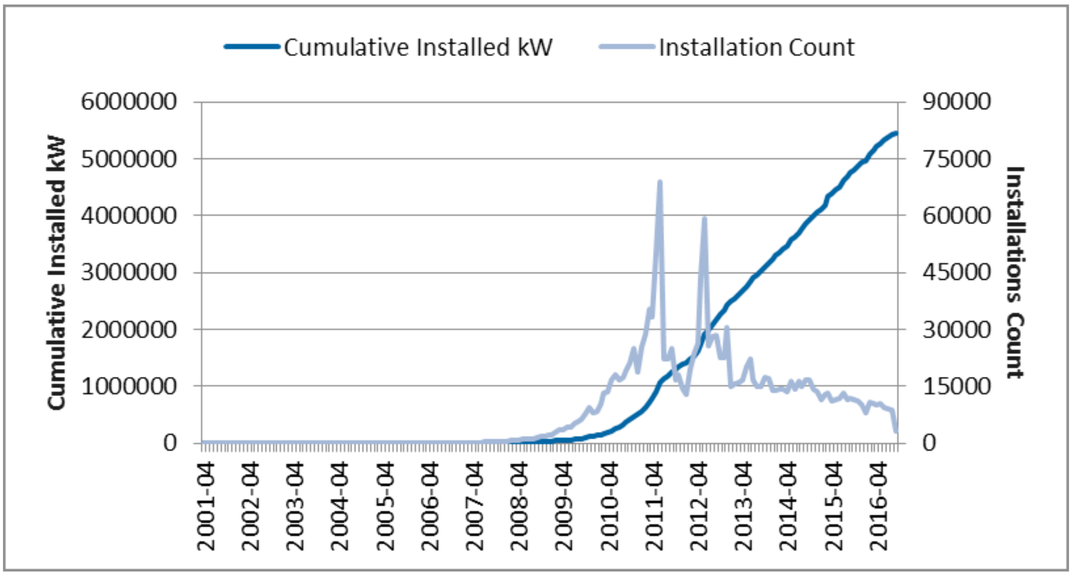


Figure 5: Development of installed PV capacity in Australia. [26]

An example of distributed PV not picking up under a net metering scheme in a developing country is Brazil. The Brazilian government's renewable energy is more focused on wind, hydro and large PV, with rooftop PV being on low priority, but a net metering scheme has been in existence for several years. Even though grid parity for residential customers has been reached in several areas in the country, a large uptake in rooftop PV has not happened yet, with a mere 21 MW of PV being installed by 2016 (see Figure 6.) There are several reasons for this, one of them being bureaucratic hurdles with grid connection requests [27]. Several modifications to the metering scheme have failed to bring any change – this indicates that a net metering scheme does not automatically grant successful development of rooftop PV in developing countries. Brazil has also introduced tax breaks for the manufacture and installation of PV units [28], but to no apparent effect so far. The main problem in Brazil seems to be a lack of financing, and the very limited financial means of the typical residential customer [29]. This is a factor that should be considered in India as well – and has been considered already, as India has a federal 30 % investment subsidy on residential PV, which Brazil does not have. However, it remains to be determined whether this is enough to produce the required development. Development should be monitored closely and action taken quickly in case the incentives turn out to be insufficient, to avoid failing the national renewable energy target.

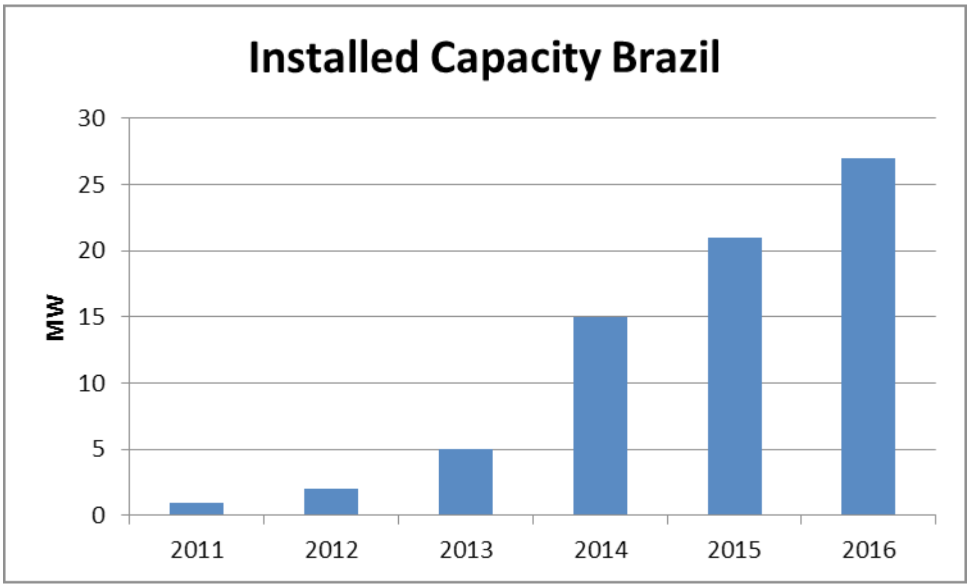


Figure 6: Development of installed PV capacity in Brazil (cumulated values).[12] [30][31]

2.3.6 Grid topology

Topology of both transmission and distribution grids may vary by country and region, but the general layout is usually somewhat similar. Terminology may, however vary:

- Extra high voltage transmission grids, typically with voltages between 200 kV and 750 kV, connect large load and generation centers and connect the system with neighboring systems.
- Sub-transmission grids in the range between 100 and 200 kV connect power plants to nearby cities and industrial areas and distribute power regionally. In some countries, such as Germany, this is already considered to be part of the distribution system.
- Primary distribution at medium voltage level (below 100 kV, also referred to as extra high tension, EHT, in India) is used for regional distribution and to supply industrial and large commercial customers.

12 16.5 MW of rooftop PV are installed as of 2016, http://www.brazilsolarpower.com/congresses/

- In most European countries, power is transformed directly from a single medium voltage level (10 – 30 kV, also referred to as high tension, HT, in India) into three phase low voltage grids which supply residential and commercial customers. Outside of Europe, especially in the Americas, an intermediate medium voltage level such as 11 or 13.8 kV is used for secondary distribution. In these countries, the low voltage (low tension, LT) connections to the end consumer are typically much shorter than in Europe and often single phase.

The voltages used for transmission and distribution in the study case countries are given in Table 8. The structures found in California are most similar to the Indian case. Both countries primarily use medium voltage primary (33 / 34.5 kV) and secondary (11 / 13.8 kV) OHL distribution grids[13] in combination with usually short low voltage feeders. Both three phase and single phase connections are used, with residential customers usually being supplied single phase. Grid structure is largely radial during normal operation, with some meshed grids only being used in urban areas in some places. Especially in California, the majority of PV units was installed in upper middle class suburban areas, similar to the development expected in India.

Table 8: Voltage levels for each country study case.

	India	Germany	California	Australia	Brazil
Transmission	220 – 750 kV	220, 380 kV	>138 kV	220 – 500 kV	230 – 750 kV
Sub-transmission	132/66 kV	110 kV	115/138 kV	66 - 132 kV	138 kV
Primary distribution	66/33 kV	10/20 kV	34.5 kV	11/22/33 kV	34.5 kV
Secondary distribution	400 V > 5KW 11 kV > 50kVA[5]	400 V, 3 ph.	4 – 13.8 kV	(11 kV)	13.8 kV
Last mile	240 V, 1 ph. 400 V, 3 ph	400 V, 3 ph.	120 V, 1 ph.[6]	240 V, 1 ph. 415 V, 3 ph.	220 V, 1 ph. 380 V, 3 ph.[7]

German distribution systems are structured differently, and rooftop PV has mainly been installed in rural areas. Rural grids mostly use comparatively long 20 kV lines or cables[14] (30 kV in some areas), supplying (all cable) low voltage grids with between 50 and 630 kVA of load and cable lengths of up to a few hundred meters. Long lines and cables combined with low voltage levels (20 instead of 34.5 or 66 kV) and low daytime load have proven to make German rural distribution grids rather prone to severe voltage swings, leading to the introduction of a number of technological innovations such as on-load tap changing automatic distribution transformers, active voltage control by PV inverters and wide-area voltage monitoring [32][33]. Australian operators have faced much similar problems, as most PV is installed in rural areas with long feeders as well [34].

These effects are less pronounced in the Californian system, although the advantages of higher voltages and shorter low voltage feeders are slightly reduced by the more predominant use of OHL instead of cables. The same will to some degree be true for the Indian system, especially when PV is integrated into urban grid areas. However, as the means of active voltage control in some Indian systems are more limited than in California, where a higher number of modern automatic on-load tap changing transformers are installed in the medium voltage (34.5 kV) grid, voltage deviations are still an issue that should be evaluated. Some Californian grid areas have displayed increased wear on tap changing transformers, indicating frequent switching operations to be necessary for voltage control [35][36].

Issues encountered by Californian distribution grid operators included load imbalances due to

13 Due to the distribution system being a grown structure per municipality, both countries display a wide range of used voltages – however, the given voltage levels are most frequently used.

14 German grid operators use underground cables exclusively for the medium voltage, but older installations in rural areas quite frequently still have OHL sections.

the primarily single phase connections of load and PV generation and protection issues caused by reverse power flows, which should also be considered in Indian grids [36].

2.3.7 Grid ownership and operation

The entity which owns the grid and the one which operates and controls it may not necessarily always be the same. Also, grids may be owned and operated by a (often state-owned) central utility which is in charge of the entire electricity system, a regional supplier and operator, or private entities.

Since the early 1990s, the development in many countries has shifted away from a centralized utility with a monopoly on generation and transmission towards more open structures with more participants, gross and retail markets. While such a structure is more complex to manage, it is intended to ensure fair access of privately owned generation to the grid. This opening of the market is expected to result in more pressure to generate at low prices and thus reduce the cost of electricity supply. Private sector involvement in India was enabled by the Electricity Regulatory Commissions Act of 1998 and the Electricity Act of 2003.

Such a system may still be largely owned by a central utility, which is required to grant grid and market access to privately owned generators, or completely unbundled with separate entities in charge of generation, transmission, distribution and retail.

Structures vary in the study case countries:

- Germany has a completely unbundled system. At distribution grid level, this means that retail supply and grid operation are conducted by separate entities. Germany has a multitude of retailers and more than 800 distribution grid operators. The grids are owned by utility companies and/or the municipalities, and operators operate them under license. Grid operators may not own or control any generation.
- In India, distribution grid operation and retail are often conducted by the same distribution company, while the grid itself is typically state-owned.
- California has a diverse structure with no mandated unbundling, but a multitude of private and public companies owning and operating the grids. These are regulated by the California Public Utilities Commission.
- Australian and Brazilian grids used to be completely state owned, but have been privatized and often sold. There are several distribution grid operators per country, some of which also act as retailers, and who also mostly own the grids they operate. Grid owners and operators may also own generation.

2.3.8 Technical and commercial losses

Losses are inevitable when transporting electricity, with the impedances of the grid assets causing thermal losses which depend on the amount of power and the distance across which it is transmitted as well as the number of transformations. If a share of power is generated locally where it is used by distributed generation, the amount of power transmitted through the grid decreases, thus losses are reduced. Distributed PV can thus help to somewhat reduce technical losses in the distribution grid. Several German distribution grid operators have reported been constantly decreasing losses with rising PV share. At very high penetration levels, this effect will be reduced or even reverse by the fact that reverse power flows that evacuate excess PV power from a grid section will also cause thermal losses. [37]

Non-technical losses, meaning electricity theft, metering failures, billing errors etc., which account for the majority of losses in the Indian system, are not directly reduced by PV.[15]

2.3.9 Technical equipment

Besides the PV panels and the inverters themselves, a wide range of technical equipment may be impacted by PV feed-in, or may impact the integration thereof. Experience from the study case countries has shown a number of equipment types to be especially important and suitable to facilitate the integration of distributed PV.

On-load tap changing (OLTC) transformers with automatic voltage regulation as the primary means of active voltage control. Traditional distribution grid structures are usually designed as load-only grids with unidirectional power flows, which may not require a great deal of voltage control. As load/generation balance and power flow directions change, it may be required to keep the voltage within the allowed boundaries. Experience from Germany and California shows that OLTC power transformers connecting the (sub)transmission grid and the distribution grid (138/34.5 kV or 110/20 kV) can contribute significantly to PV integration, especially if coupled with a wide area management system (see below), by reacting to the PV-induced voltage fluctuations. However, with high PV shares in the low voltage grid, the regular high/medium voltage OLTC – which German and Californian grids were usually already equipped with – may not be sufficient to control the voltage on longer feeders. In this case, distribution transformers with OLTC capabilities have been deployed in some areas.

Voltage control by PV inverters can also help to mitigate the voltage problems that may be induced by high PV feed-in. In Germany, California and Australia, PV inverters have been required to provide voltage control by being able to operate at an off-unity power factor. Actual use of the capability varies, in some areas, PV operates at a fixed offset power factor, others use a Q-V characteristic (controlling reactive power based on measured voltage at the connection point), and some larger PV units are remotely controlled.

Real time monitoring and control systems, such as SCADA systems, allow the grid operator to react to changes in the grid immediately, possibly even automatically. In some rural areas in Germany with high renewable energy feed-in in the distribution grid, wide area monitoring systems have been set up. Linking the OLTC voltage control up with voltage measurements from different points in the grid allows the OLTC to not only "see" the voltage at the transformer, but also react to voltage drops or rises along the feeders and adjust the tap settings accordingly.

Active power control of PV inverters is also widely used, as a small amount of curtailment during worst case situations may benefit the grid while only losing a very small fraction of the energy that could be generated (3 % p.a. are considered acceptable in Germany, for example.)

Germany has recently attempted to kick-start a large scale roll-out of PV batteries for self-consumption through incentives and subsidies. While sales of batteries have increased, the success of the program remains to be assessed. However, PV batteries can help integrate PV power if charged in a way that not only optimizes for self-consumption, but also cuts the PV peak to reduce grid loading (see Figure 7.)

15 On a side note, Italy has been able to reduce its non-technical losses through the introduction of smart meters along with its PV roll-out. This allows the operator to monitor the energy consumption of the households on a feeder and compare it with the actual feeder load, making it possible to detect energy theft and/or erroneous metering.

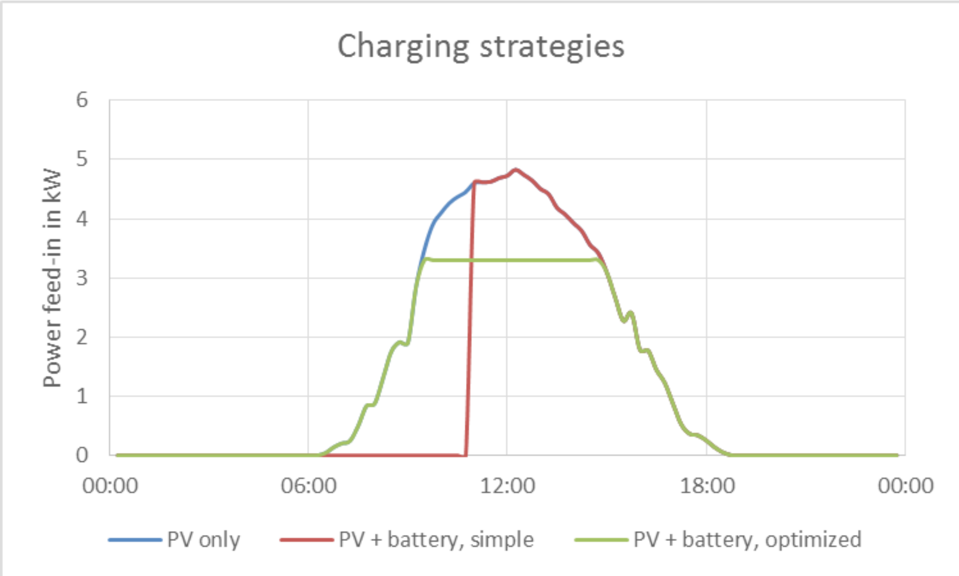


Figure 7: Power fed back to the grid for different layouts. PV only (blue), PV with battery for self-consumption only (red) and PV with battery for self-consumption, optimized to shave the PV peak off.

This can be combined with household demand side management controlled by a smart meter, which has not been widely used in Germany so far, but will be a logical result of the implementation of varying end consumer prices as planned in California (see section 2.3.4, example in Figure 8.)

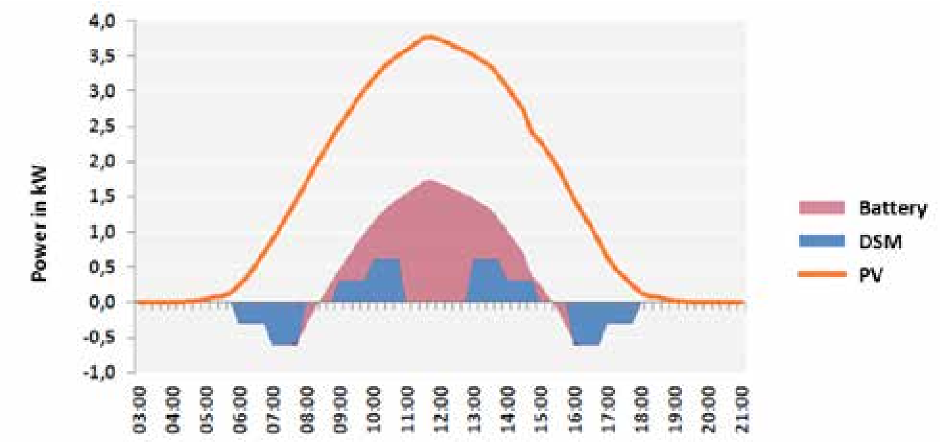


Figure 8: Optimized operation of PV, battery and household demand side management, as developed by Energynautics for the distribution grid study in the German federal state of Rhineland-Palatinate. [38]

Based on the review of Indian distribution grids within this study, it can be concluded that all of the equipment types mentioned above are available in India and also used by some DISCOMs. However, use is not widely spread, with some DISCOMs having no means of directly controlling the voltage in their grid, and no or very rudimentary SCADA systems. As PV integration is just getting started, it may provide the chance of introducing an active voltage control instance in the form of voltage controlling PV inverters.

2.3.10 Grid codes

Technical requirements for generating units are specified in the grid code, which is typically developed by the grid operator, but also involves other stakeholders such as generator operators and manufacturers. The necessity for grid codes arose with the unbundling of power systems in Europe in the 1990s, but vertically integrated systems may also need grid codes if privately owned generation is allowed. Grid codes introduce a set of rules and requirements generators must fulfil, often combined with legal frameworks that oblige the grid operator to connect generators compliant with those rules. Grid codes should not be considered to be fixed sets of rules, but must be updated and revised as grids, policy and technology change. National renewable energy policy should be reflected in the grid code in a way that the requirements set are adequate for the planned expansion of renewable generation.

The German grid code documents – a variety of those exist, with different codes being applicable to different voltage levels and generation types – can serve as a good example for the development of grid codes at rising shares of renewable generation. The documents have been constantly revised and improved, not without experiencing some pitfalls of inadequate planning. Australia and California have also substantially revised their requirements in the last decade to accommodate rising PV shares, but have not reached the extremely high PV penetration of Germany yet.

A. Power system impact

The most notable example of a failure to anticipate the increase in PV generation is the 50.2 Hz issue that was created by an inadequate grid code requirement. Distributed PV units were initially required to disconnect if the grid frequency exceeded 50.2 Hz. In 2007, German PV capacity exceeded 3 GW, which is the amount of primary reserve provided in the European interconnected system. This meant that from this point on, if the frequency rose above 50.2 Hz on a sunny day – indicating excess generation, meaning a balancing failure already existed – the sudden loss of more than 3 GW of generation would occur, leading to a potential blackout. By the time the requirement was changed, capacity had exceeded 20 GW, and a costly retrofitting scheme implementing a gradual power reduction at high frequency had to be executed. As the European grid has a high amount of inertia and very stable frequency, the 50.2 Hz threshold was never actually exceeded [39][40].

The Indian grid code currently requires PV units to disconnect at 50.5 Hz, possibly creating a very similar problem at quickly rising PV shares. Learning from the German case and considering the ambitious Indian targets, this should be revised as quickly as possible to include gradual power reduction or staggered disconnection. IEEE 1547, which sets the connection standards in California, suffers from a similar issue, while the Australian grid code already includes the same requirement as the updated German codes.

This issue also serves as an example for the necessity for communication between distribution and transmission system operators (DSO and TSO.) Frequency control is taken care of exclusively by the TSO, however, generation connected to the distribution grid is relevant for that task. This means that the grid code requirements for distributed generation – typically set and enforced by the DSO – also have to address issues relevant to the TSO, requiring a communication link between the two in grid code development.

B. Distribution grid issues

During the early years of rooftop PV integration, reverse power flows were expected to become a major problem at rising capacities. As distribution grids were designed as load-only grid with unidirectional power flow, a reversal of power flow in case PV generation on a feeder exceeded load was widely regarded as a hazard. In the case of California, in 1999, this led to the restriction of PV installed capacity on a feeder to 15 % of its peak load to avoid reversed power flows in any situation. The reasoning was that minimum load of a distribution feeder typically amounts to around 30 % of its peak load, and with a safety margin of 100 %, 15 % was the value accepted to be safe under any circumstances [41].

This rule has been widely used in other countries as well and is still applied in several Indian states, sometimes expanded to 30 % of peak load, or 15 % of transformer rating [42]. Meanwhile, this rule has been dropped altogether in California, as international experience especially from Germany has shown that reversed power flows in distribution grids are not inherently dangerous. Neither Germany nor Australia employ any type of general limit on feeder PV penetration. There are cases in Germany where the grid operator will not allow any additional PV to be connected to individual feeders that regularly experience excessive voltage swings due to PV feed-in. However, under German renewable energy legislation, grid operators are required to reinforce the grid in such a case and can only temporarily suspend new connections until the reinforcement is in place [43].

In Germany and Australia, where most PV was connected to rural grids, voltage rises through PV feed-in quickly became one of the most pressing issues. The voltage ranges allowed in the low voltage grids in the study case countries are given in Table 9. With Germany being the first to react, all high-PV study case countries – Germany, California and Australia – have introduced requirements for PV inverters to be able to operate at offset power factors to mitigate the impact on the voltage. In Germany, for example, units above 3.68 kW_p must be able to realize power factors between 0.95 capacitive and 0.95 inductive and adhere to a Q(U) characteristic which is set by the grid operator based on the grid characteristic[16] [44].

Table 9: Allowed voltage ranges in the low voltage distribution grids.

	India	Germany	California	Australia	Brazil
Maximum	1.10 p.u.[8]	1.10 p.u.[9]	1.06 p.u.	1.10 p.u.	1.06 p.u.
Maximum preferred	-	+ 0.04 p.u.[10]	1.05 p.u.	1.06 p.u.	1.05 p.u.
Minimum preferred	-	- 0.04 p.u.	0.95 p.u.	0.98 p.u.	0.92 p.u.
Minimum	0.90 p.u.	0.90 p.u.	0.87 p.u.	0.94 p.u.	0.87 p.u.
Max. voltage rise at connection point	-	0.03 p.u.	-	-	-

Australian and Californian grid operators have set similar requirements. The impact of PV on the voltage in highly loaded, primarily urban Indian distribution grids is still to be determined, but it would be very advisable to revise the Indian grid codes to include voltage control requirements for PV inverters similar to those in Germany, California and Australia, which it currently does not have.

Overloading of cables, lines and transformers has also been a widespread issue encountered by German distribution grid operators at rising PV shares, especially in areas with low load, but much roof space. In principle, installed PV capacity on a feeder is limited by the rating of the assets connecting it to the higher voltage level. If PV capacity on a low voltage feeder is limited to the transformer rating, the amount of power that is actually fed in is potentially overestimated – especially in northern countries like Germany, PV almost never reaches its peak output. It may be sensible to curtail peak power during the few hours in a year where it is actually reached. Little energy is lost, while the amount of PV that can be integrated is raised significantly. German energy legislation thus requires all PV above 30 kW_p to be able to be curtailed remotely, and PV below that threshold to be either remotely curtailable or capped at 70 % of its peak power [21] [43].

California currently considers requiring remote control from PV inverters for different reasons concerning power system impact – if the PV share keeps increasing, conventional generators may at some point no longer be able to cope with the daily ramps required [45]the California Independent System Operator published the \u201cduck chart,\u201d which shows a significant

16 Smaller units must be able to realize the same power factors, but this is a provision for the future – no Q(U) characteristic is set by the operator yet.

drop in mid-day net load on a spring day as solar photovoltaics (PV. This serves as another example for the necessity of communication between DSOs, TSOs and regulators. Considering the significant amount of distributed PV power, it is recommended that India should look into this issue as well. However, the German approach of capping inverter power may not be feasible for areas with significantly higher insolation like California, Australia or India, where peak PV power is reached much more frequently.

3. PV development

3.1 Worldwide PV market development

3.1.1 Historical development

The historical development of grid connected solar PV worldwide has exceeded all expectations in the last decade. By the end of 2015, there were almost 250 GW of PV installed worldwide, with almost 50 GW being connected in 2015 alone (see Figure 9 and Figure 10.) The IEA PV roadmap from 2010 forecasted 200 GW of installed capacity and a market of 34 GW/y for 2020. Similar numbers exist in more details for various countries and regions, all showing a similar development, with forecasts regularly vastly underestimating the increase in installed capacity once there is a business case for PV.

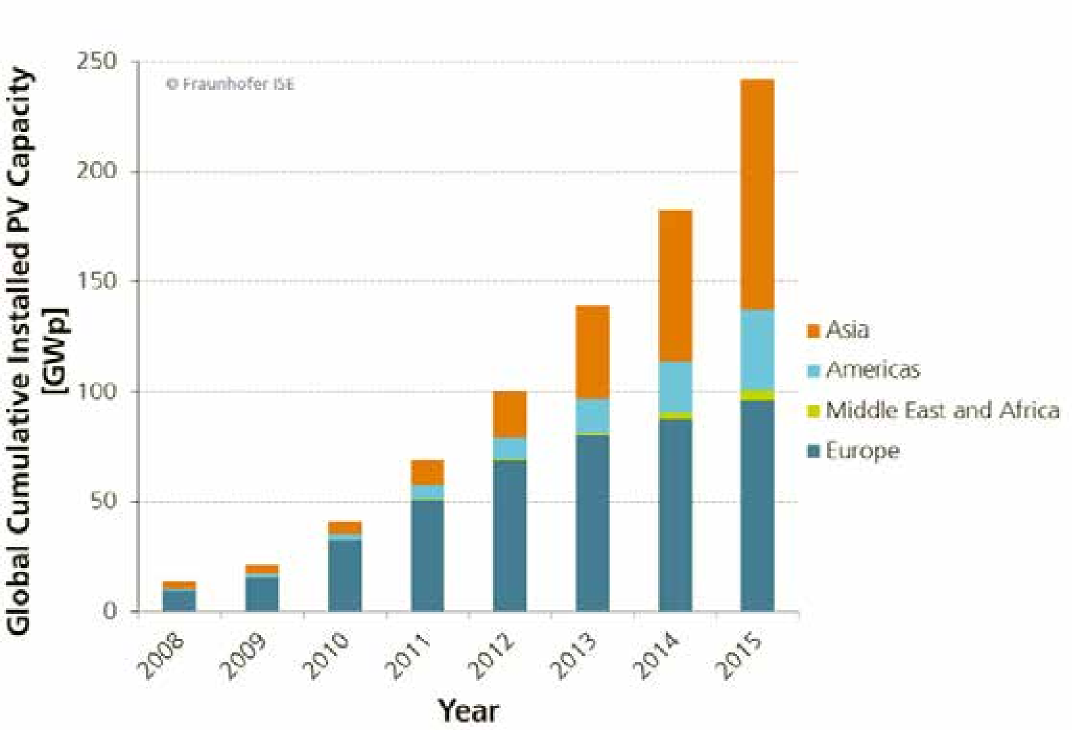


Figure 9: Worldwide PV development 2008 – 2015. [17]

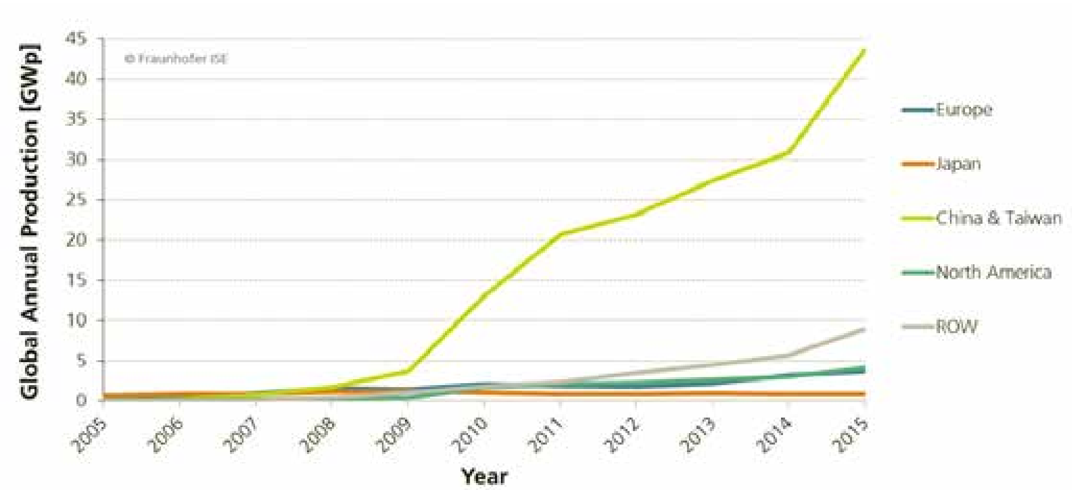


Figure 10: Global annual production of solar modules 2005- 2015. [17]

Price reductions through scaling effects (see Figure 11) have been similarly underestimated, with residential PV attaining grid parity in European countries from 2010 on, Spain and Italy being the first. Figure 12, based on data from 2014, gives an overview of the development, however, PV has reached grid parity in additional countries since, including several Indian federal states and more than 20 US federal states [46].

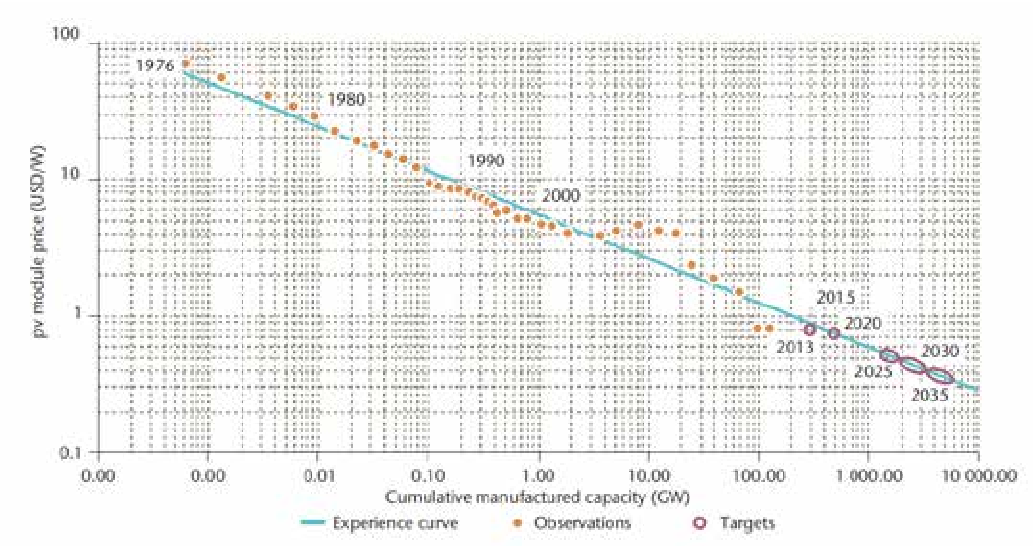


Figure 11: Development of PV module prices. [47]

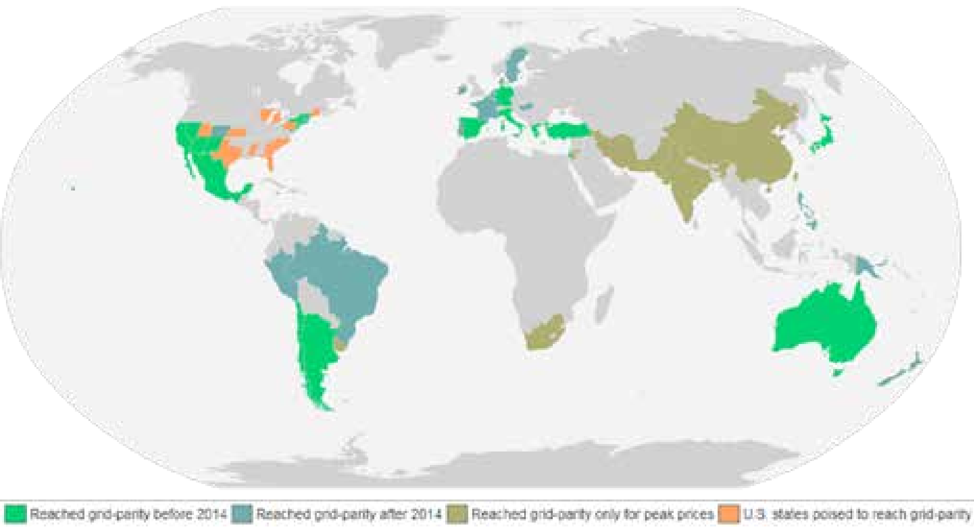


Figure 12: PV grid parity worldwide in 2014. [48][17]

Due to the lower tariffs usually paid for electricity by commercial and industrial customers, grid parity for commercial and industrial PV was reached later, starting in Cyprus and Malta in 2010/11 and including multiple European countries [49] by late 2016. Grid parity has also been reached for commercial and industrial customers in several Indian federal states [50] – this is, however, somewhat of a special case, as in India, those customers actually pay a higher electricity tariff than residential customers.

Only with grid parity will net metering without any additional incentives be sufficient to make PV a business case. Especially commercial and industrial grid parity is expected to boost PV installations, as large customers with the cash for investments available will save large amounts of money by installing PV.

17 Graphic from wikipedia, based on data given in [48], available at: https://en.wikipedia.org/wiki/Grid_parity#/media/File:Grid_parity_map.svg

3.1.2 Expected development

Despite a recent slowdown of PV development, the market is expected to continue growing as more and more countries develop renewable energy policies and start investing in solar power. In installed capacity, PV is expected to remain the third largest renewable energy source behind hydropower and wind (see Figure 13.) Data from different studies forecast between 750 and 2800 GW of PV capacity installed worldwide by 2030 (see Figure 14 and

Table 10.) With a set target of 100 GW of PV by 2022 and expectations of up to 200 GW by 2030, India, which is currently still a medium small market at 9 GW of installed capacity, will become a major player in PV installation in the coming decade (see Figure 15.)

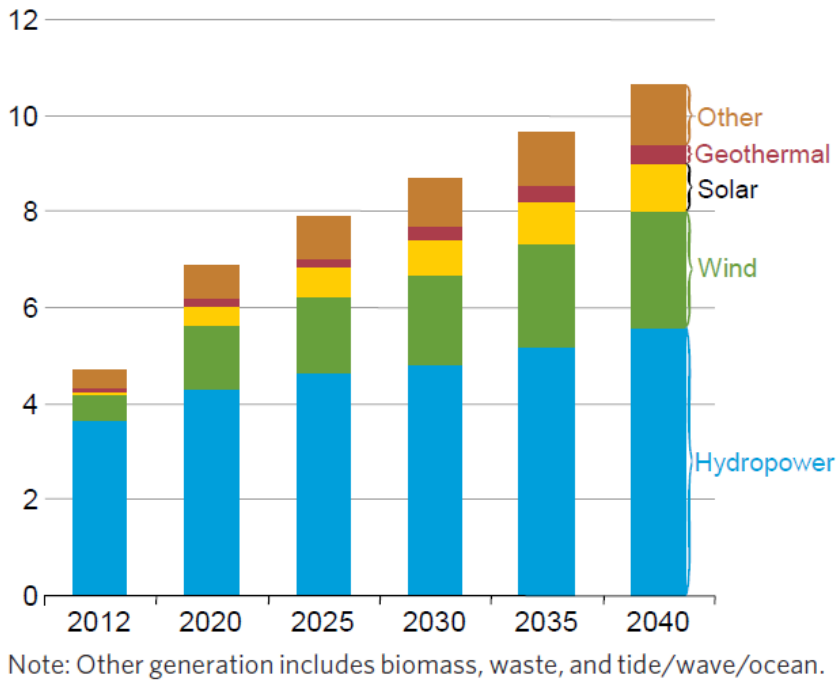


Figure 13: Expected development of renewable generation until 2040 according to the US Energy Information Administration EIA. [51]

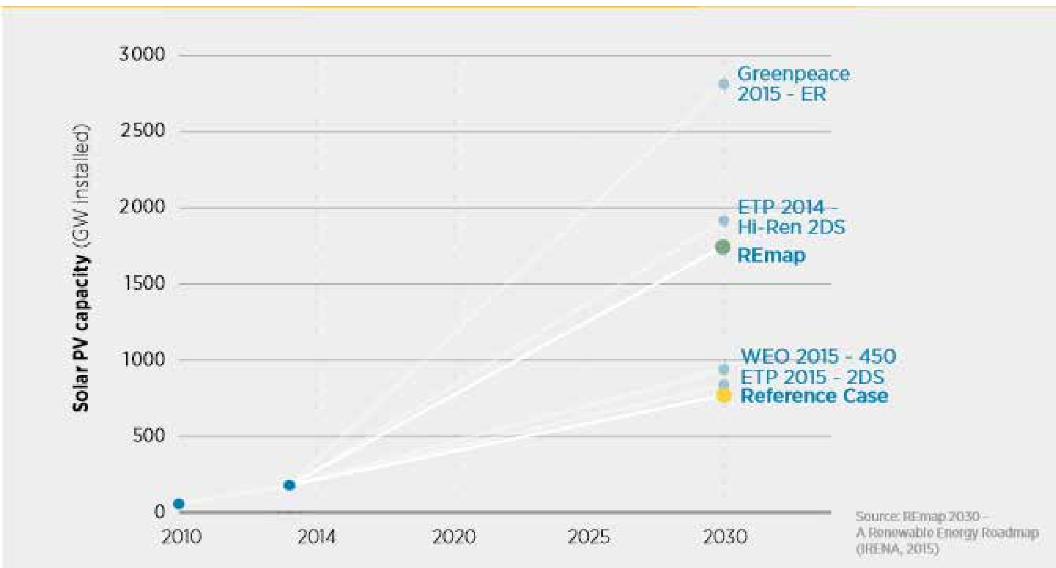


Figure 14: Different forecasts for worldwide installed PV capacity 2030, as compiled by IRENA. [52]

Table 10: Different projections of installed PV capacity until 2020.[18]

Forecasting company or organization	Cumulative by 2020	Ø Annual installation
IEA (main case, 2015)[53]	429 GW	42 GW
SPE/EPIA (low scenario, 2016)[54]	490 GW	46 GW
IEA (accelerated case, 2015) [55]	515 GW	55 GW
Grand View Research (2015)[56]	490 GW	52 GW
PVMA (medium scenario, 2015) [57]	536 GW	60 GW
IHS (10.5% CAGR, 2015)[58] [11]	566 GW	65 GW
BNEF (New Energy Outlook 2016[59]	650 GW	80 GW
Fraunhofer (17% CAGR, 2015) [60]	668 GW	82 GW
GTM Research (June, 2015)[61]	696 GW	86 GW
SPE/EPIA (high scenario, 2016)[54]	716 GW	97 GW

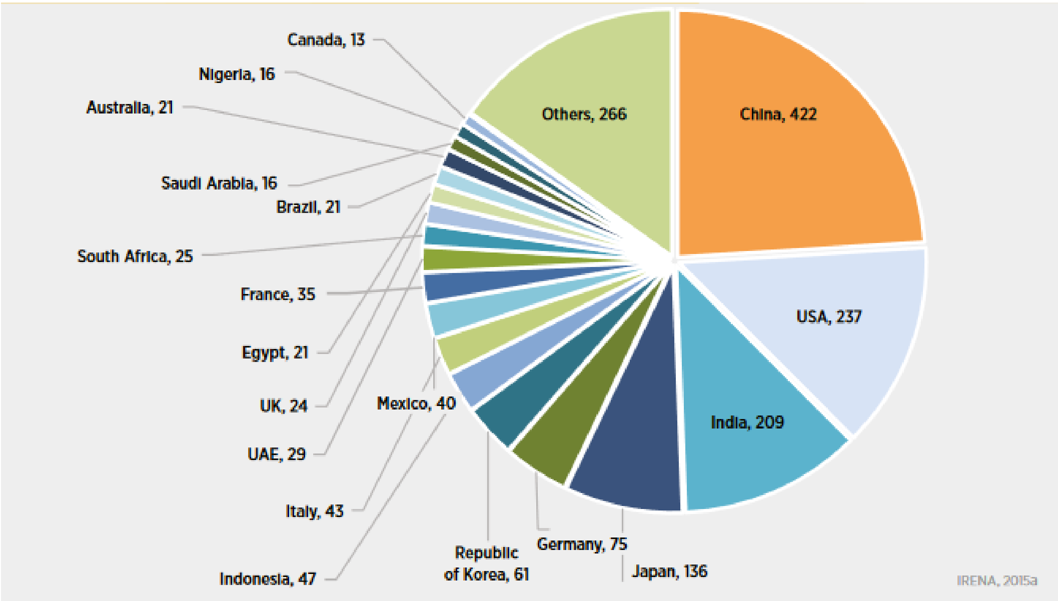


Figure 15: PV deployment 2030 by country, according to the IRENA Renewable Energy Roadmap. [52]

While initial development of the European trendsetter countries focused on distributed, roof mounted PV on mostly residential buildings, the current trend especially in the developing world goes towards multi-MW scale centralized units [52]. This is also reflected in the Indian renewable energy targets that call for utility scale installations to make up 60 % of the installed PV capacity [62]. Even with the focus on utility scale installations, prices for roof mounted PV will drop further as basically the same technology is used [52].

3.2 Current situation of distributed PV in India

3.2.1 Solar resources

India receives good amount of solar radiation with an annual average of 4.5 to 6.5 kWh/m²/day (see Figure 16). Availability of roof or suitable ground space is another important factor to generate solar power in an effective and economical way. It is important to assess and utilize solar radiation data for specific areas for which systems are to be designed. There are different sources from where solar data are available. MNRE has released solar radiation data for 23 locations across India through a joint project with the Indian Meteorological Department. MNRE through the National Institute of Wind Energy (NIWE) and supported by GIZ has now set up more than 120 advance solar radiation monitoring stations across the country for collecting and

18 Table structure taken from Wikipedia page https://en.wikipedia.org/wiki/Growth_of_photovoltaics, updated with recent values where possible and referenced directly with original sources. Projections without freely available sources deleted.

monitoring solar data. NIWE has also published a national solar energy atlas in 2014. [19]

Daily solar patterns are generally well predictable during summer where there is little overcast, but more varied during winter or monsoon season. Due to the size of the country, more exact data on seasonal variability has to be assessed on a more regional level. Figure 17 shows the difference between summer and monsoon season in Gujarat, a state in western India which has the highest solar potential in the country.

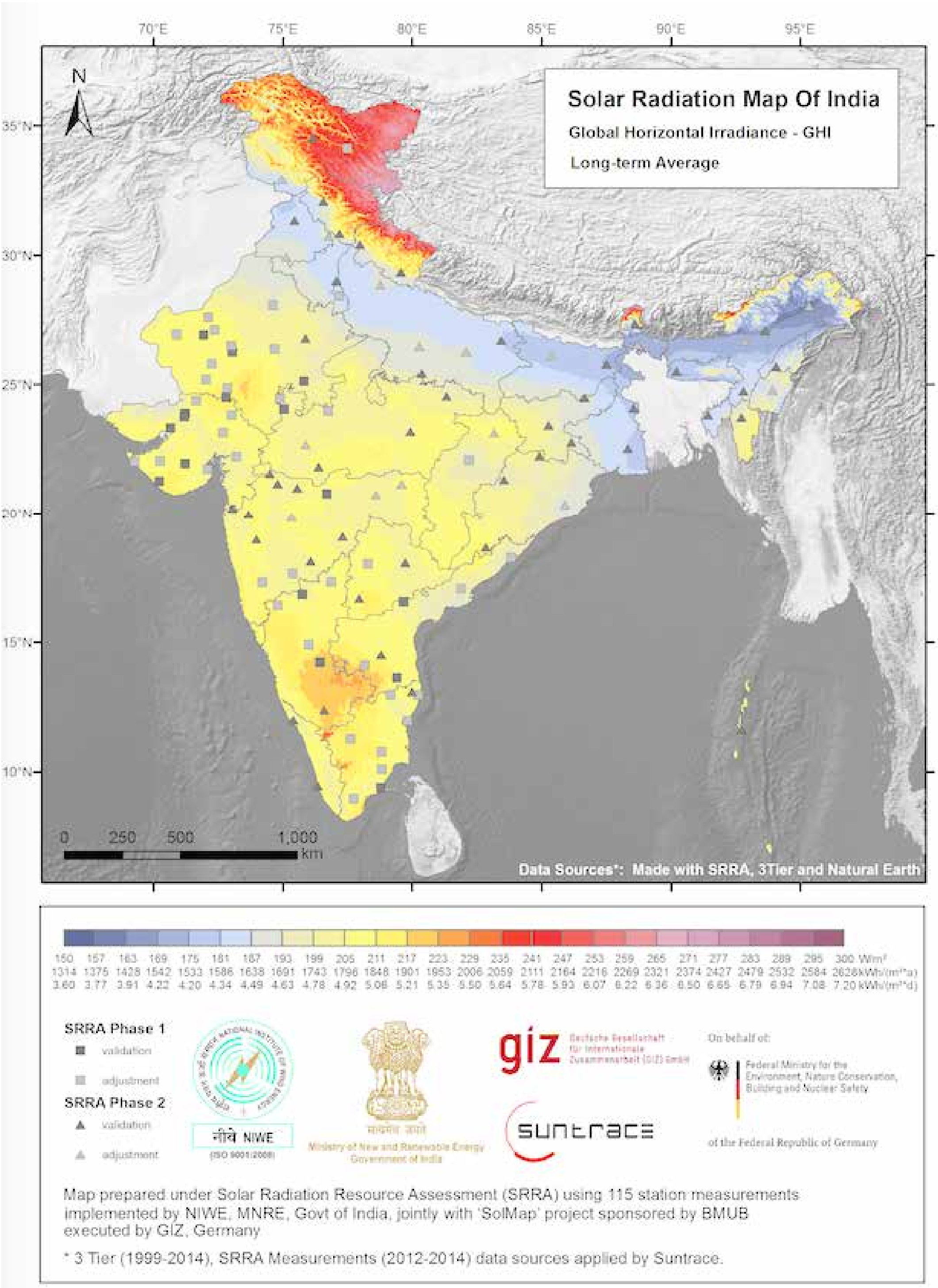


Figure 16: Solar radiation map of India. [63]

19 The National Aeronautical Space Administration (NASA) in the USA also provides worldwide data on the web: available at free of cost from the website http://eosweb.larc.nasa.gov/sse/.

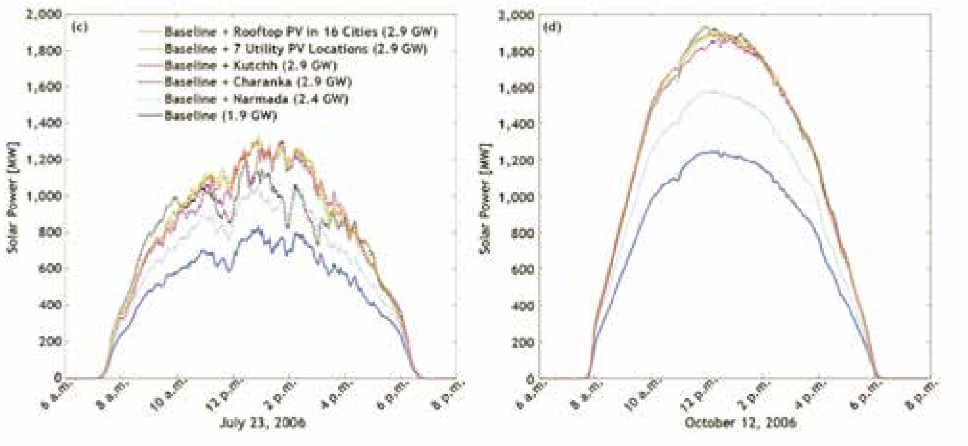


Figure 17: PV power output calculated from measurements of solar irradiation in Gujarat, 2006, monsoon season and dry season. [64]

3.2.2 Roof mounted PV

By the end of 2016, a total of around 8700 MW of solar PV are connected to the Indian grid, of which 1020 MW are distributed roof mounted installations [50]. National incentives for PV, both roof mounted and centralized, exist, mainly in the form of capital cost subsidies. Centralized utility scale PV has been subsidized under the Jawaharlal Nehru National Solar Mission since 2010 [65], or, for very large projects of more than 500 MW, under the Ultra Mega Solar Park program of the Ministry of New and Renewable Energy [66]. Incentives for roof mounted PV, which this section will be focused on, consist of both capital subsidies and metering schemes.

Like centralized installations, roof mounted PV has been subject to federal subsidies since 2010. The frameworks have been changed several times, with an initial subsidy of 30 % of capital cost, later reduced to 15 %, and since 2016 raised to 30 % again, but with subsidies now only applicable to resident, institutional and social sector customers [67]. A maximum subsidy of 70 % is given states that are given the Special Category status due to geographical and/or socio-economic disadvantages (North Eastern States, Sikkim, Jammu and Kashmir, Himachal Pradesh and Uttarakhand, Lakshadweep, Andaman and Nicobar Islands)

Most of the Indian federal states have net metering schemes for rooftop PV in place. As of March 2017, all states have released regulatory framework for promotion of distributed PV through net metering mechanism [50].

Different from European countries, where most PV installations are small and connected to the low voltage grid, there is currently a much higher share of larger PV on industrial and commercial buildings in India. Most of those installations are connected to the 11 kV medium voltage grid [50]. Capacities have since grown significantly, but the focus on PV on commercial and industrial buildings has remained so far.

As already mentioned, development may take a different route quickly. As rooftop PV for industrial and commercial customers has reached grid parity in several states (see Figure 18), the Indian government has decided to subsidize such installations no longer, as the incentive set by grid parity and high prices for grid power (see section 2.1.4) is considered to be sufficient to sustain development. Subsidies for PV for residential customers are raised back to 30 % of capital cost nationally to increase development in this sector [67]. This may in the near future lead to a shift towards a higher capacity of PV installed on roofs of residential buildings, thus leading to a higher amount of PV being connected to the low voltage grids.

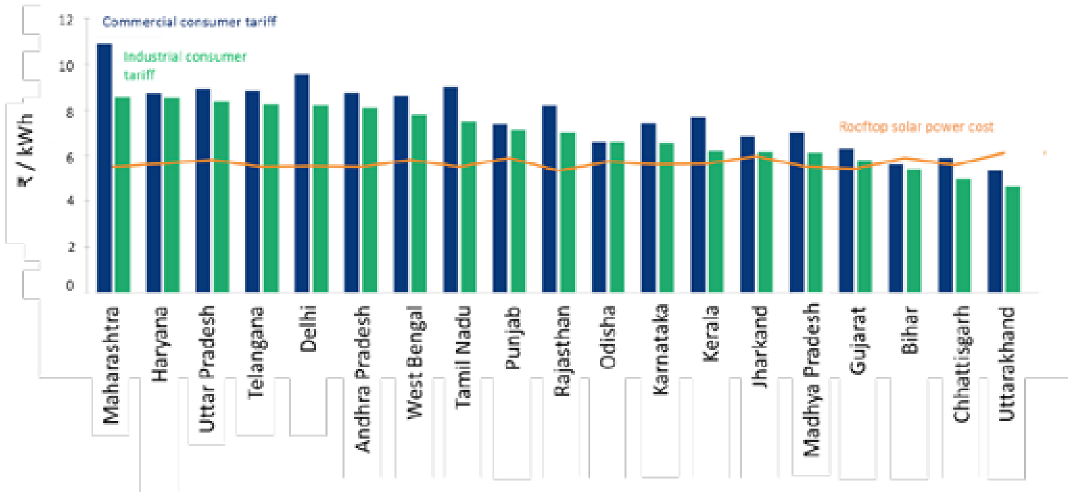


Figure 18: Grid parity of rooftop PV in selected Indian states, 2016. [50]

3.2.3 Non-grid connected solar PV

The quality of residential and commercial power supply in large parts of India is sub-par, with distribution grids experiencing frequent blackouts and brownouts. These are mostly called by faults on the last mile and load shedding used by the distribution companies to control deviations from their day-ahead schedule. To cope with the situation, the number of backup generators installed by customers is extremely high, some estimates going up to an installed backup capacity exceeding 170 GW in India's 180 GW peak system [68]. The use of lead-acid battery based uninterruptible power supplies (UPS) is also common. According to PV Magazine, as far back as 2011 there was already a strong business case for roof-mounted PV coupled with batteries or diesel generators to reduce fuel cost of a backup power supply [69].

PV prices have since dropped significantly, reinforcing the business case and leading to an increase in installed capacity [70]. PV that is not connected to the power grid has no direct impact on the system (besides reduced electricity demand) and is thus not monitored by the distribution and transmission companies. However, if adequate incentives for privately owned, roof-mounted and grid connected solar PV are introduced, these capacities may have an impact as they could possibly be connected to the grid at little additional cost and effort. Connected PV capacity may thus increase quickly in areas that already have a high share of previously installed, non-connected PV.

3.3 Expected development of distributed PV in India

3.3.1 National and state targets

The national target of 40 GW of rooftop and 60 GW of utility scale PV to be installed by 2022 is distributed to the states by the MNRE. This distribution is based on size, population, solar potential and economic power of the states (see Table 11.) The states and their SERCs are responsible for the enforcement of these targets. The main enforcement mechanism is the renewable purchase obligation (RPO), with which states oblige their DISCOMs to purchase a certain percentage of their total electricity from renewable sources[20]. Within the state RPOs, the percentage that has to come from solar PV each year is specified, from which a trajectory towards the final goal of each state can be derived (see Table 12.)

RPOs have been in existence since 2010 (mostly for other renewable sources like small hydro

20 An analysis of the state RPOs can be accessed at the MNRE: http://mnre.gov.in/file-manager/UserFiles/Solar%20RPO/analysis-of-state-RPO-regulations.pdf

and biomass), but have largely been notorious for a lack of enforcement, see section 4.1.1 for more details.

Table 11: State wise solar PV Target [71]

States	Rooftop PV Target by 2022	Total Solar Target by 2022
Maharashtra	4700	11926
Uttar Pradesh	4300	10697
Andhra Pradesh	2000	9834
Tamil Nadu	3500	8884
Gujarat	3200	8020
Rajasthan	2300	5762
Karnataka	2300	5697
Madhya Pradesh	2200	5675
West Bengal	2100	5336
Punjab	2000	4772
Haryana	1600	4142
Delhi	1100	2762
Bihar	1000	2493
Odisha	1000	2377
Telangana	2000	2000
Jharkhand	800	1995
Kerala	800	1870
Chhattisgarh	700	1783
Jammu and Kashmir	450	1155
Uttarakhand	350	900
Assam	250	663
Dadra and Nagar Haveli	200	449
Goa	150	358
Puducherry	100	246
Himachal Pradesh	320	209
Daman and Diu	100	199
Meghalaya	50	161
Chandigarh	100	153
Manipur	50	105
Tripura	50	105
Mizoram	50	72
Nagaland	50	61
Arunachal Pradesh	50	39
Sikkim	50	36
Andaman and Nicobar Islands	20	27
Lakshadweep	10	4
Total	40000	100967

Table 12: Solar renewable purchase obligation (RPO) Trajectory for the period from 2016-17 to 2018-19 [72]

State	Solar RPO (2.75%) required (2016-17) (MW)	Solar RPO (4.75%) required (2017-18) (MW)	Solar RPO (6.75%) required (2018-19) (MW)
Andhra Pradesh	867	1584	2376
Arunachal Pradesh	7	14	21
Assam	138	262	411
Bihar	447	942	1599
Chhattisgarh	458	847	1277
Delhi	478	831	1188
Goa	75	137	206
Gujarat	1803	3318	4948
Haryana	740	1332	1965
Himachal Pradesh	43	66	79
Jammu and Kashmir	168	326	504
Jharkhand	362	635	916
Karnataka	895	1579	2280
Kerala	272	475	675
Madhya Pradesh	956	1737	2582
Maharashtra	2339	4249	6401
Manipur	11	22	36
Mizoram	8	16	24
Meghalaya	11	19	25
Nagaland	9	17	26
Odisha	326	579	839
Punjab	662	1154	1651
Rajasthan	1104	1997	293
Sikkim	2	4	5
Tamil Nadu	1635	3037	4626
Telangana	863	1576	2363
Tripura	17	30	43
Uttarakhand	114	194	269
Uttar Pradesh	1777	3363	5165
West Bengal	855	1541	2282
Chandigarh	15	25	34
Daman and Diu	40	72	105
Dadar and Nagar Haveli	107	190	276
Puducherry	56	101	148
Total	17660	32271	48308

3.3.2 Expected development in Delhi and Madhya Pradesh

From the wide array of different state targets, the cases of Delhi and Madhya Pradesh which are being investigated within this study, shall be addressed with a little more detail.

Development of rooftop PV in India in general and in Delhi and Madhya Pradesh more specifically is not expected to be homogeneous. Investments in PV will most likely start in the wealthier areas, leading to a sharp rise in PV installations and high penetration levels locally, while other, financially less stable areas may not be impacted at all.

Under the current targets, 1100 MW of rooftop solar should be connected in Delhi by 2022[21]. Rooftop space available for PV installations is estimated to be approximately 31 square kilometers. With a typical value of 0.08 kWp per m^2 of roof space, this results in a potential of around 2500 MW of rooftop PV in total. The official 2022 target of 1100 MW under the national solar policy will cover about half of that, leaving some potential to be tapped by future development. It can be expected that the financially more stable areas will invest in PV first and reach the limit set by available roof space quite fast, while the roof space left for future investments by 2022 will be in the poorer areas of Delhi.

The current target for Madhya Pradesh is 2200 MW of installed rooftop PV by 2022. Different from Delhi, Madhya Pradesh is a regular state with a much larger area, so the total available rooftop space is not as easy to determine. With the population being around 73 million, as opposed to 17 million in Delhi, it can be expected that less rooftop space restrictions apply.

Both states have introduced detailed solar rooftop policies with net metering schemes and additional incentives and published guidelines on the implementation of solar installations.

A. Regulatory framework in Delhi

Besides the net metering arrangement, the State Government is offering generation based incentives at a fixed tariff of INR 2/kWh of gross solar energy generated for three years on a first-come-first-serve basis. Delhi Electricity Regulatory Commission (DERC) has issued further regulations and guidelines for the implementation of rooftop solar and its support by the state:

- DISCOMs are not allowed to limit PV installations in low voltage grids to less than 20 % of the supplying distribution transformer's capacity. The Commission may also assess the allowed capacity through an independent agency if necessary.
- Non Time of Day Tariff Consumers (mainly residential): During any billing period, if customer generation exceeds consumption, the surplus units shall be carried forward to the next billing period as energy credit.
- Time of Day Tariff Consumers (industrial, commercial): The electricity consumption in any time block i.e. peak hours, off-peak hours shall be first compensated with the electricity generation in similar time blocks in the same billing cycle. Energy units can be carried over to the next period, moderated as per the relevant rebate/surcharge percentage of ToD tariff applicable for the relevant year.
- DISCOMs may incentivize customers to provide energy from distributed generation, PV or other, during peak load hours.
- The technical requirements of equipment and electrical parameters (current, voltage, frequency, harmonics, etc.) are governed by the CEA's 'Technical Standards for Connectivity of the Distributed Generation Resources'.
- The DISCOM is to investigate the feasibility of grid interconnection based on grid hosting capacity and contracted load of the customer.
- Distributed generators connected to the grid should not have a rated capacity lower than 1 kWp.

B. Regulatory framework in Madhya Pradesh

Madhya Pradesh Electricity Regulatory Commission (MPERC) has introduced an updated net metering scheme in 2015. The key points of this regulation are:

21 The state is expecting an additional 900 MW to be connected between 2022 and 2025.

- PV capacity installed in a low voltage grid shall not exceed 30 % of the rating of the distribution transformer supplying it. DISCOMs are obliged to monitor the amount of PV that can still be installed on every distribution transformer, and publish this data with yearly updates.
- Time of day tariff consumers (mainly industrial and commercial): The electricity consumption in any time block (e.g. peak hours, off-peak hours, etc.) shall be first compensated with the electricity generation in the same time block. Any cumulated excess generation over consumption in any other time block in a billing cycle shall be accounted as if the excess generation occurred during the off-peak time block.
- At the end of the each financial year, any net energy credit which remains unadjusted shall be paid by the Distribution licensee to the consumers at the average pooled cost of power purchase as mentioned in the retail supply tariff order of that financial year.
- During any billing period, if customer generation exceeds consumption, the surplus units shall be carried forward to the next billing period as energy credit.
- The technical requirements of equipment and electrical parameters (current, voltage, frequency, harmonics, etc.) are governed by the CEA's 'Technical Standards for Connectivity of the Distributed Generation Resources'. All the cost related to augmentation shall be borne by the consumer.

4. Factors potentially limiting rooftop PV integration in India

4.1 Regulatory issues

4.1.1 Lack of enforcement

While all Indian states have been assigned a solar target for 2022 to reach the national target of 40 GW of rooftop and 60 GW of utility scale solar, an effective means of making sure the targets are reached is lacking. The main means of enforcement of solar targets are the renewable purchase obligations (RPO) mentioned in section 3.3. States oblige their DISCOMs to purchase a certain amount of renewable energy by a certain date, often including a specific requirement for solar power. DISCOMs regularly fail to comply with the RPO, and most states neither monitor nor enforce RPO compliance. The CERC has stated that the SERCs are in charge of compliance and complained that the CERC itself has no power over enforcement of solar targets as far back as 2013. [73] This lack of a central authority in charge of monitoring renewable energy targets seems to be very detrimental to their fulfillment. However, due to pressure from CERC, CEA and the federal government, the SERCs have recently become aware of this issue and are expected to control the states and DISCOMs more effectively in the future. [74]

Similar problems can be expected to occur with grid code requirements for PV units. The lack of experience on the DISCOMs' side, as well as their often dire financial situation, may lead to a lack of compliance control mechanisms. This should be addressed by the CERC and the SERCs quickly, as the installation of large shares of unchecked and possibly non-compliant PV may be a threat to operational security.

4.1.2 PV penetration limits set by DISCOMs

The limits set on distributed generation by some distribution companies are outdated and should be subject to review within this study. In 1999, the California Public Utilities Commission (CPUC) recommended limiting generation on distribution grid feeders to 15 % of the feeder's peak load to avoid reverse power flows [41]. The reasoning behind this was that minimum feeder load is usually around 30 % of peak load, and with a safety margin of 50 %, 15 % of peak load could safely be integrated. This rule is still applied by some Indian states, sometimes with the full amount of 30 %, or in the form of PV penetration being limited to 15 % of distribution transformer capacity. The rule has since been revoked in California, but is still accepted as a standard in other parts of the world, leading, among others, to the following problems:

15 % of peak load is too high of a safety margin, as has been understood by CPUC in the meanwhile as well, significantly hindering large scale deployment of distributed PV.

Reverse power flows, a completely new concept in 1999, are regularly managed in many countries' distribution grids, including Germany, Italy, Spain, California and Australia.

It is sometimes suggested that 15 % is the amount that can be integrated without any further safety precautions or grid codes. This is true when considering only the distribution feeder in question, but a total of 15 % of uncontrollable PV in a power system may cause system wide issues with frequency control and in cases of faults. In some states (see Table 13), considerably higher installed capacities are allowed, with up to 65 % of the capacity of the distribution transformer. These limits are less critical than the 15 % limit, and some SERCs are revising their limits as well, however, it remains usual for a SERC to set a fixed limit. Only the operators in Maharashtra, Telangana and Tripura allow an increase of the PV penetration after a load flow study has been conducted in the relevant area. This approach – setting a limit of how much PV can be integrated safely, and conducting more detailed calculations to possibly increase the penetration once the limit is reached, is sensible and could be adopted by other operators as well.

Additionally, SERCs in many states set limits on how much PV can be connected by a single customer, sometimes in the form of a MW limit, some based on the registered load of the customer. Especially in the latter should be subject to the same revisions as the penetration level limits, while the fixed MW limits are usually quite high (500 kW and above, this includes installations connected directly to 11 kV) and in line with federal rooftop PV legislation.

Table 13: Solar installed capacity limits in India by state, according to state codes and regulations.

State or union territory	Limits for individual customers	Installed capacity limits as % of DT capacity
Andaman and Nicobar Islands union territory	<500 kWp	50% of the capacity of the DT
Andhra Pradesh		60% of the rated capacity of the DT
Arunachal Pradesh	<1000 kWp	15% of peak capacity of DT
Assam	40% of contracted load, 2016, 80% of contracted load of Individual, 2017 draft	Specified by commission from time to time, 2015, 20% of peak capacity of DT, 2017 draft
Bihar	<Sanctioned load	15% of the capacity of the DT
Chandigarh union territory	<500 kWp: 80% of the sanctioned load	50% of the capacity of the DT
Chhattisgarh	Not Specified	
Dadra and Nagar Haveli union territory	<500 kWp	50% of the capacity of the DT
Daman and Diu union territory	<500 kWp	50% of the capacity of the DT
Delhi	No limit specified (depends on feasibility)	Not less than 20% of the rated capacity of the DT
Goa	<500 kWp	50% of the capacity of the DT
Gujarat	<50% of the sanctioned load	65% of peak capacity of DT
Haryana	<Connected load	30% of the peak capacity of the DT in case of interconnection is at LT and 15% of the peak capacity of the PT in case of interconnection is at HT
Himachal Pradesh	<80% of the sanctioned contract demand for consumers under two part tariff <30% of the sanctioned connected load for consumers under single part tariff	30% of the rated capacity of the DT
Jammu and Kashmir	<50% of the sanctioned load of the consumer	20% of the rated capacity of the DT
Jharkhand	<100% contracted load	15% of the rated capacity of the DT
Karnataka	<100% contracted load	If PV plant > 50 kW - 80% of the rated capacity of the DT If PV >50 kW – line current should be less than 80% of the rated current carrying capacity of the line
Kerala	<100% contracted load	For generation at LT: 15% of the rated capacity of the DT, above 15%, till the cumulative capacity of the solar energy systems connected to the DT, reaches the average load on the said transformer between 8 AM and 4 PM during the period of seven days succeeding the date of submission of application For generation at HT: Cumulative capacity connected to the distribution feeder under a particular power transformer is less than 80% of the average load as to 365 days preceding the date of submission
Lakshadweep union territory	<500 kWp	50% of the capacity of the DT
Madhya Pradesh	<1MWp at HT	30% of peak capacity of DT
Maharashtra	<100% contracted load	40% of the rated capacity of the DT, allowed to exceed upon detailed load study
Manipur	<100% contracted load	40% of the rated capacity of the DT

Meghalaya	<100% contracted load	15% of the peak capacity of the DT
Mizoram	<100% contracted load	40% of the rated capacity of the DT
Nagaland	<80% of the sanctioned load	15% of the peak capacity of the DT
Odisha	Not Specified	75% of the peak capacity of the DT
Puducherry union territory	<500 kWp	50% of the capacity of the DT
Punjab	80% of the sanctioned load	30% of the rated capacity of the DT
Rajasthan	80% of the sanctioned load	30% of the capacity of the DT
Sikkim	<100% contracted load	For generation at LT: 15% of the rated capacity of the DT, above 15%, till the cumulative capacity of the solar energy systems connected to the DT, reaches the average load on the said transformer between 8 AM and 4 PM during the period of seven days succeeding the date of submission of application For generation at HT: Cumulative capacity connected to the distribution feeder under a particular power transformer is less than 80% of the average load as to 365 days preceding the date of submission
Tamil Nadu	<100% contracted load	30% of the rated capacity of the DT
Telangana	For Residential and Government consumers: up to a maximum of 100% of the consumer's sanctioned load; For Industrial, Commercial and Other Consumers: up to a maximum of 80% of the sanctioned load / contracted demand of the consumer	For LT consumers, 50% of the rated capacity of the DT. For HT consumers, 50% of the maximum load permitted on the feeder, allowed to exceed upon detailed load study
Tripura	<100% contracted load	15% of the rated capacity of the DT, allowed to exceed upon detailed load study
Uttar Pradesh	<100% contracted load	15% of the rated capacity of the DT
Uttarakhand	<500	15% of DT, issue raised to increase this value
West Bengal	>5 kW, injection shall not be more than 90% of the consumption from the licensee's supply in a year	Not Specified

4.2 Market and financial issues

4.2.1 Market development

The market structure through which the DISCOMs procure power from the transmission grid is quite inflexible. DISCOMs generally have to stick to a day-ahead schedule, or even to long term contracts, leading to problems in balancing load and the amount of procured power already [42][68]. With fluctuating generation in the system, these problems will be aggravated, with DISCOMs possibly having to pay penalties for schedule deviations if no intra-day balancing mechanisms are introduced.

4.2.2 Financial performance of distribution companies

In present state of affairs each DISCOM needs to accept excess generation from solar rooftop projects and reimburse it at the rate announced by the regulator (discussed earlier under section 2.1.4) but as the penetration grows the increased distributed solar will decrease retail sales of the DISCOM, thus reducing their revenues and loading of this loss on to other consumer in the retail supply tariff. Additionally, since commercial and industrial consumers are also cross subsidizing other consumers by paying a higher tariff, it is most likely that they become independent and start generating their own electricity thus leaving behind a reduced pool of cross-subsidizing consumers. These factors lead to a passive opposition from DISCOMs. However it may be solved by introducing appropriate regulatory measures to rationalize the tariff system.

4.2.3 Financing issues

The rooftop solar sector is traditionally associated with having special financing needs. This is primarily due to the small project size, high upfront cost of project and credit risk associated with small scale lending. The above challenges are observed at different levels with residential and commercial or industrial consumers.

As per CPI research the commercial and industrial (C&I) consumers are reluctant to invest the high upfront amount required to install rooftop solar capacity given energy generation is regarded as non-core business activity. There are also concerns about operation and maintenance costs of solar PV assets. The C&I customers tend to favor signing up long term Power Purchase Agreement (PPA) contracts with an annual cost escalation rate agreed with the developer, which allows them to manage their cash flow

The PPA model also has a set of challenges, for example, poor legal enforcement of PPA contracts, leading to high lending risk for banks, poor bankability and creditworthiness of industrial and commercial users due to a variety of reasons.

In addition, banks are reluctant to lend to rooftop solar projects because of high perceived risks and limited information on the performance and track records of rooftop solar investments. The cost of solar PV panels and the balance of system continue to fall annually adding to the perceived risk factor for the banks. The resale value of primary assets will be lower than the sanctioned loan amount should a customer defaults on a loan.

4.3 Technical issues

4.3.1 Distribution system

Technical issues possibly limiting PV integration in Indian distribution systems are less pronounced than regulatory and economic problems. A preliminary analysis of Indian distribution grid structures including review of previous studies suggests that the following issues should be investigated with a special focus.

The last instance of voltage control is usually the transformer that steps down from the transmission level to 66 kV or 33 kV. Beyond this point, there is no active voltage control in the distribution system. Power transformers and distribution transformers often cannot change their ratio according to load and PV penetration. Thus, voltage quality should be focused on in Indian distribution grid studies, including the consideration of reactive power control of PV inverters, on-load tap changing transformers at least for the step from 66 or 33 kV to 11 kV, switchable or power electronic based reactive compensation and wide area voltage control. However, as many Indian customer suffer from regular brownouts and voltage drops on the feeders are high, the introduction of distributed PV may actually increase voltage quality at first, with control issues only arising at very high shares of PV.

Another set of issues to be analyzed during this study includes protection settings and anti-islanding regimes. Protection, especially at voltage levels below 33 kV, may not be able to detect faults during times of high PV generation when power flow is reversed. Protection settings must thus be analyzed and, if necessary, revised.

4.3.2 Grid codes, power system impact and communication

PV in the distribution grid may cause stability problems in the transmission grid if grid code requirements are not set properly. For this, communication between the regional and national transmission grid operators and the DISCOMs is necessary. The behavior of distributed generation during faults in the transmission system may affect the power system in its entirety – if, for example, all PV disconnects automatically at a certain frequency threshold, stability may be endangered if PV share is high enough.

5. Example Grids in Delhi and Bhopal

5.1 General information

5.1.1 Relevant voltage levels

Depending on the penetration levels that can be expected, rooftop PV may impact all voltage levels even beyond the distribution grid, possibly leading to adjustments of operational procedures and equipment in the transmission grid and on the power system level. However, PV distribution is not expected to be homogeneous, especially during the early stages of development. Installed capacity in selected areas with a customer base that is financially strong and willing to adopt the technology early on may grow very quickly. International experience shows that in such cases, the impact of PV feed-in on the distribution grid may already be very high, while no larger power system impact is observable yet.

BRPL and MPMKVVCL operate distribution grids at voltage levels of 33, 11 and 0.4 kV. BRPL also operates some 66 kV grids. Rooftop PV will be connected to the 0.4 kV low voltage grid and, for larger units on commercial or industrial buildings, directly to the 11 kV grid. Considering the previously mentioned inhomogeneous distribution, these grids can be expected to be impacted by PV feed-in first and most severely. It is thus sensible to focus on the 11 and 0.4 kV grids in this study, as issues such as reversed power flows and voltage range violations will appear there first.

Depending on the voltage control instances present in the distribution grid, which are quite different for the two DISCOMs, the operation of the upstream network may also be relevant to the studies. If the upstream network and the 11 kV level are connected with on-load tap changing transformers controlling the voltage, the voltage swings will not be transferred between the two levels, and the upstream network can be mostly disregarded. However, if this is not the case, every variation of voltage will also be transferred into the lower voltage levels, and vice versa.

5.1.2 Grid structure and operation: Delhi

BRPL'S distribution grid is supplied from the overlaying 220 kV transmission grid operated by the state transmission utility Delhi Transco Limited. Using on-load tap changing transformers with a rated apparent power of typically 100 MVA, the 220 kV grid feeds BRPL'S 66 kV grid. From the general topology, the 66 kV grid is a meshed grid, but it is usually operated with open switches as a radial grid with connection alternatives and increased redundancy.

Depending on the location of the 66 kV substations, the 66 kV grid directly supplies 11 kV feeders, or feeds into the 33 kV grids which then supply the 11 kV level. In the city where load density is high and distances are short, more extensive 33 kV grids are used and only the 11 kV feeders next to a 66 kV substation are fed directly from 66 kV. Longer distances with lower load in rural areas are more often bridged by longer 66 kV feeders which then directly connect to 11 kV. Both 33 and 11 kV are operated as radial grids, but often exhibit ring or meshed structures, especially in urban areas, which allow for multiple connection options for each feeder and a degree of redundancy. Transformers feeding the 11 kV feeders are on-load tap changing transformers, and capacitor banks for voltage and power factor control are installed in many 66, 33 and 11 kV substations.

11 kV feeders in the city are rather short due to the high load density, often less than 2 km, while rural feeders can reach total lengths of more than 10 km. The different load density is also reflected in the number and size of the distribution transformers supplied by an individual 11 kV feeder, with fewer but considerably larger transformers installed on urban feeders and a

higher number of small ones on a rural feeder.

All voltage levels operated by BRPL are partially overhead lines, partially underground cables. The urban grids in the city of Delhi itself have a high share of XLPE cables, especially at 11 kV and below, while overhead lines are more prominent in the outskirts and the rural areas outside of Delhi.

Delhi Transco Limited is responsible for voltage control in the transmission grid as well as for tap changing operations at the 220/66 transformers. The taps on the transformers are manually controlled and switched only a few times a year to account for seasonal demand changes, but usually do not respond to the daily fluctuations in the load or the subsequent voltage drops. This means that there is effectively no direct voltage control in the distribution grids, voltage fluctuations in the transmission grid are passed on directly to the lower voltage levels. However, voltage can be influenced to some degree with the switchable capacitor banks connected to some substations.

If DTL does not let the voltage on the 220 kV side of its transformers drop too far, this may have been adequate for the operation of load-only grids. Reduced residual loads or reverse power flows, which come with increased distributed generation, may require better voltage control. This is one of the reasons why BRPL is currently retrofitting almost all their 66/11 kV and 33/11 kV transformers with automatic voltage regulation. These transformers already possess on-load tap changing capability, but have so far been manually controlled as well (see

Table 14.) With automatic voltage regulation, the transformers will maintain the voltage on the 11 kV side at around unity, with the voltage range set between 0.98 and 1.02 p.u.

Table 14: Transformers and their control modes in the BRPL distribution grid.

Transformer	Controlled by	On-load tap changing	Control mode
220/66 kV	DTL	Yes	manual
66/33 kV	BRPL	Yes	manual
66/11 kV	BRPL	Yes	manual, active voltage control of secondary side currently being installed
33/11 kV	BRPL	Yes	
11/0.4 kV	BRPL	No	none

Shunt capacitors are connected to 11, 33 and 66 kV busbars to provide reactive power. Providing reactive power locally instead of drawing it from the transmission grid reduces line and transformer loading and thus technical losses. Reactive currents also have a greater impact on the voltage due to the mainly reactive impedance of lines and cables. Capacitor banks thus boost the voltage at the point of connection, which is beneficial especially in highly loaded load-only grids with high line voltage drops.

5.1.3

5.1.4 Grid structure and operation: Bhopal

Similar to Delhi, Bhopal is also supplied by a 220 kV transmission grid operated by the state transmission company. However, instead of the DISCOM operating a 66 kV grid themselves, subtransmission is handled by a separate company, M.P. Power Transmission Co. Ltd (MPPT), at 132 kV. The 132 kV level directly connects to 33 kV and 11 kV (for feeders close to the 132 kV substation) and is a meshed grid, while the distribution grid itself is operated radially. There is a considerable amount of meshing at the 33 kV level, though, and some at 11 kV level in the inner city as well, but switches are usually left open during normal operation. The multiple options of supplying each grid area provide extra redundancy in case of planned or unplanned outages.

Different from Delhi, the MPMKVVCL distribution grids are all overhead line (OHL) grids, with shorter and stronger lines with fewer distribution transformers being used in the city where load density is high, and longer and weaker lines supplying a higher number of distribution transformers outside. The general structure and the expected issues are thus quite similar to those expected in Delhi, with the difference that currently, no undergrounds cables are used in Bhopal.

However, no means of automatic voltage control is present. On-load tap changing transformers are used for 132/33 kV and some of the 33/11 kV connections, but none employ automatic voltage regulation. The 132/33 kV transformers are controlled by the subtransmission company, which will adjust the tap setting manually if the voltage deviates too much from the nominal value, but actual switching operations are rare and the voltage deviation is typically quite high. Those 33/11 kV transformers with on-load tap changing capability are usually only switched twice a year to account for the seasonal change in load. This means that a greater amount of attention has to be paid to voltage control and the impact of voltage in the upstream network when integrating PV into the grids in Bhopal.

Table 15: Transformers and their control modes in the BRPL distribution grid.

Transformer	Controlled by	On-load tap changing	Control mode
132/33 kV	MPPT	Yes	manual
33/11 kV	MPMKVVCL	Rarely, mostly no	Manual/none
11/0.4 kV	MPMKVVCL	No	none

Shunt capacitors are connected to 11, 33 and 132 kV busbars to provide reactive power. Providing reactive power locally instead of drawing it from the transmission grid reduces line and transformer loading and thus technical losses. Reactive currents also have a greater impact on the voltage due to the mainly reactive impedance of lines and cables. Capacitor banks thus boost the voltage at the point of connection, which is beneficial especially in highly loaded load-only grids with high line voltage drops. Shunts in Bhopal are switchable in steps and controlled with automatic power factor controllers.

5.2 Urban feeder Delhi

5.2.1 Upstream network

The Delhi urban feeder is supplied from an upstream network of 220 kV (transmission), 66 and 33 kV (distribution.) The 66 and 33 kV networks are meshed, but during normal operation, switches are left open, forming radial feeders. The feeder is normally supplied by:

- Three 220/66 kV transformers, rated at 100 MVA each;
- 4 km 66 kV double circuit carrying a maximum of 2 x 110 MVA;
- A 66/33 kV power transformer, rated at 50 MVA;
- 6.4 km 33 kV double circuit cable and 0.5 km double circuit OHL carrying a maximum of 2 x 30 MVA.

There are multiple alternate paths to the relevant feeder from different 220 and 66 kV substations, the path normally used is marked with an arrow. Other (radial) 33 and 11 kV feeders are supplied by the 66/33 kV substation (hence the transformer rating of 50 MVA.)

On-load tap changers are considered to be installed at 33/11 kV power transformers with enough taps to avoid being unable to control the voltage at LT side of the transformer. Therefore, the voltage of the 11 kV and LV network is decoupled from the upstream network. The upstream network will not be considered during simulations, since it does not have an impact on the limitations of PV integration.

5.2.2 Medium voltage (11 kV)

The 11 kV feeder is set up as a radial grid with two branches, made up of a total of 3.1 km of single circuit 300XLPE underground cable with a maximum carrying capacity of 5.7 MVA. The structure is shown in Figure 19. There are four 11/0.4 kV substations on the feeder with two distribution transformers each. The transformers each feed a low voltage grid of their own and are not connected in parallel on the low voltage side. Due to the urban setting with high load density, distribution transformers are quite large, with seven 630 kVA units and one 990 kVA unit. The total installed transformer capacity is 5.4 MVA, so the supplying cables are sufficient to carry the full transformer capacity. Peak load is 2.5 MW. Short cable lengths and strong cables indicate that no large voltage swings can be expected on the feeder.

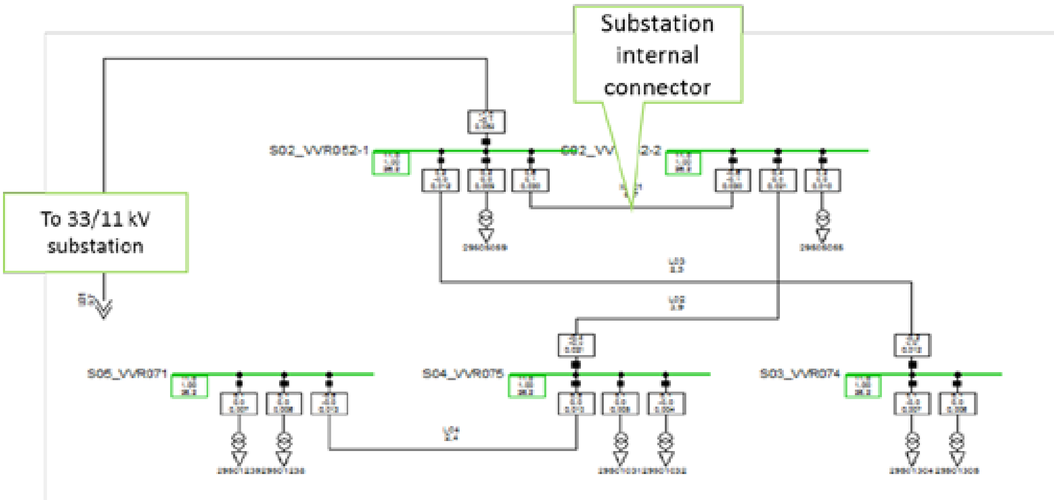


Figure 19: PowerFactory SLD of 11 kV feeder.

5.2.3 Low voltage (400 V)

Low voltage networks used are strictly radial, with each distribution transformer feeding three or four individual low voltage feeders. Average feeder length is 230 m, with lengths ranging from 36 to 720 m. A total of 4318 m of low voltage underground cable and 2146 m of low voltage OHL are installed in the area. Cable types are mostly 4x300 cables, OHL mostly Dog ACSR (aluminium conductor, steel reinforced), no further information on the types was provided. Lengths of each feeder were provided by type, as were loading values[22] of each conductor on each feeder.

The low voltage grid is a TN system, meaning a separate neutral conductor exists. As visible in a data sample in Figure 20, some of the low voltage feeders show severe asymmetric loading with high current on the neutral conductor. The reason for this characteristic is still to be determined, as single phase customer connections are not uncommon in India, these may be causing the asymmetry.

22 Unspecified whether average, maximum or snapshot loading.

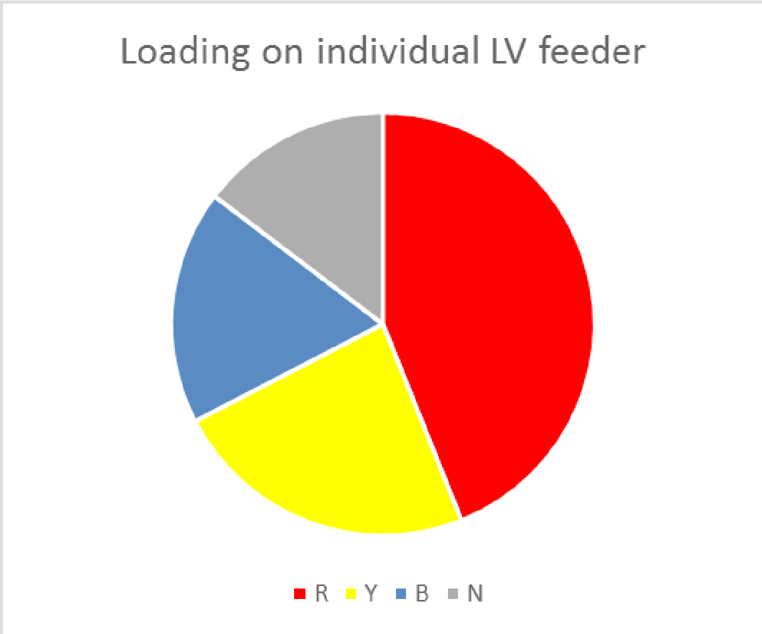


Figure 20: Loading per conductor (red, yellow, blue are phase conductors, N/grey is neutral) of sample LV feeder, showing highly asymmetrical load.

5.2.4 Currently installed PV

A small amount PV is already connected to one of the low voltage grids, with two units of a combined installed capacity of 80 kW on top of a school. Both units have inverters that are compliant with the German grid code and could thus provide reactive power for voltage control if necessary.

5.3 Rural feeder Delhi

To determine the impact of distributed PV on the grid in a rural area, BRPL provided data for two 11 kV feeders located south west of Delhi. The grid area is located on the very edge of the National Capital Territory of Delhi, reaching the border to the neighboring state of Haryana.

5.3.1 Upstream network

Compared to the urban upstream network, the structure supplying the rural grid is simpler.

- Four 220/66 kV transformers, rated at 100 MVA each, supplying a double busbar 66 kV system where multiple 66 kV feeders and a 66/11 kV substation are connected;
- 12 km 66 kV double circuit OHL from 220/66 kV substation to 66/11 kV substation, carrying a maximum of 2 x 83 MVA.

There are no alternative connections to supply the 66/11 kV substation.

Similar to the urban feeder, on-load tap changers are considered to be installed at 66/11 kV power transformers with enough taps. The same conclusion as for the urban feeder can be drawn (no influence on 11kV voltage from the upstream network) and the upstream network will be omitted during simulations.

5.3.2 Medium voltage (11 kV)

The two feeders for which data was supplied by BRPL for analysis are located in a rural area. Both feeders have roughly similar characteristics, bridging distances of around 10 km with a mix of ACSR OHL and underground cables (see Table 16.) The grid was modelled in PowerFactory according to the data delivered by BRPL.

Table 16: Cable and line lengths and installed distribution transformer capacities of relevant 11 kV feeders.

	Feeder 1	Feeder 2
Dog type ACSR, 5.7 MVA	19.8 km	16.7 km
150 XLPE cable, 3.8 MVA	5.6 km	-
300 XLPE cable, 10.1 MVA	5.3 km	2.6 km
Total	30.7 km	19.3 km
Installed DT capacity	5.16 MVA	5.20 MVA

As line lengths and geo coordinates delivered did not match up, the line lengths were estimated based on the geomap representation in PowerFactory. Naming conventions of nodes and distribution transformers allowed for the localization of most of them on a map, showing that the line lengths provided by BRPL must have been incorrect, while the geo coordinates were largely correct. Both feeders supply a number of villages in the area:

- The feeder 1 supplies three villages – with the largest one including a large bus depot and a school outside the village – as well as several farms and settlements outside the villages, and number of water pumping stations.
- Feeder 2 supplies four villages and a small number of farms outside the villages;

Feeder 1 supplies a higher number of customers, is longer than the Feeder 2, and has more branches and a higher percentage of cables, while Feeder 2 is a typical more lightly loaded feeder with mostly OHL.

Both feeders have the main loads attached towards the end of the feeder. Longer cabled sections starting at the 66/11 kV substation pass by several villages – which are supplied by other feeders connected to the same substation– before branching out to the supplied villages a few kilometers outside. Based on the characteristic of the grid with considerably longer lines than those in urban areas, it can reasonably be expected to be more prone to voltage swings as load and generation characteristics change through the introduction of PV power.

BRPL is currently retrofitting the three transformers at the 66/11 kV substation to automatically regulate the voltage on the 11 kV side and thus decouple it from voltage swings in the upstream network. Each transformer supplies a busbar section with five to seven 11 kV feeders. The sections are not connected to each other during normal operation and can thus be independently controlled by the transformers as well as by a switchable stepped capacitor bank attached to each section.

5.3.3 PV power plant

According to the information provided by BRPL, an open field, utility scale PV power plant is proposed to be constructed in the area, with either 3.5 MW of installed capacity. Several options for connection of the unit will be evaluated:

- Construction of one or two new lines or cables for direct connection to the 66/11 kV substation;
- Connection to either 11 kV feeder;
- A split of the power plant capacity and connection partly to Feeder 1, partly to Feeder 2.

5.3.4 Low voltage (400 V)

Low voltage grids supplied by the two 11 kV feeders are of varying size and load, as evident by the delivered distribution transformer data and their location:

- 300, 400 or 630 kVA transformers are used to supply the main villages or parts of the main villages;

- 100 kVA transformers are used for the majority of other grids, such as farms, outside settlements, commercial customers (school, bus depot) or water supply stations;
- 16 kVA and 25 kVA transformers are used for single houses outside the villages as well as for street lighting.

Customers are marked as all residential by BRPL, but given the topology, other customer classes such as water supply stations, agricultural and commercial customers can be expected. However, due to the provision of sufficient measured load time series data (see section 6), customer classification is less important here.

5.4 Urban feeder Bhopal

5.4.1 Upstream network

The 11 kV feeder in urban Bhopal is not really supplied by an upstream network below 132 kV, as it is located very close to a 132 kV substation. Inside the substation, voltage is stepped down from 132 to 33 to 11 kV. The only relevant upstream lines are two Dog type conductor ACSR circuits that connect two 33 kV busbars inside the substation.

Connection of 132 kV and 33 kV is implemented with two manually controlled on-load tap changing transformers of 40 and 63 MVA rating, controlled by the subtransmission operator. The large 33 kV busbar supplied multiple 33 kV feeders as well as the interconnector to the 33/11 kV busbar inside the same substation.

5.4.2 Medium voltage (11 kV)

Two 33/11 kV transformers without on-load tap changing (OLTC) capability, rated at 5 and 8 MVA, supply the 11 kV busbar. The busbar is split in two isolated sections during normal operation, leaving the relevant 11 kV feeder and one other feeder to be supplied by the transformer rated at 5 MVA. Each 11 kV busbar section is equipped with a 1200 kVAr capacitor bank for reactive power compensation.

The feeder consists of a total of 2.7 km of OHL, with 1.33 km of Rabbit type ACSR rated at 2.9 MVA, 1.32 km of Raccoon type ACSR rated at 3.8 MVA, and a very short (40 m) section of 95AB air cable rated at 4.4 MVA. The structure is radial during normal operation, but for redundancy, the feeder can also be supplied from the other side, with an open connection to another 11 kV feeder at its end.

The 11 distribution transformers connected are smaller than on the urban feeder in Delhi, rated from 100 to 315 kVA, with mostly 200 kVA transformers installed. Installed transformer capacity is 2.22 MVA, and peak load according to MPMKVVCL is 1.08 MW.

5.4.3 Low voltage (400 V)

The 11 kV feeder supplies 11 low voltage grids with around 700 customers, domestic as well as office buildings.

5.4.4 Currently installed PV

90 kW of rooftop PV are already installed in the area, connected to two different distribution transformers. Considering the low loading of the transformers, reversed power flows may already be present in the two low voltage grids where the PV is connected.

5.5 Rural feeder Bhopal

For analysis of the issues to be expected with PV integration in a rural area, MPMKVVCL provided data on the structure of a distribution grid connecting some outskirts of Bhopal to the nearby villages. It consists of a larger 33 kV structure and detailed data of a single 11 kV feeder at the end of this structure.

5.5.1 Upstream network

The upstream network is connected to the subtransmission grid by a 132/33 kV substation with two transformers rated at 40 and 20 MVA, which supplies multiple 33 kV feeders. The relevant feeder mainly consists of a total of 9.4 km of double circuit OHL with Dog type ACSR conductors, carrying a maximum of 27 MVA, and 2.11 km of similar single circuit OHL carrying a maximum of 13 MVA. The feeder, depicted as an SLD in Figure 21, connects five 33/11 kV substations with a total installed transformer capacity of 36.3 MVA. Each substation has capacitor banks for reactive power compensation connected to its 11 kV side, rated from 1200 kVAr in the smaller substations to 2 x 1500 kVAr in the larger ones.

Only two of the installed 33/11 kV transformers have on-load tap changing capability, and those are typically kept at a fixed setting as well. Combined with the manually switched 132/33 kV transformer operated by the subtransmission company, no active direct voltage control instance currently exists, and voltage in the grid is completely dependent on the voltage in the subtransmission grid. However, the shunt capacitors in the 132/33 kV substation are used to influence the voltage as well as compensate the power factor.

The relevant feeder which is modelled in detail is connected to the 33/11 kV substation at the end of the 33 kV feeder.

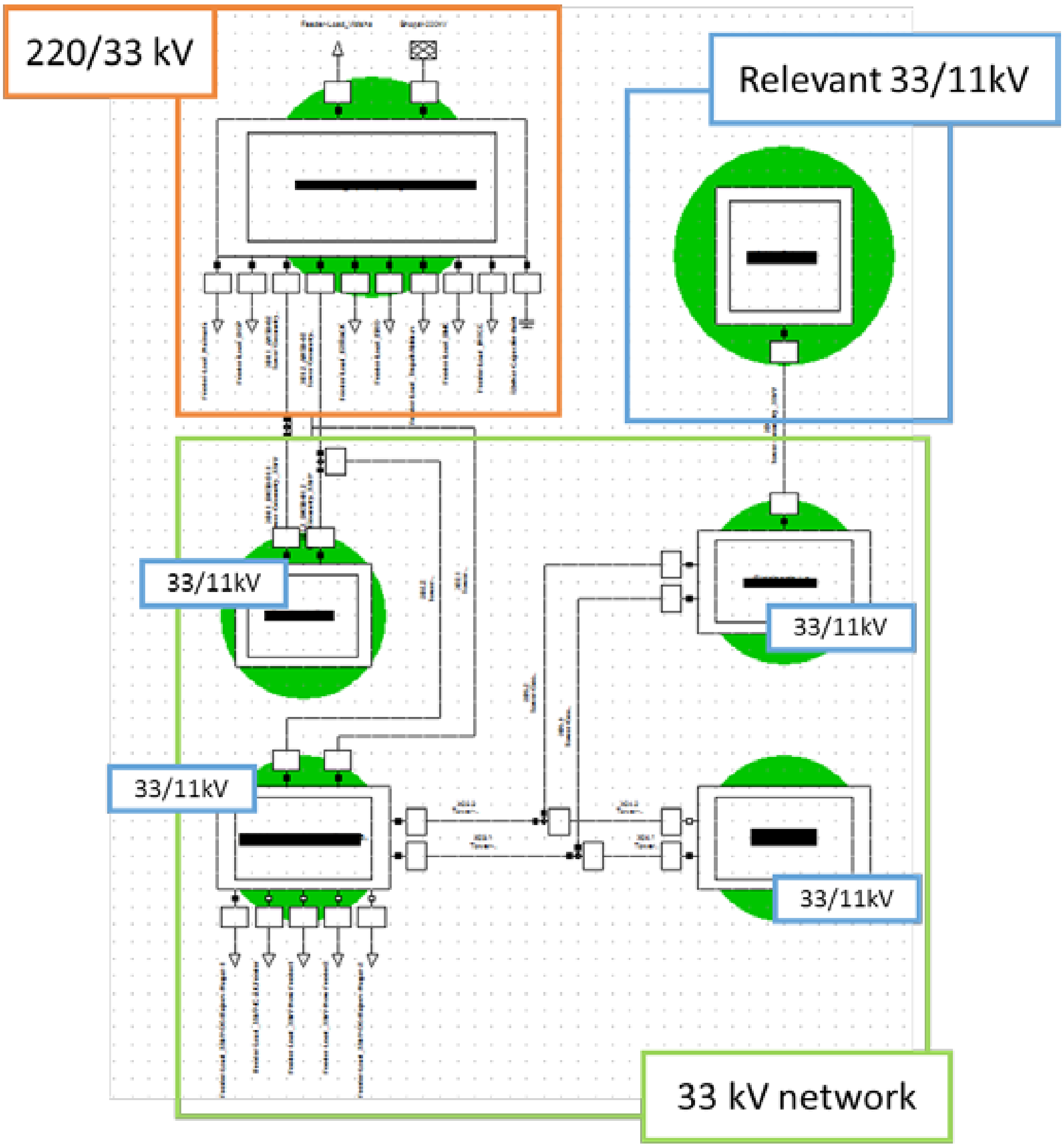


Figure 21: Upstream network structure (PowerFactory SLD.)

5.5.2 Medium voltage (11 kV)

The 11 kV feeder to be analyzed connects several small villages outside Bhopal and consists of a total of 11 km of OHL. All lines are Raccoon type ACSR that carry a maximum of 3.8 MVA. The feeder is connected to the 33 kV level with a 5 MVA off-load tap changing transformer, fixed at a 1:1 per unit ratio. A total of four 11 kV feeders can be connected to the 11 kV busbar, but only two are connected in normal operation while the others are supplied by other substations. The relevant feeder is a radial structure as shown in Figure 22. The feeder supplies a total installed capacity of 3.69 MVA of distribution transformers at a peak load of currently 1.55 MW.

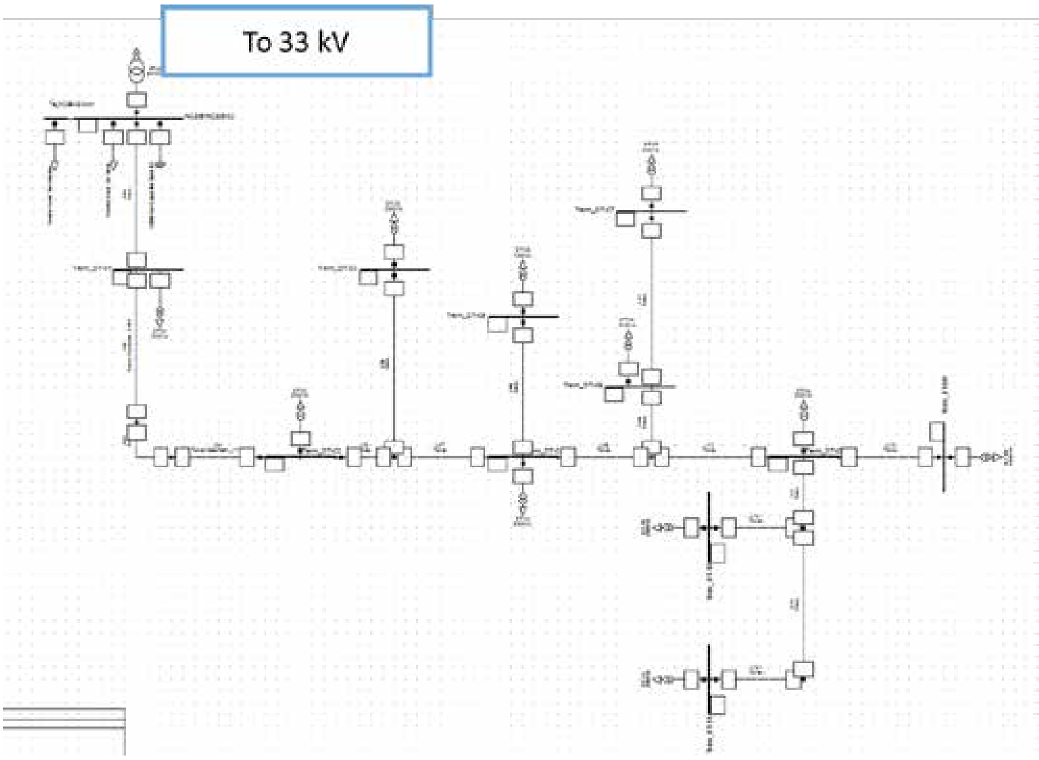


Figure 22: PowerFactory SLD of Bhopal rural 11 kV feeder.

5.5.3 Low voltage (400 V)

This 11 kV feeder feeds 33 individual low voltage grids, mostly connected by 200 kVA distribution transformers. Those grids have radial structures and a mix of residential, commercial and agricultural customers, as specified by MPMKVVCL.

5.6 Comparison of key characteristics

Key characteristics of all five feeders are listed in Table 17. Comparing those, the following facts are of special importance:

- The rural feeders supply comparable installed load capacities to the urban feeders, but their line lengths are longer by four to ten times, indicating possible voltage problems;
- The rural 11 kV grid in Bhopal is shorter than those in Delhi, but is supplied by a longer 33 kV grid structure without voltage control, resulting in similar issues;
- The urban feeders are rather lightly loaded and have strong lines, cables and transformers, making overloading less probable;
- Light loading of urban feeders can lead to reverse power flows even at low PV penetrations, may require a revision of protection settings;
- The rural feeders in Delhi may be used to evacuate power from a PV power plant, which may overload even the strong grid structure.

Table 17: Comparison of relevant 11 kV grids.

	Delhi urban	Delhi rural 1	Delhi rural 2	Bhopal urban	Bhopal rural
Supplied from	33 kV	66 kV	66 kV	132/33 kV	33 kV
Dominant cable/ line type	300XLPE cable, 5.7 MVA	Dog ACSR OHL, 5.7 MVA	Dog ACSR OHL, 5.7 MVA	Rabbit ACSR OHL, 2.9 MVA	Raccoon ACSR OHL, 3.8 MVA
Length OHL	-	19.8 km	16.7 km	2.7 km	11.0 km
Length UG cables	3.1 km	10.9 km	2.6 km	-	-
Total length	3.1 km	30.7 km	19.3 km	2.7 km	11.0 km
Installed DT capacity	5.4 MVA	5.2 MVA	5.2 MVA	2.2 MVA	3.69´´7 MVA
Peak load	2.50 MW	3.4 MW	3.0 MW	1.1 MW	1.6 MW
Expected main issues	Protection, reversed power flow	Voltage control, asset overloading (PV power plant)		Protection, reversed power flow	Voltage control

6. Measured data

Measured operational data from the relevant grid area greatly facilitates modelling and improves the quality of model and results. Relevant data includes measurements of voltage, current, active and reactive power at different points in the grid in different time resolutions (preferable: hourly or sub-hourly) during normal operation.

Measurements can either be available as outputs of SCADA systems or other monitoring mechanisms, or they can be procured through a project specific measuring campaign using Phasor Measurement Units or similar devices. Necessary data and typical availabilities are specified in Table 18.

In the following sections, the data provided by BRPL and MPMKVVCL, its format and quality and the needs for adjustments and corrections will be discussed.

Table 18: Measured load and voltage data required for grid modelling and simulation.

Data	Typically available	Additional requirements
Voltage, HV	Voltage at all busbars through SCADA system	Sufficient
Voltage, MV	Voltage at secondary side of HV/MV transformer	Sufficient for modelling. For model validation, measurements from other locations in the grid (feeder end) may be useful.
Voltage, LV	None	
Load, HV	Power flow through HV/MV transformer	Active and reactive power measurements may be available, can be used for model validation
Load, MV	Peak load at MV/LV transformers	Feeder load time series (active power) are often available for MV. For LV grids, only peak load may be available, if at all.
Load, LV		

6.1 Measured Load Data

6.1.1 Active and reactive power

A. 11 kV level and distribution transformers

Active and reactive power measurements for both Delhi grid areas were delivered by BRPL. The knowledge of the current distribution of load in the grid and the characteristics of consumers are valuable for a valid simulation model, so the main focus was on the load distribution in the relevant 11 kV grids. For both areas, measured time series, mostly spanning across more than a year, at distribution transformer level were delivered. The data sheets included three phase active and reactive power and voltage measurements in 30 minute time steps, as well as the energy drawn by the transformer and the underlying low voltage grid within each time step (see Figure 23 for an example.)

DATETIMET	ACTIVE_B_PH	ACTIVE_Y_PH	ACTIVE_R_PH	REACTIVE_B_PH	REACTIVE_Y_PH	REACTIVE_R_PH	VBV	VYV	VRV	NO_PWR_DU_MI	KWH_ABS
Apr-01-2015 12:30:00 AM	56.028	0	48.852	18.492	-16.284	9.384	235.75	234.6	234.37	0	69
Apr-01-2015 01:00:00 AM	35.2	0	45.54	19.596	-15.456	8.832	235.29	234.37	234.37	0	67.56
Apr-01-2015 01:30:00 AM	52.992	0	48.852	19.044	-16.56	8.28	238.97	237.59	237.82	0	67.08
Apr-01-2015 02:00:00 AM	35.2	0	45.54	19.596	-16.56	8.832	238.97	237.59	238.05	0	67.92
Apr-01-2015 02:30:00 AM	54.096	0	44.436	19.32	-16.008	8.28	238.05	236.67	236.9	0	66.24
Apr-01-2015 03:00:00 AM	54.372	0	43.816	19.596	-16.56	7.452	238.51	237.13	237.36	0	66.12
Apr-01-2015 03:30:00 AM	69	0	60.996	19.596	-16.284	8.28	237.82	236.21	235.75	0	73.8
Apr-01-2015 04:00:00 AM	91.356	0	74.796	21.252	-17.112	6.348	234.14	234.37	233.45	0	94.8
Apr-01-2015 04:30:00 AM	98.808	0	96.6	20.7	-15.732	6.348	229.77	229.54	227.93	0	118.92
Apr-01-2015 05:00:00 AM	108.468	0	105.432	20.976	-15.456	7.176	225.17	226.09	223.56	0	134.04
Apr-01-2015 05:30:00 AM	106.536	0	112.884	15.456	-6.9	6.624	223.56	224.02	219.38	0	141.24
Apr-01-2015 06:00:00 AM	114.816	0	115.092	12.696	-6.9	4.692	222.18	224.02	219.65	0	139.56
Apr-01-2015 06:30:00 AM	110.676	0	107.916	13.248	-7.176	4.968	221.55	222.87	220.11	0	128.28
Apr-01-2015 07:00:00 AM	105.432	0	96.876	17.112	-11.868	8.28	226.78	227.24	224.94	0	122.28
Apr-01-2015 07:30:00 AM	106.26	0	97.152	17.388	-11.868	8.556	227.01	227.47	224.94	0	118.68
Apr-01-2015 08:00:00 AM	85.008	0	80.04	18.768	-11.04	7.728	230.46	230.46	228.39	0	103.32
Apr-01-2015 08:30:00 AM	94.116	0	79.764	21.252	-13.8	8.556	229.77	230.46	228.85	0	102.48
Apr-01-2015 09:00:00 AM	77.556	0	69	15.456	-15.18	10.764	230.92	230	228.16	0	92.16
Apr-01-2015 09:30:00 AM	75.072	0	61.548	20.424	-8.832	9.384	225.63	226.32	224.94	0	82.44
Apr-01-2015 10:00:00 AM	75.9	0	56.856	15.18	-13.248	5.52	230.92	230.92	230.69	0	83.76

Figure 23: Example of delivered data sheet for a distribution transformer with active, reactive power and voltage measurements per phase as well as total energy consumed within each time step. Missing active power values for one phase due to instrument malfunction marked in red.

For the urban feeder, mostly consistent time series for all distribution transformers were delivered, allowing for detailed load modelling of several months (urban) or an entire year (rural.) Some gaps in the data due to malfunctions of measuring or communications equipment had to be filled (see section 6.1.2.)

For the Delhi rural feeders, similar data of good quality is available for roughly one third of all installed distribution transformers. Due to the sheer number of transformers installed, not all of them are equipped with measuring devices. On others, measurements started only very recently, thus no substantial amount of data could be collected, or the data had large gaps. However, the data for most of the larger transformers is of sufficient quality, and there is enough data for some smaller and more remote transformers to assign each one a load characteristic and corresponding time series (see section 6.1.3.)

No distribution transformer level measurements are available at MPMKVVCL.

B. 11 kV feeder loads

Feeder load data was provided for the relevant 11 kV feeders in Bhopal by MPMKVVCL. This load data was delivered in the form of 15 minute values of average phase current for one year, as well as maximum and minimum power factor and reactive power demand per month. As there are no distribution transformer load time series available in Bhopal, detailed 11 kV feeder data is crucial for the objectives of the project.

No 11 kV feeder load data was made available by BRPL. The total load time series of the 11 kV feeders that are modelled in detail can be calculated from the load time series of the attached distribution transformers and the corresponding technical losses (calculation via PowerFactory.) However, for the rural feeders, this will be somewhat inaccurate as data is unavailable for some transformers.

C. Upstream network and parallel 11 kV feeders

Load characteristics and distribution and the resulting power flows in the upstream network influence the voltage in the grid and thus also impact the underlying 11 kV and low voltage grids.

For the grids in Bhopal, loads attached to all substations in the upstream network up to the 132/33 kV transformer have to be considered. This was delivered in the form of loading data of 33 kV lines and 33/11 kV transformers by MPMKVVCL[23]. This data is still lacking reactive power data, which has been requested.

Due to the decoupling of the voltage in the upstream network and the 11 kV feeders through the use of the automatically voltage regulating tap changing transformers between 66 or 33 and 11 kV in the BRPL grid, these effects can be disregarded, and further information about load in the upstream network is not required. Sample day load data of busbars and feeders in the upstream network were provided by BRPL anyway to model the power flows in the network correctly if necessary.

Other 11 kV feeders attached to the same 11 kV busbar as the feeders that are modelled in detail, however, influence the voltage on that busbar and thus directly impact voltage on the relevant feeder as well as the switching regime of the transformer. Information on the total load supplied by each 66/11 or 33/11 kV transformer was supplied by BRPL and MPKVVCL in the form of time series of active and reactive power flows across the transformer, which is sufficient for modelling.

23 At the point of the draft report, some incomplete data was available and the rest requested from MPMKVVCL, who confirmed they will be able to deliver it.

6.1.2 Filling data gaps

Wherever data is measured over a longer time period, data gaps and erroneous measurements can be expected. Malfunctions of measuring instruments or the communication equipment necessary to submit the data are not uncommon. For this reason, data has to be reviewed and corrected if necessary and possible.

Some of the distribution transformer load data provided for the rural feeders had more gaps than actual data (see Figure 24) and was disregarded. The time period for which the most detailed data was made available was December 2015 to December 2016. Data which did not include this time span was also disregarded. Data for the urban feeder consistently included December 2015 to December 2016, no data had to be discarded.

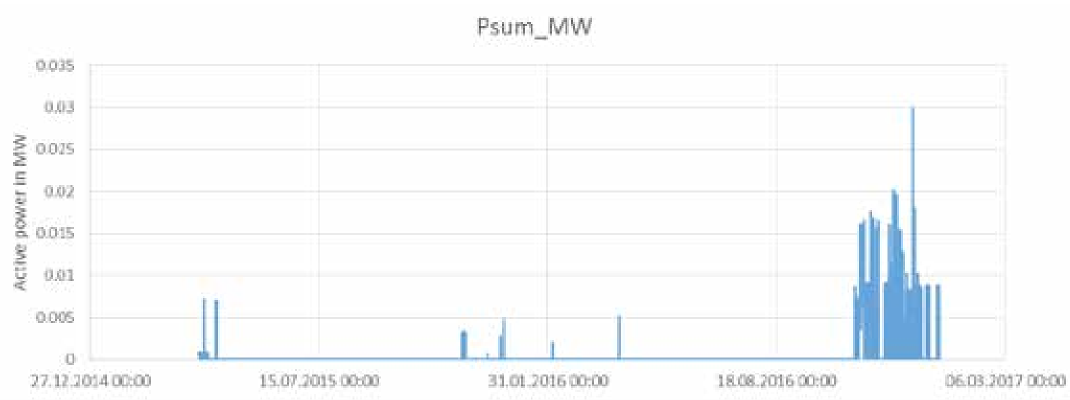


Figure 24: Distribution transformer data from a rural feeder, rendered unusable by very large gaps.

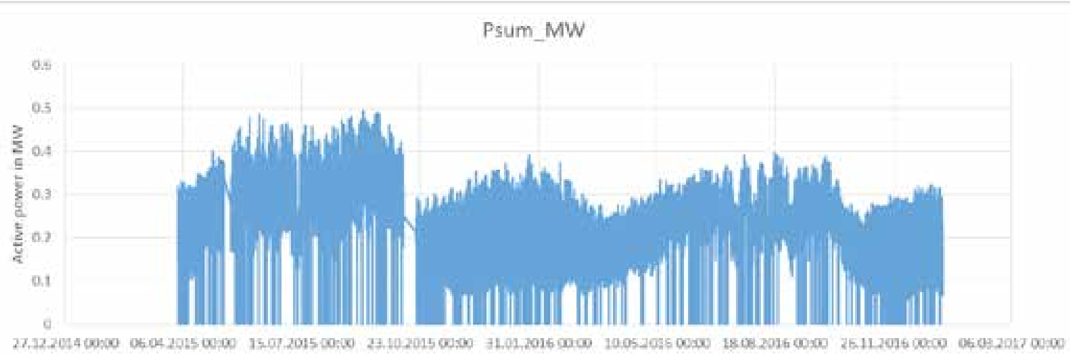


Figure 25: Distribution transformer data from a rural feeder, complete, but with gaps.

The data provided for the Bhopal grids consistently contained the full year 2016 in 15 minute steps. As measured data was only obtained for the 11 kV level and above, measurements were conducted in manned substations under close supervision of the staff. Data errors were thus a lot less frequent than they were with the data from distribution transformers, which was collected automatically and largely unsupervised. However, this means that distribution transformer load data is lacking for Bhopal and has to be estimated from the delivered load keys (see section 6.1.4.)

For the data from the relevant time periods, data gaps were treated as follows:

- The most frequent type of error proved to be the outage of one of the three phase power measurements with a zero voltage reading, which leads to an incorrect reading of total active and reactive power. This was fixed by assigning the average of the two measured phases to the missing phase (see Figure 26.)

- A zero or empty reading of voltage on all three phases in the Delhi data was interpreted as a measurement device outage, unless marked as an actual power outage by BRPL. Unmarked outages were interpolated linearly as a first approach and will be assigned a load profile from similar days if the actual data is needed for any simulation.
- Gaps in the (active power only) data from Bhopal were interpreted as power outages on the relevant feeder.

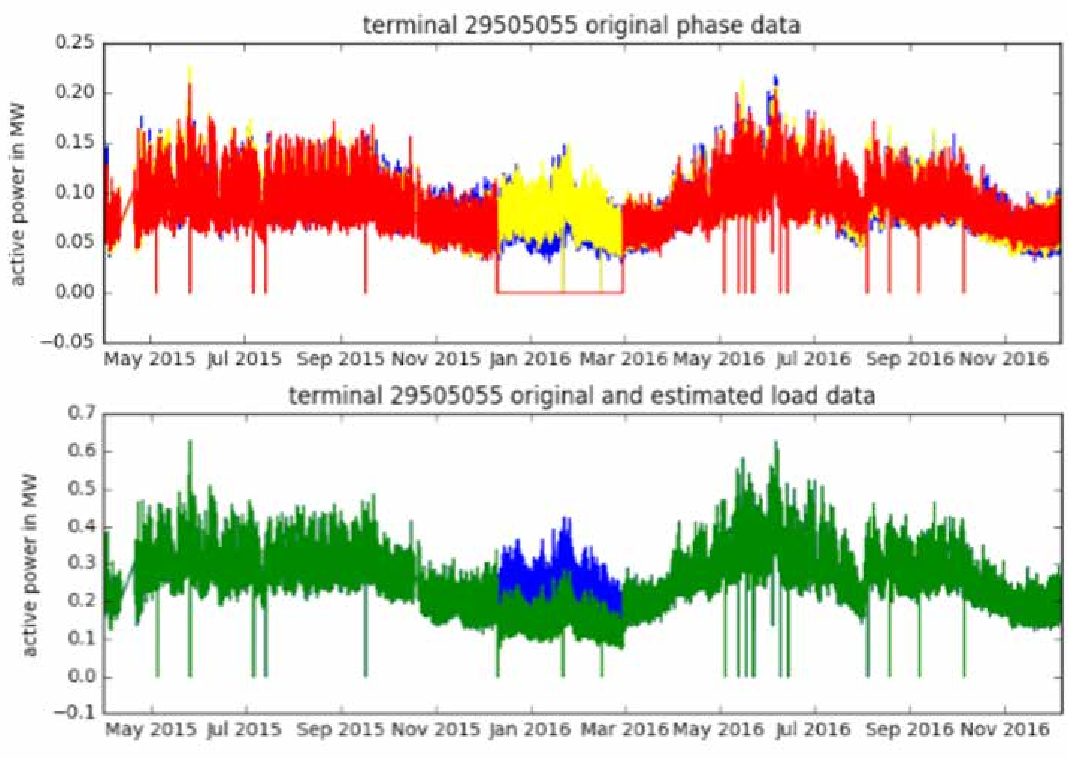


Figure 26: Load data of a 630 kVA transformer in urban Delhi. Power per phase (upper figure) with one phase clearly missing for two months, calculated (green) and corrected (blue) total power (lower figure.) Total data gap for a week to the left of the figure is filled in by linear interpolation.

6.1.3 Classification of low voltage grids (Delhi rural feeders)

As detailed load data was not available for all distribution transformers on the Delhi rural feeders, the missing data had to be filled in based on an analysis of the available data. Transformers with missing or erroneous data were classified based on the installed unit and its location, taking into account the surroundings using OpenStreetMap and Google Maps. Each was assigned a peak load calculated from values of similar transformers with available data, yielding the classification given in Table 19. Notably, transformers in villages are overloaded by the peak load, however the overload is less than 20 % and occurs only for a few hours each year, which is judged to be not uncommon from the available load data. Transformers outside the villages are generally lightly loaded, as some, despite being rated at 25 or 100 kVA, only supply a single farm or house with a peak demand of a few kW.

Each transformer is assigned a normalized time series (per unit values) for active power, and a power factor time series, both from a representative similar unit in the area. As mentioned in section 6.1.1B, these load values will be adjusted to have the 11 kV feeder load match up with the actual values once those become available.

Table 19: Classification of distribution transformer loads on the rural 11 kV feeders in Delhi.

Load location (from map)	Transformer rating	Assumed peak load
Village	400 kVA	450 kW
Village	100 kVA	120 kW
Small settlement	100 kVA	90 kW
Outside farm	100 kVA	60 kW
Single house or other	25 – 100 kVA	15 - 30 kW
Water supply	100 kVA	87 kW

6.1.4 Load key development (Bhopal feeders)

As no directly measured load series at distribution transformers were made available for the Bhopal feeders, the load attached to each transformer and its characteristic have to be estimated based on the following available data:

- Number of customers supplied by the DT;
- Maximum load of the DT (partly available);
- Installed load capacity at the DT (available due to the maximum power fee paid by customers);
- Classification of attached customers;
- Typical load profiles for customer classes obtained from MPMKVVCL and other sources;
- Customer electricity billing data made available by MPMKVVCL, sometimes in monthly resolution.

This data allows for the creation of a time dependent load key for each feeder, which distributes the total 11 kV feeder load – which is available as a time series – to the distribution transformers.

6.1.5 Low voltage load modelling (Delhi urban feeder)

For the urban feeder in Delhi, data on the structure of the underlying low voltage grids was made available by BRPL. Data included:

- Feeder number per distribution transformer;
- Total length of each feeder;
- Cable and line types used on each feeder, including lengths, but no information about location of sections on the feeder;
- Peak loading of each feeder with current values for all three phases and the neutral conductor.

From this data, a slightly simplified simulation model of the low voltage grids can be set up with the following assumptions:

- The power flowing through the distribution transformer, both active and reactive, is always split up between the supplied feeders as indicated by the key calculated from the peak load values;
- Loads are distributed evenly on the feeder (impact of shifting more load towards or away from the transformer can be assessed by using the corresponding tool in PowerFactory);
- Feeders composed of different line and cable types are always starting with the type with the highest ampacity and descending from there along the line.

6.1.6 Load characteristics

The daily and seasonal load characteristics of the different grids are diverse, but generally, load will increase during summer due to air conditioning. In areas with a higher number of business customers who need and can afford air conditioning around the clock, this can lead to stronger increase during the day than during the night, which leads to a higher amount of the PV power generated in the area to be consumed locally and reduces reversed power flows (see Figure 27, lower graph.) In areas with more residential customers, load in summer can be higher during the night due to nightly A/C use (see Figure 28.) Low load during the day can lead to reversed power flows, creating situations known from other countries with high PV shares on residential buildings with low daily demand such as Germany or Italy.

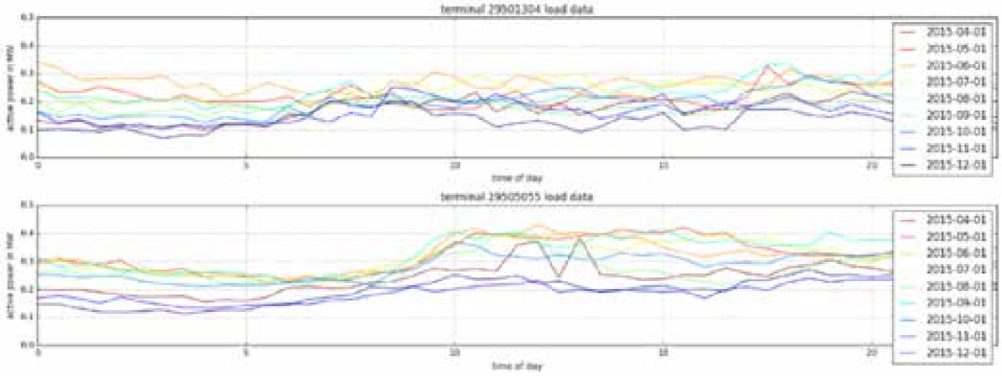


Figure 27: Daily load profiles of two urban distribution transformers in Delhi from the first day of each month.

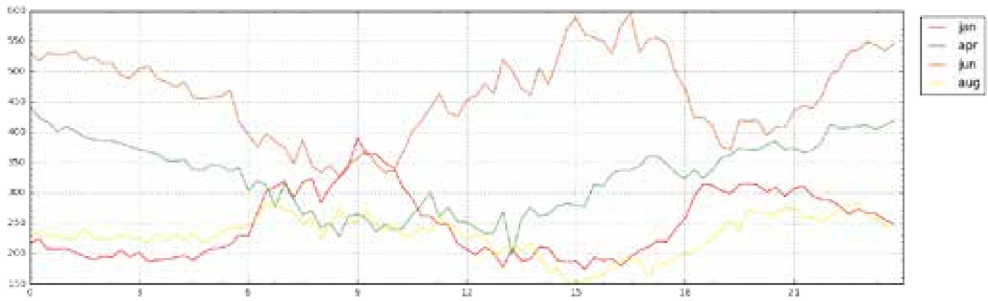


Figure 28: Daily load profiles of an urban 11 kV feeder in Bhopal from the first day of each month.

This characteristic is even more pronounced in the villages and farms supplied by the rural feeders in Delhi, with mid-day often exhibiting the lowest daily load values during all seasons. During summer, load is generally higher, with a peak in the late evening, while in winter and spring, the peaks are in the morning and in the evening (see Figure 29 and Figure 30). Water supply stations often exhibit a higher daily load during summer, possibly due to irrigation, but make up less than 1 % of the feeder load (see Figure 31).

The load characteristic with low daily load and load peaks in the morning, evening and night allow the assumption that initially, reversed power flows can reasonably be expected for some areas already at quite low PV penetration levels. If a high degree of self-consumption of PV power is desired, it is sensible to consider either energy storage – possibly making use of the backup batteries already installed in some areas – or demand side management to shift some of the load towards mid-day.

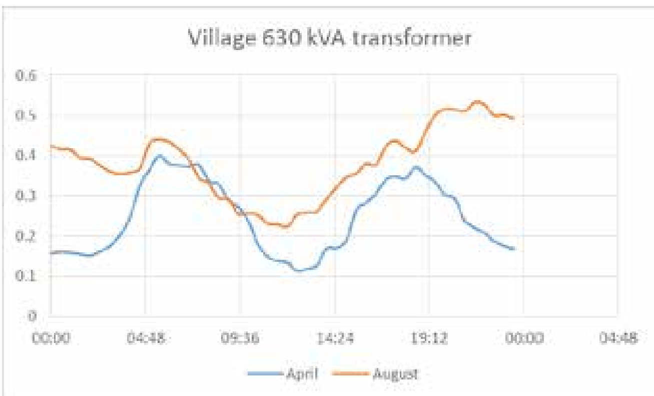


Figure 29: Load data for a transformer supplying a part of a village on a rural feeder for a day in April and one in August.

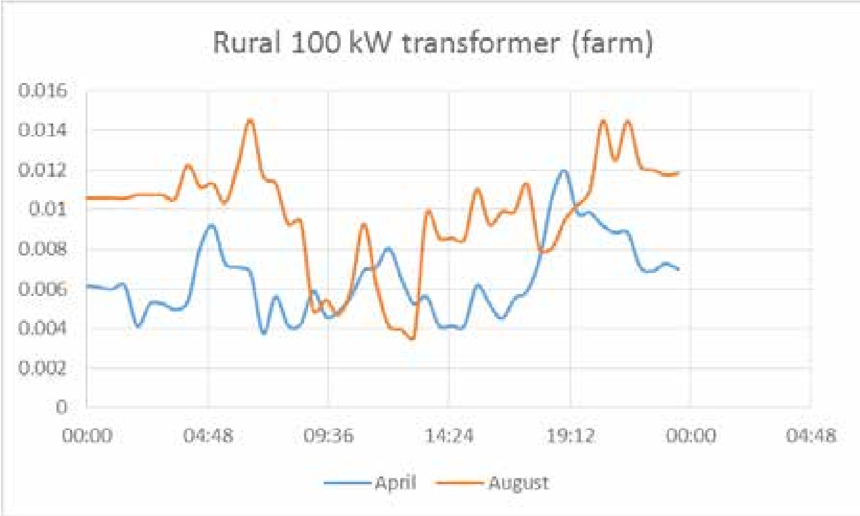


Figure 30: Load data for a transformer supplying a farm on a rural feeder for a day in April and one in August.

Figure 31: Load data for a transformer supplying a water supply station on a rural feeder for a day in April and one in August.

For the rural grid outside Bhopal, the characteristic looks different and much more favorable to PV integration. Loading is highest during the day and in winter and summer alike, but is lower during the intermediate seasons (see Figure 32.) This characteristic may be caused by commercial activity in the area, which takes place during the day, in combination with only a low share of air conditioning. The load shape is thus very similar to those found in European countries.

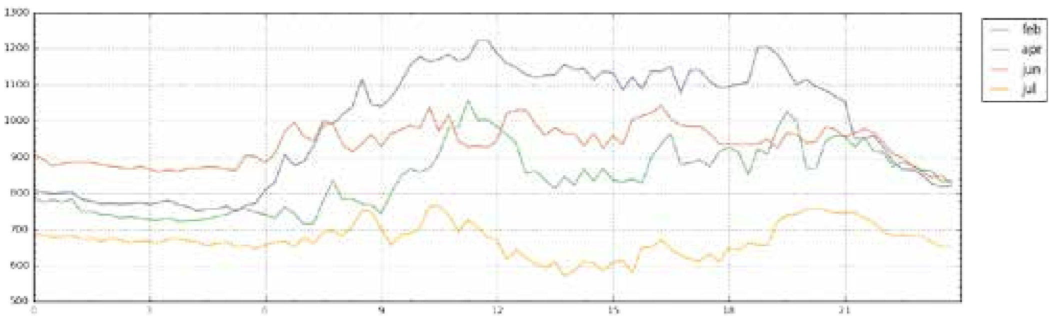


Figure 32: Daily load profiles of a rural 11 kV feeder in Bhopal from the first day of each month.

6.2 Data on Voltage Control

Especially in long, lightly loaded rural grids, voltage may be the critical grid parameter impacted by rising PV penetrations. It is crucial to obtain valid information about the current voltage control mechanisms and their quality to analyze this impact and draw the correct conclusions and recommendations.

6.2.1 Transformers

The typical last instances of voltage control in distribution grids are on-load tap changing transformers. On-load tap changing (OLTC) transformers are mostly used in the high and medium voltage levels. The transformer ratio can be adjusted in loaded state. This may be done automatically (via computer control) during operation, which allows for active automated voltage control. A typical application of such a transformer is the link between transmission and distribution grid, while medium voltage transformers within the distribution grid are often manually controlled. This can be done remotely – allowing for capabilities similar to an automatically operated transformer, albeit slightly more cumbersome – or on site by switching. The latter is often done only seasonally, leaving the transformer at a fixed ratio for long stretches of time.

Off-load tap changing transformers need to be unloaded and switched off to change the ratio. This type of transformer is usually used in medium and low voltage networks. The ratio is typically set to a value deemed appropriate to the specific application and left there for the life of the unit. This means that off-load tap changing transformers provide no means of operational voltage control.

For the BRPL grid area, it has been established that the current means of voltage control – manual switching of the OLTC transformers connecting 220, 66, 33 and 11 kV – is insufficient, and the transformers stepping down to 11 kV will be upgraded with automatic voltage regulation. The current plan is to set the controls to 1 p.u., with switching operations being conducted if the voltage exceeds 1.02 p.u. or drops below 0.98 p.u. on the secondary (11 kV) side. This ensures that the voltage at the 11 and 0.4 kV levels is only subject to line voltage drops in the grids themselves, but not to fluctuations in the upstream network.

The transformers in the MPMKVVCL grid are not equipped with any automatic voltage regulation and are mostly left set at a fixed ratio. As even the transformer stepping down from 132 kV is not automatically controlling the voltage, voltage in the distribution grid is directly tied to the 132 kV voltage. The analysis of voltage measurements (see section 6.2.3) is necessary to assess the voltage fluctuations before the introduction of PV and subsequently the impact of rising PV penetrations.

6.2.2 Compensators

Compensators are used to both provide reactive power locally to loads that have an offset power factor, and to control the voltage. They can have inductive and capacitive components and consist of either fully analog parts or switched power electronics.

In both the BRPL and MPMKVVCL distribution grids, analog switched capacitor banks are used to provide reactive power to the mostly inductive load and boost the voltage if necessary. The banks relevant for the simulation in the 11 kV grids are installed in the 66/11 kV substation and connected to the 11 kV busbars. They are used to bring the power factor of the inductive 11 kV grid closer to unity and thus reduce loading on the power transformers and upstream network. As in Delhi, the power transformer controls the voltage at the 11 kV busbar, compensators do not represent an instance of active voltage control, but may slightly impact the voltage. Changes in their operational patterns may be required at rising PV shares, especially if PV inverters provide active voltage control, which will be investigated in the study. For Bhopal, it may be feasible to readjust some of the compensator controls – or install automatic control in the first place – to provide active voltage regulation instead of power factor control.[24]

6.2.3 Measured voltage

As indicated in previous chapters, voltage control in distribution grids in both Delhi and Bhopal is currently insufficient, with no automatic voltage regulation present. BRPL is currently in the process of upgrading its grid with automatic voltage regulation, as most transformers above 11 kV level have on-load tap changing capability which is currently still operated manually.

The reason for this is clearly visible in the voltage measurements delivered by BRPL. Regulations in India demand distribution grid voltage to be kept between 0.90 and 1.1 p.u., which currently cannot always be provided. As visible in Figure 33, voltage during a winter day drops across the highly loaded urban 66 kV grid, reaching low points at 0.85 p.u. at the 66 kV side of the 66 kV substation. The 66/11 kV transformer is, in this case, set to a tap setting that boosts voltage to an acceptable level on the 11 kV side, but it still stays below the nominal voltage. Voltage rises and drops propagate throughout the entire network without being compensated anywhere.

During summer, problems are more severe as demand is higher due to A/C use. Figure 34 shows a day with extremely low 66 kV voltage, which is then compensated for by a manually switched 66/11 kV transformer, which is not always the case. Deploying automatic voltage control will facilitate such operations, and most likely avoid drops to 0.90 p.u. in the first place.

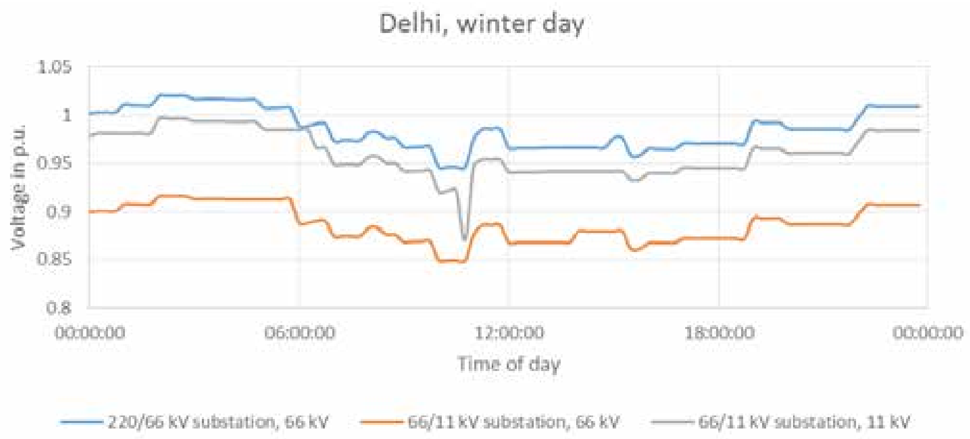


Figure 33: Voltage measurements of 66 and 11 kV level grids in urban Delhi, winter day. No switching.

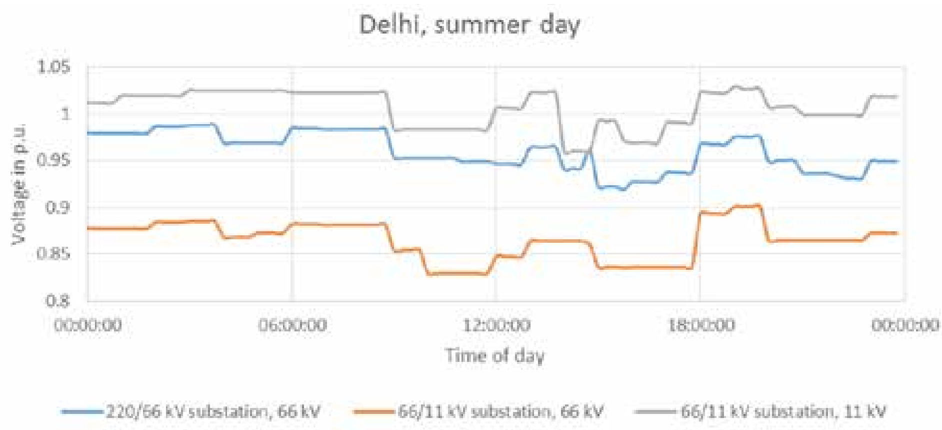


Figure 34: Voltage measurements of 66 and 11 kV level grids in urban Delhi, summer day. Tap positions (66/11 kV) are switched during the day.

24 Due to the location of the compensators, this turned out to have relatively little impact on PV hosting capacity in the grids where simulations were conducted.

In rural areas with longer lines, voltage problems are even more widespread. If voltage is already well below 1 p.u. at the 11 kV busbar, which frequently happens in summer, and drops further along highly loaded, long 11 kV lines and across distribution transformers, the voltage delivered to the end customer may not fulfill the quality requirements any more. Figure 35 shows voltage measurements from the low voltage side of a rural distribution transformer during summer 2016. Besides the quite frequent power cuts and/or measuring outages, voltage drops below 0.90 and even 0.80 p.u. quite frequently. Employing automatic tap changing at the 66/11 kV or 33/11 kV transformer could prevent this by setting the voltage to a higher value at the 11 kV busbar – possibly higher than 1 p.u., to account for line voltage drop, and adjust it if necessary due to changing load, or PV feed-in.

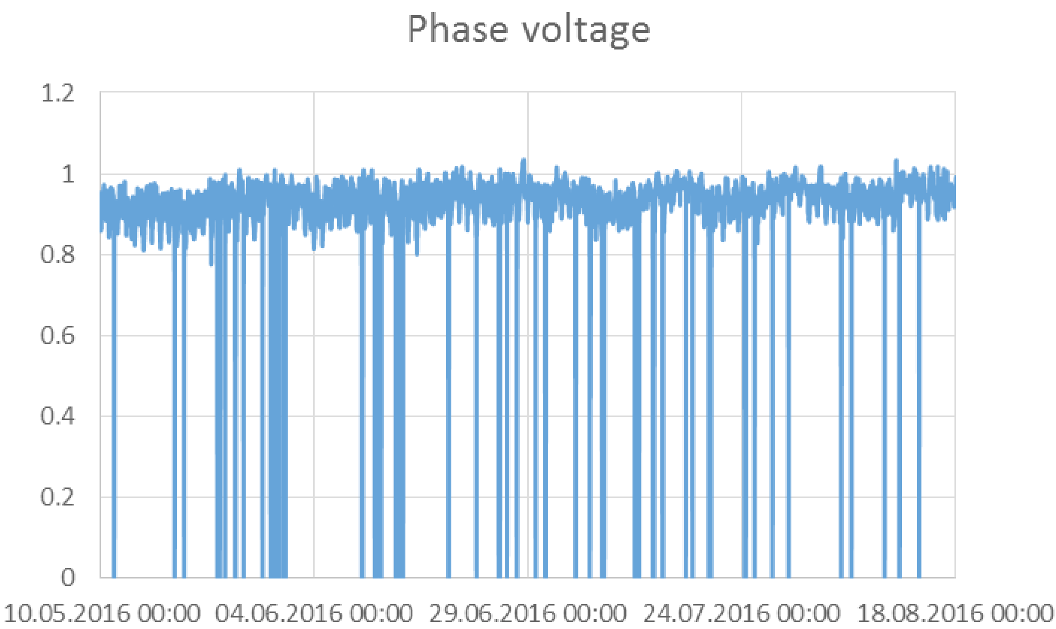


Figure 35: Voltage measurements of the secondary (400 V) of a distribution transformer in rural Delhi, showing gaps as well as voltage frequently dropping below 0.9 p.u.

Although voltage measurements provided by MPMKVVCL for the grids in Bhopal are less detailed, they are sufficient to identify similar problems with voltage control. MPMKVVCL's grids have no means of voltage control and no plans for upgrades either and are thus completely dependent on the voltage supplied from the 132 kV grid. That itself shows large daily fluctuations, indicating insufficient voltage control even in the subtransmission grids. On average, voltage rises and drops by 0.05 p.u. daily, with maximums exceeding 1.05 p.u. and minimums of 0.96 p.u. and below (see Figure 36 and Figure 37) – for the low load winter, summer values have yet to be provided.

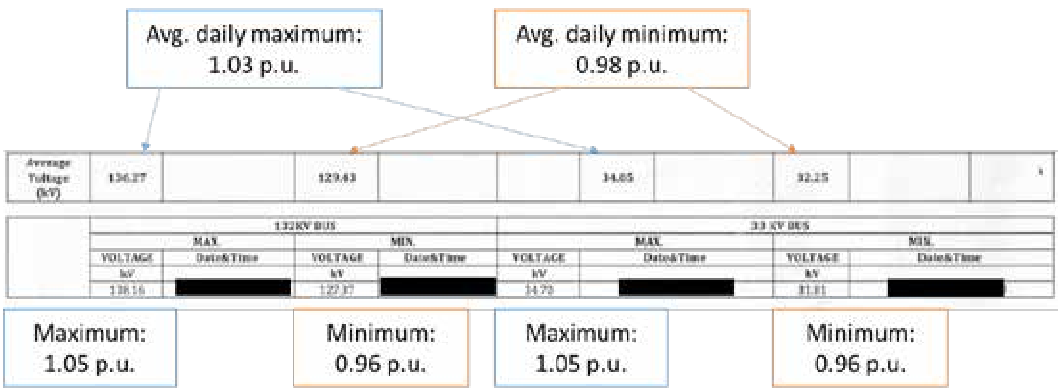


Figure 36: Voltage measurements from Bhopal for one month, 132 and 33 kV, minima and maxima.

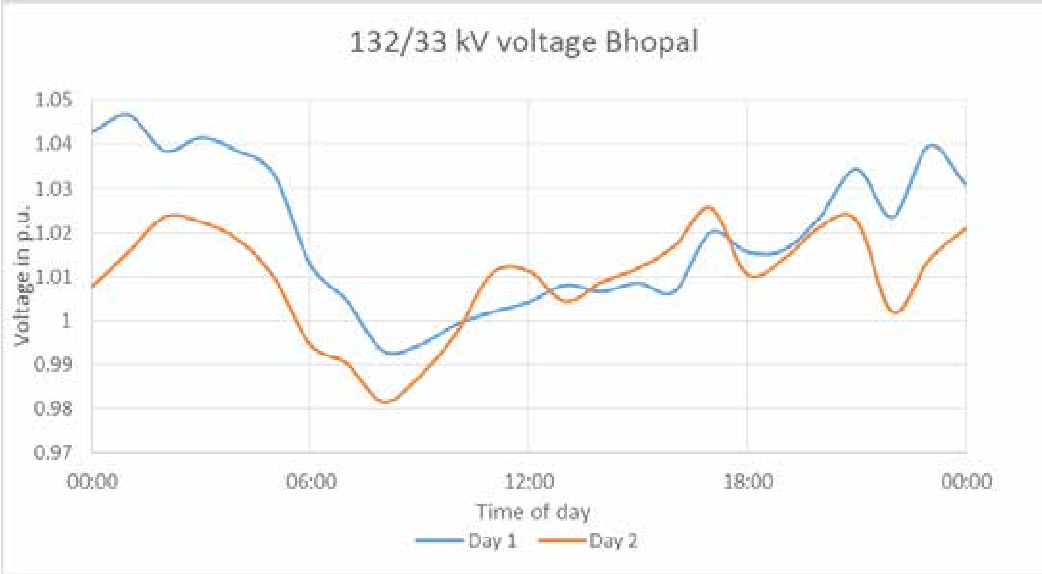


Figure 37: Voltage measurements in 132/33 kV substation in Bhopal across two days.

With the voltage drops across the long rural 33 and 11 kV lines, and additional voltage rises that may be introduced by PV, voltage control will most likely be the limiting factor for PV integration in Bhopal, if transformers and shunt controllers are not upgraded or PV units provide voltage control themselves. In the latter case, however, PV may actually be beneficial to security and quality of supply.

6.2.4 PV inverters

According to the data provided by BRPL and MPMKVVCL, the inverters of the PV units already installed in the relevant grid areas are able to provide reactive power for voltage control. It is unclear if, and how, this capability is currently used. On-sites visits revealed the Chinese-made inverters are actually compliant to the specifications of the German grid code (see Figure 38), which requires active local voltage control, so future use of their advanced capabilities should not be problematic.

Figure 38: Nameplates of PV inverters in Bhopal (left) and Delhi (right.) Reactive power range is marked in orange, statement of compliance with the German low voltage grid code in yellow. Serial numbers etc. have been obscured.

6.3 Solar Data

6.3.1 Roof space

The availability of roof space can be the limiting factor for PV integration in urban areas. While it will obviously also limit the amount of actual rooftop PV that can be installed anywhere else, there may be space for open field PV in rural areas, and the average amount of rooftop per customer is usually larger due to the higher share of agricultural and commercial buildings.

For the urban areas, scenarios will be developed using the estimated available roof space as a limit for the amount of PV that will be considered in the study. First estimates of the available roof space using OpenStreetMap indicate a maximum of around 100 % distribution transformer capacity will be the maximum for the urban feeder in Delhi, while the values for Bhopal will be a bit higher at 120 – 150 %.

6.3.2 Measured data at inverter level

Measured feed-in data at inverter level for already existing rooftop units has been provided by both BRPL and MPMKVVCL, partly as 15 minute time series and partly as daily energy values. The data delivered is sufficient for modelling of a yearly time series for inclusion in the models.

Different from European and American systems, it should be noted that currently installed PV units suffer from low efficiency and/or high losses, especially in summer. Maximum output is only slightly above 70 % of installed peak panel capacity. Some of this has to do with weak connections, but the most severe factors impacting PV output are heat (reducing efficiency) and dust. These will not be mitigated by the installation of newer equipment. Due to the high insolation, the energy yield in both Delhi and Bhopal is still quite high (13 – 15 % capacity factor) despite these drawbacks, but far off the 20 % capacity factor that could theoretically be reached.

Measured PV data shows the highest PV generation in April, when the sun is shining but the temperature is still not overly high, slightly dropping in May and June due to the lower efficiency at high temperatures (see Figure 39.) After that, the rain season sets it, leading to higher fluctuations and overall less generation, but except for the winter months of December and January, peaks can still come close to the maximum value reached in April.

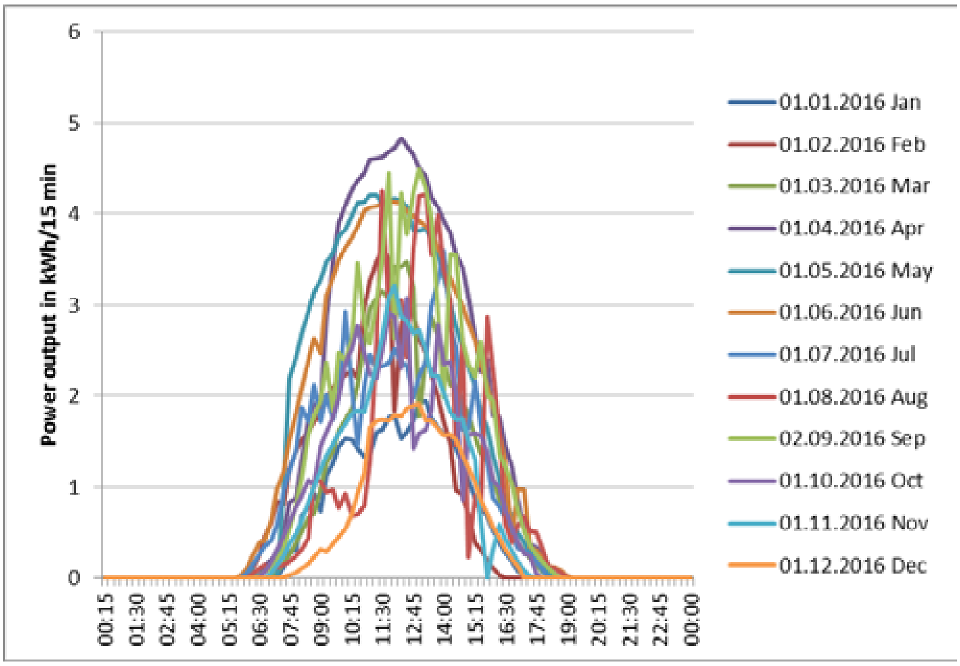


Figure 39: Output of a 25 kWp PV installation in Delhi for the first day of each month. Nominal output would be 6.25 kWh/15 min.

7. Model setup and simulations

7.1 Model setup in Powerfactory

7.1.1 General approach

The simulations proposed for the project will be quasi-dynamic load flow calculations, each one simulating a full day in 15 minute snapshots. For each grid, a worst case day was selected, with the highest ratio of PV to daily load.

The scenarios for all feeders were simulated with five different PV penetration levels, defined as percentages of the total installed distribution transformer capacity. The chosen penetration levels were dependent on the location. In the simulations of each penetration level, if a problem was encountered, a number of possible solutions were implemented and simulated independently. For each of the solution, PV penetration was increased step wise as to determine the highest penetration percentage where problems occur again and further PV penetration would not be possible.

7.2 Simplifications and assumptions

7.2.1 Worst case situations

As previously described, the most critical situation for PV integration in a distribution grid is the situation with low load and high PV feed-in, resulting in the maximum instantaneous penetration of load on a feeder. For each feeder, this required the analysis of load data to find the day with the lowest load at 12:00 noon, where PV feed-in can be expected to reach its peak. This was done in two steps, first by finding the days with the lowest daily energy consumption, and among those finding the one with the lowest mid-day load.

7.2.2 Voltage tolerances

According to the Indian National Electric Code 2011, the voltage at the low voltage level is 230/400 V with an allowed tolerance of ±10 %. From the last instance of voltage control, typically an on-load tap changing transformer, these 10 % have to be distributed along the medium voltage levels and the low voltage level..

In the case of Bhopal, voltage control is provided by 132/33 kV power transformer. Assuming a rough distribution of voltage drops and rises as given in Figure 40, this results in an allowed voltage range of ± 5 % for the 33 and 11 kV MV level that was considered in the simulations. This leaves another 5 % for the low voltage networks.

In Delhi, voltage is controlled by 33/11 kV or 66/11 kV power transformers. For the urban grid where the low voltage level was modelled in detail, the voltage distribution as given in Figure 41 was applied. For the rural feeder, only the 11kV level was considered, with an allowed voltage range of ± 5 %. This leaves another 5 % for the low voltage networks.

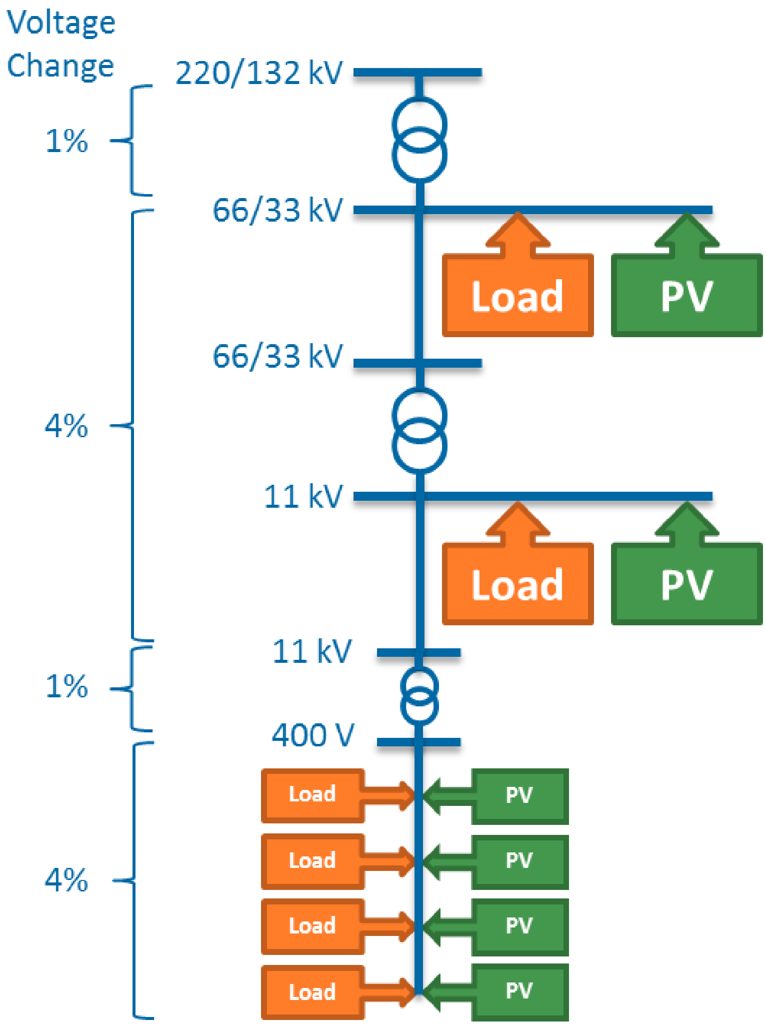


Figure 40: Voltage profile / tolerances Bhopal.

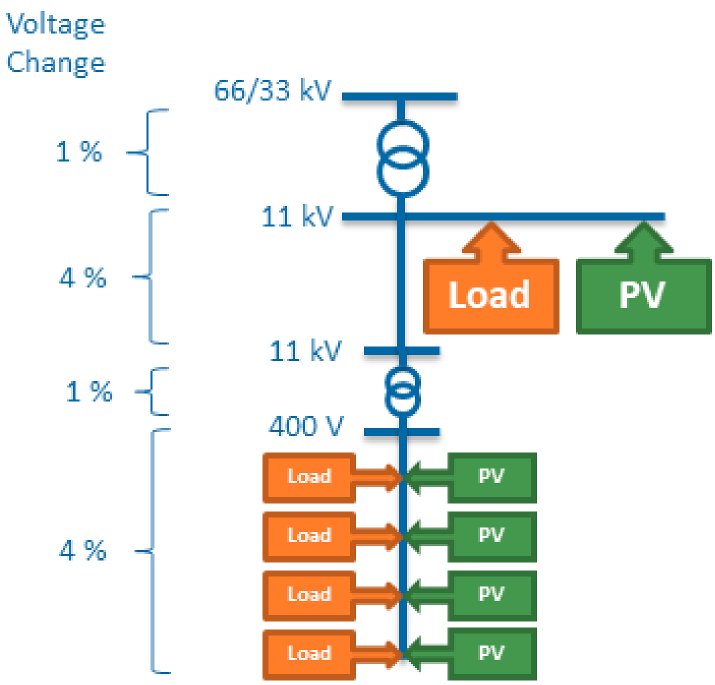


Figure 41: Voltage profile / tolerances Delhi.

7.2.3 Voltage control

For all simulations, the assumption was taken that the last instance of voltage control can keep the voltage at the controlled busbar between 0.99 and 1.01 p.u., with the analysed worst case being 1.01 p.u. Both in Delhi and Bhopal, this is not currently the case. In Delhi, voltage control is currently not provided by the 66/11 and 33/11 kV power transformers, but BRPL is in the process of retrofitting those with automatic voltage control, so the assumed adequate control capability can be assumed for the future scenarios presented in this study.

In Bhopal, voltage is controlled by the 132/33 kV transformers manually, and is often inadequate. According to the supplied data, the voltage at the controlled 33 kV busbar is around 1.0 p.u. during the day or even lower. Assuming a worst case of 1.01 p.u. at this point is reasonable. However, it should be noted that there are cases where the voltage at the 33 kV busbar rises to 1.05 p.u. or even slightly above, although these cases are rare (low voltage being the more common case.)

Simulation results with different PV penetration levels and different voltages at the 33 kV busbar in the rural feeder from Bhopal are shown in Figure 42. The obvious result is that if the voltage at the last instance of voltage control is too high due to inadequate control, the additional voltage rise induced by PV cause violations at considerably lower penetration levels than with adequate voltage control. The maximum PV shares determined in the following sections are thus only possible if adequate voltage control is provided at the assumed points (132/33 kV transformer in Bhopal, 66/11 or 33/11 kV transformers in Delhi.) Automatic voltage control at the last on-load tap changing transformer can thus be viewed as a prerequisite to successful PV integration.

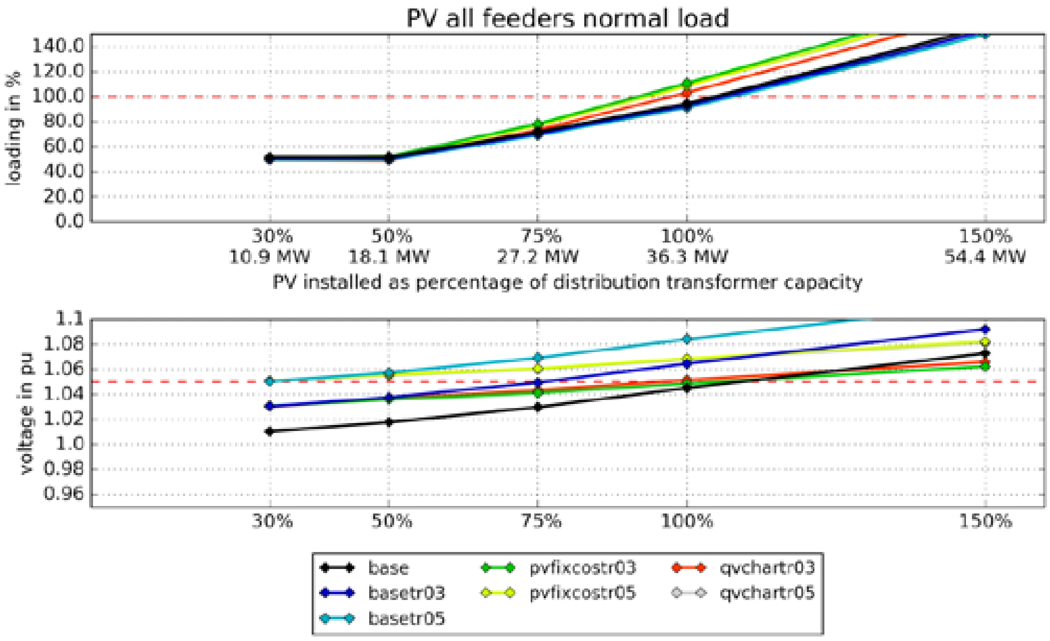
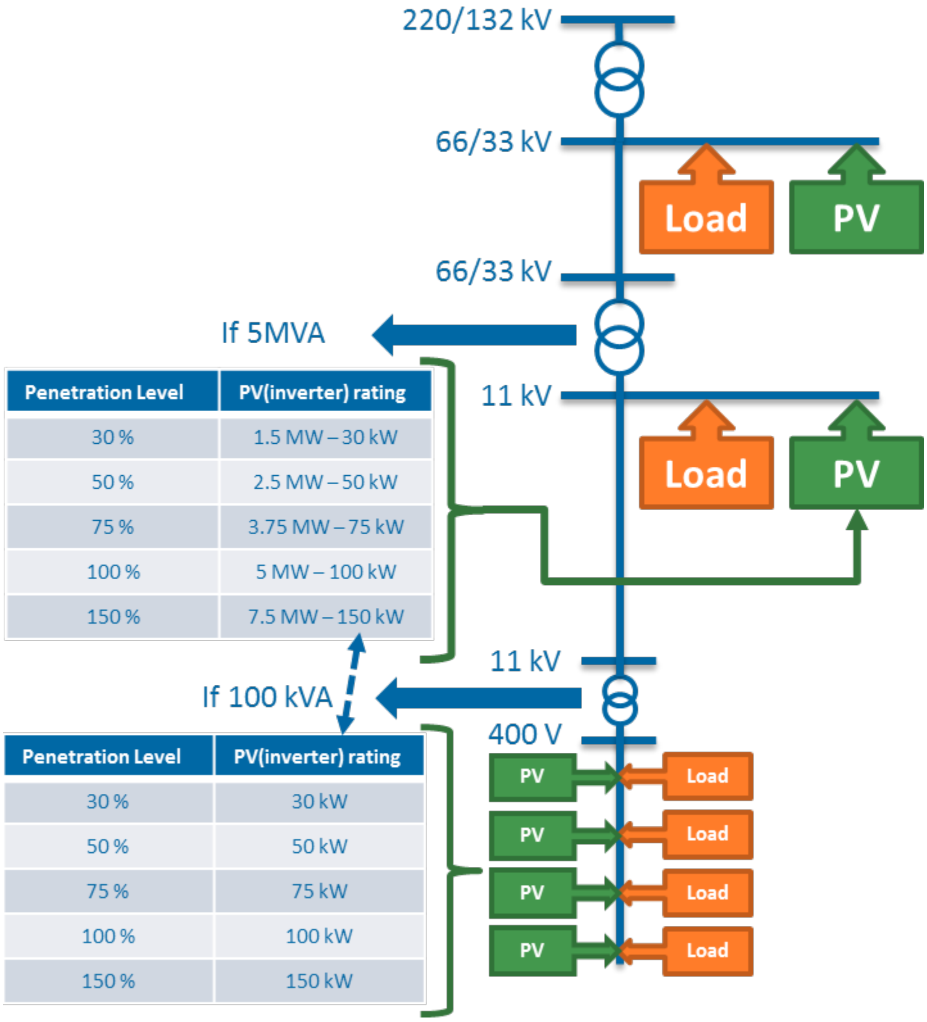


Figure 42: Maximum asset loading and voltage at different penetrations of rooftop PV, as percentage of distribution transformer capacity.

Base is the base case with 1.01 p.u. at the busbar, basetr03 has 1.03 p.u., basetr05 has 1.05 p.u. The other lines show how the voltage rise can be somewhat mitigated by reactive power from PV inverters.

7.2.4 PV on other 11 kV feeders (Bhopal rural)

The networks for all cases are modelled and simulated from the last instance of voltage control downwards. In Delhi and in the urban grid in Bhopal, the last instance of voltage control is at the same busbar to which the 11 kV feeders that are modelled in detail are attached. In the rural grid in Bhopal, however, the detailed 11 kV feeder model is fed by an extensive 33 kV network, which is also modelled. Other 11 kV feeders connected to this network are modelled as load/generation equivalents. To assess the impact of a large scale rooftop PV roll-out on the 33 kV network, different PV penetrations are not only considered on the detailed 11 kV feeder, but also in the load/generation equivalents according to Figure 43.



Penetration Level	PV(inverter) rating
30 %	1.5 MW – 30 kW
50 %	2.5 MW – 50 kW
75 %	3.75 MW – 75 kW
100 %	5 MW – 100 kW
150 %	7.5 MW – 150 kW

Penetration Level	PV(inverter) rating
30 %	30 kW
50 %	50 kW
75 %	75 kW
100 %	100 kW
150 %	150 kW

Figure 43: Consideration of Impact of Parallel feeders

7.3 Scenarios

Simulation scenarios were set up to provide worst case analysis for the actual grids that were modelled, as well as model cases for other distribution system operators. Scenarios vary slightly for each of the modelled grids.

7.3.1 Distribution of rooftop photovoltaic plants along the feeder

The distribution of the generation along the feeder has a noticeable effect on the voltage profile. A homogeneous distribution of load and PV capacity as shown in Figure 44 will, in case of PV generation exceeding feeder load, cause a lower voltage rise than a case where most of the PV generation is concentrated at the end of the feeder, as in Figure 45. The latter represents the worst case, while the former is the most common development, so both were considered.

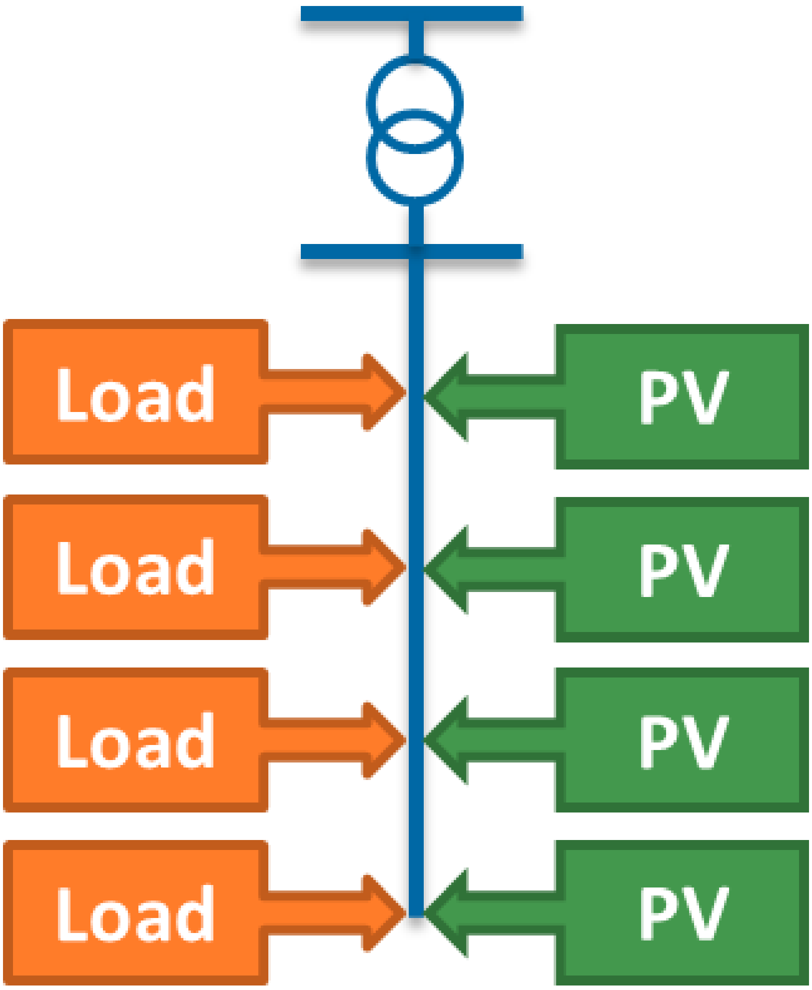


Figure 44: Rooftop photovoltaic plants equally distributed along feeder

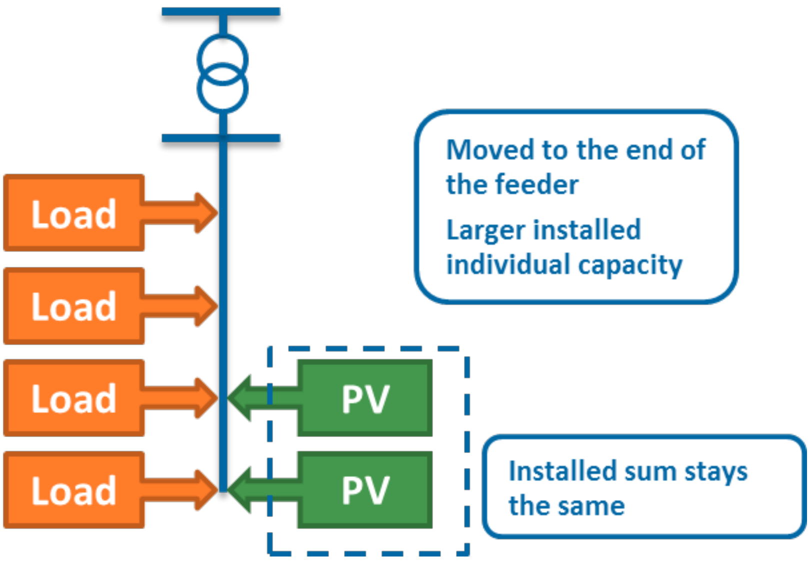


Figure 45: Rooftop photovoltaic plants concentrated at the end of the feeder

7.3.2 Presence of utility scale photovoltaic plants within the feeder

The Indian solar target includes medium scale projects connected to the 11 kV level. A few scenarios, considered only for the rural feeder examples, are dedicated to investigating the impact the utility scale photovoltaic plant would have while also ramping up the rooftop solar plants. The impact of the solar plant in the feeders may vary depending on their position (Figure 46.)

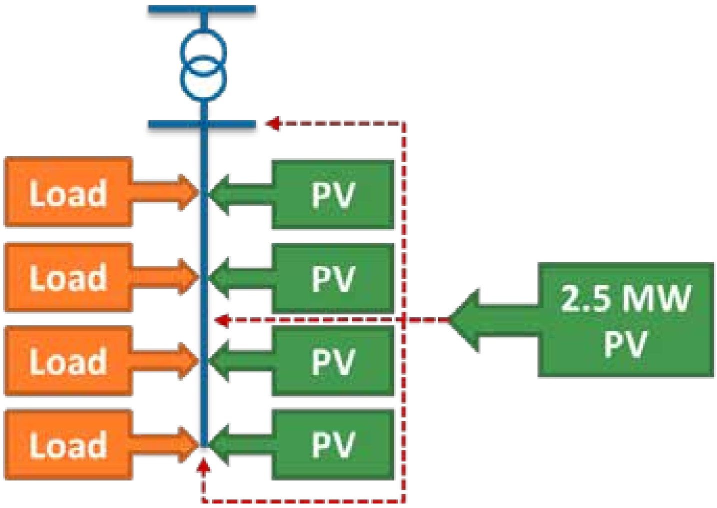


Figure 46: Presence of a utility scale photovoltaic power plant

In the case of Delhi, an actual utility scale solar plant with the size of 3.5 MW is currently planned and an investigation on appropriate connection points was conducted. The subsequent scenario focuses on the optimal connection point and the impact of the plant on the feeder's hosting capacity for rooftop PV.

For the rural feeder in Bhopal, no PV power plant is actually planned, but to provide a case study for such an installation on a feeder with those characteristics, a 2.5 MW power plant with multiple connection options was introduced for some scenarios.

7.3.3 Impact of increase in load with time

According to current planning, India expects an increase of approximately 25 % (roughly 5 % per year) in electricity demand in the time span between 2017 and 2022. For the model feeders, this expected increase is assumed to be utilized mainly for air conditioning. To make some valid assumption on the characteristic of such a loads, available data from Florida and California was analysed. Both regions have a high share of A/C demand during the day due to high temperatures are located on a latitude similar to Delhi and Bhopal. The load behaviour from these regions was used to estimate the additional load. A typical average load per household in two regions in California is given in Figure 47. A distinct peak demand in the evening can be identified, similar to what is observed in Indian grids.

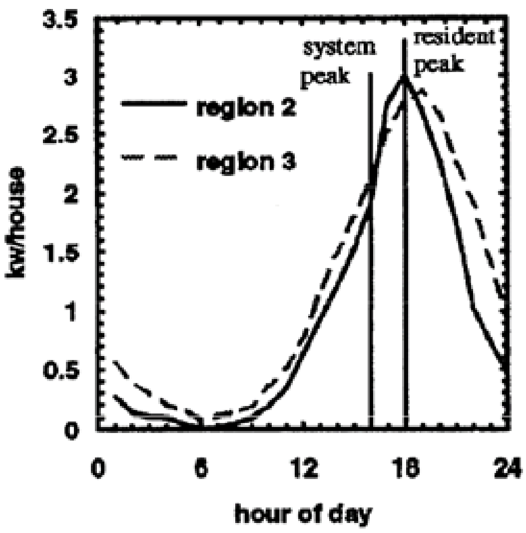


Figure 47: Air conditioning demand as a function of time (region2 = Sacramento, CA and region3 = Fresno, CA)[75].

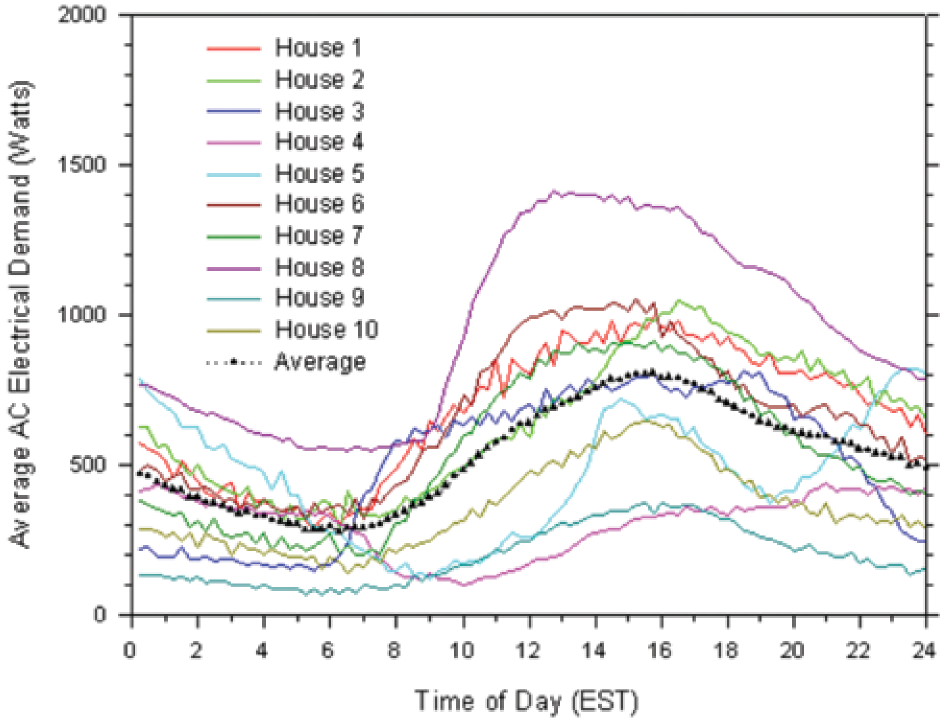


Figure 48: A/C electricity demand of individual houses and their average in a low-income area with hot climate in Florida 1996. Source: Florida Solar Energy Center

The shape of the aggregated load profile in Florida as shown in Figure 48 is very similar to the profile of California, but the peak is shifted slightly towards mid-day. The peak load at Florida occurs at approximately 4 PM and the minimum load is during night-time at about 6 AM.

The aggregated demands of California and Florida due to air conditioning load have similar sinusoidal behaviour with an evening peak and a night-time minimum. The average load from Florida as shown in Figure 48 was adapted to the case in India and utilized to create a synthetic load profile of A/C load for Delhi and Bhopal. The resulting profile is shown in Figure 49.

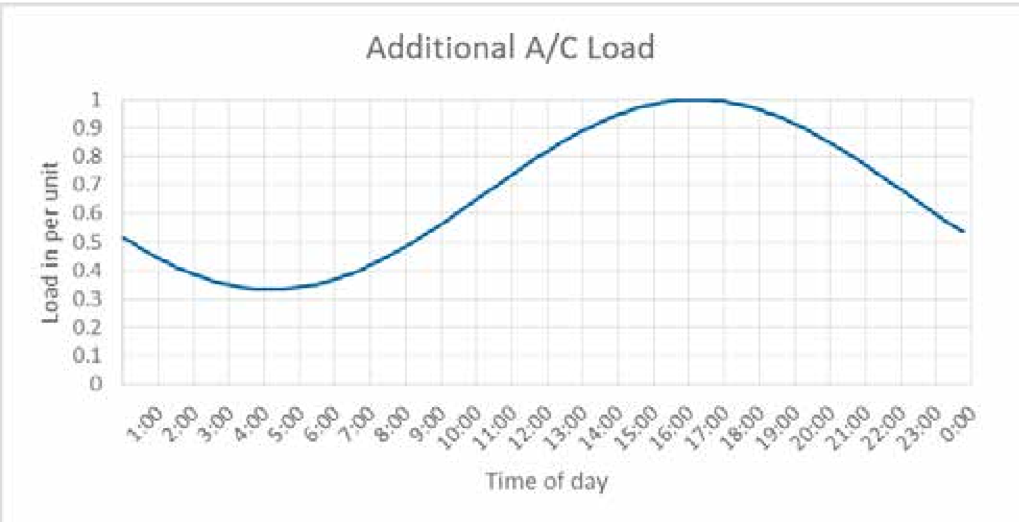


Figure 49: Synthetic A/C load profile

In addition to the active power demand, air conditioning load consumes reactive power, operating at power factors in the range of 0.7 to 0.8 lagging. [76] A/C load is subsequently modelled with a power factor of 0.8 lagging, assuming modern equipment with somewhat lower reactive power consumption than old models.

7.3.4 Modifications to topology and assets

A number of hypothetical scenarios have been developed based on the data provided to present model cases for other areas with different grid characteristics and to give an outlook on possible future development:

- The Delhi urban grid is a very strong grid, with large cable and line cross sections and thus little line overloading or voltage problems. To present a case of a weaker urban grid, a scenario with the same loads and line lengths, but smaller cross sections (weaker grid) was simulated.
- The Bhopal urban feeder and both rural feeders consist primarily of overhead lines. To present a case with a higher share of cables – which may be relevant for other operators, or in some future scenario with a shift to cables in general – models of those grids in which all overhead lines are replaced with cables were set up and simulated.

7.3.5 Urban Scenarios

The variations that were used the urban networks are listed in Table 20.

Table 20: Scenarios in Urban Grids

Scenario No.	Delhi Urban Scenarios	Scenario No.	Bhopal Urban Scenarios
1	PV equally distributed	1	Rooftop PV equally distributed along the feeder with normal load
2	PV equally distributed with adapted load	2	Rooftop PV equally distributed along the feeder with adapted load
3	PV at the end of the feeder	3	Rooftop PV with higher PV at the end of feeder with normal load
4	PV at the end of the feeder with adapted load	4	Rooftop PV with higher PV at the end of feeder with adapted load
5	PV at the end of the feeder with lower cable crosssection	5	Rooftop PV with overhead lines converted to cables with lower crosssection

7.3.6 Rural Scenarios

The rural networks were less similar to each other, thus there is a higher amount of variation in the scenarios, as shown in Table 21.

Table 21: Rural Scenarios for Delhi and Bhopal

Scenario No.	Delhi Rural Scenarios	Scenario No.	Bhopal Rural Scenarios
1	PV power plant	-	-
2	PV equally distributed	1	Rooftop PV equally distributed along the feeder with normal load
3	PV equally distributed with adapted load	2	Rooftop PV equally distributed along the feeder with adapted load
4	PV equally distributed with a 3.5 MW PV power plant	3A	Rooftop PV with a PV power plant at the Beginning of the feeder
		3B	Rooftop PV with a PV power plant at the Middle of the feeder
		3C	Rooftop PV with a PV power plant at the end of the feeder
5	PV equally distributed with the network fully cabled	4	Rooftop PV with overhead lines converted to cables with similar cross-section

7.3.7 Specific modifications based on location

As the only grid having data available for the LV grid, the Delhi urban network was modelled with detailed generic LV networks based on the provided data, with load connections every approximately 25 m along the feeder. For the equally distributed PV Scenario 1, a PV system has been installed at each of these loads. The sum of all PV systems within each LV network is expressed as a percentage of the distribution transformer's capacity. The generation per feeder is distributed based on the same key used for the splitting of loads, so a very homogeneous relation of load and installed PV was assumed.

The following changes have been applied to the other Scenarios, based on the described configuration of Scenario 1:

- Scenario 2: Every load was exchanged with the adapted load.
- Scenario 3: For the installation of PV at the end of the feeder, each PV system was connected at a load starting from half of the lines length. The sum of the installed PV along the feeder had to stay the same, resulting in doubling the individual PV system size.
- Scenario 4: Same as Scenario 3 combined with the exchange of all loads as adapted loads.
- Scenario 5: The cable cross-section of every LV cable (300 mm²) got reduced to 150 mm².

The total installed PV size was based on a percentage of the installed distribution transformer capacity. The considered levels of installed PV in Delhi and Bhopal were nearly identical, but differed at lower percentages as shown in Table 22. The differences were requested by the grid operators.

Table 22: Installed PV in each modelled feeder.

Feeder	PV installed as percentage of distribution transformer capacity				
Delhi urban	20%	50%	75%	100%	150%
Bhopal urban	30%	50%	75%	100%	150%
Delhi rural	15%	40%	75%	100%	150%
Bhopal rural	30%	50%	75%	100%	150%

7.4 Technology Options

A subset of the solutions to problems caused by high PV penetrations as described in section 1.1 was implemented in the simulation models, which is described in the following. All solution approaches were simulated independently of each other, and all were implemented in all scenarios.

7.4.1 Reference Case

The reference case presents each network "as is," with the previously assumed assumptions. Voltage is fixed at 1.01 p.u. at the 33 kV busbar (Bhopal) or the 11 kV busbar (Delhi), assuming adequate capabilities of the voltage controlling power transformer.

7.4.2 Automatic on-load tap changing at MV level (66/33/11 kV)

For the Delhi grids, automatic voltage control by on-load tap changing 66/11 and 33/11 kV transformers is included in the base case.

In the Bhopal grids, this is not the case, the upgrade of 33/11 kV transformers to automatic voltage control was thus considered as a possible solution that may increase the PV hosting capacity. In most cases with transformers connecting 33 kV to 11 kV voltages in Bhopal, a 3 % voltage change per tap was provided. This was translated to a control threshold from 0.98 p.u. to 1.02 p.u. voltage at the low tension side of the transformer. The worst case of the voltage at the secondary side being controlled to 1.02 p.u. was considered in the simulations.

7.4.3 Wide area voltage control

Wide area voltage control is defined as using voltage measurements from different points in the grid as an input to the voltage controlling on-load tap changing transformer, which will aim for a setpoint that allows all points included in the control scheme to operate within the allowed voltage range.

For the single feeder analysis conducted in this study, a simplified version could be used. Voltage is measured at a point at the middle of the feeder (instead of the secondary transformer side) and the transformer is controlled accordingly. This allows the voltage controller to notice a PV induced voltage rise on the feeder and mitigate it by lowering the voltage at the transformer busbar.

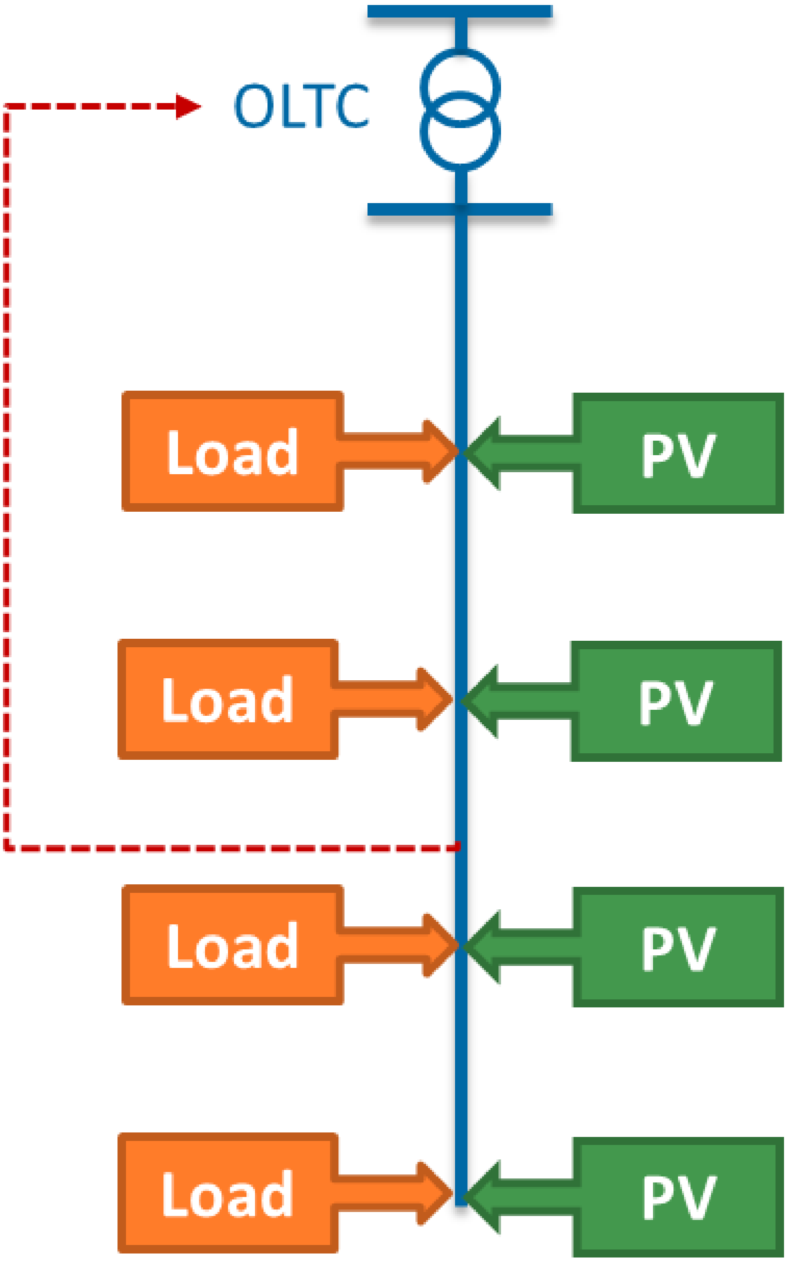


Figure 50: Wide Area Control

7.4.4 Shunt compensators for voltage control

The grids in Bhopal are equipped with a number of shunts for reactive power control. These are switchable on-load and are used to control the power factor, indirectly influencing the voltage as well by changing the reactive power flows. In case of PV induced voltage rises, these can be used in a voltage-sensitive instead of a power factor-sensitive mode and thus provide an additional instance of voltage control.

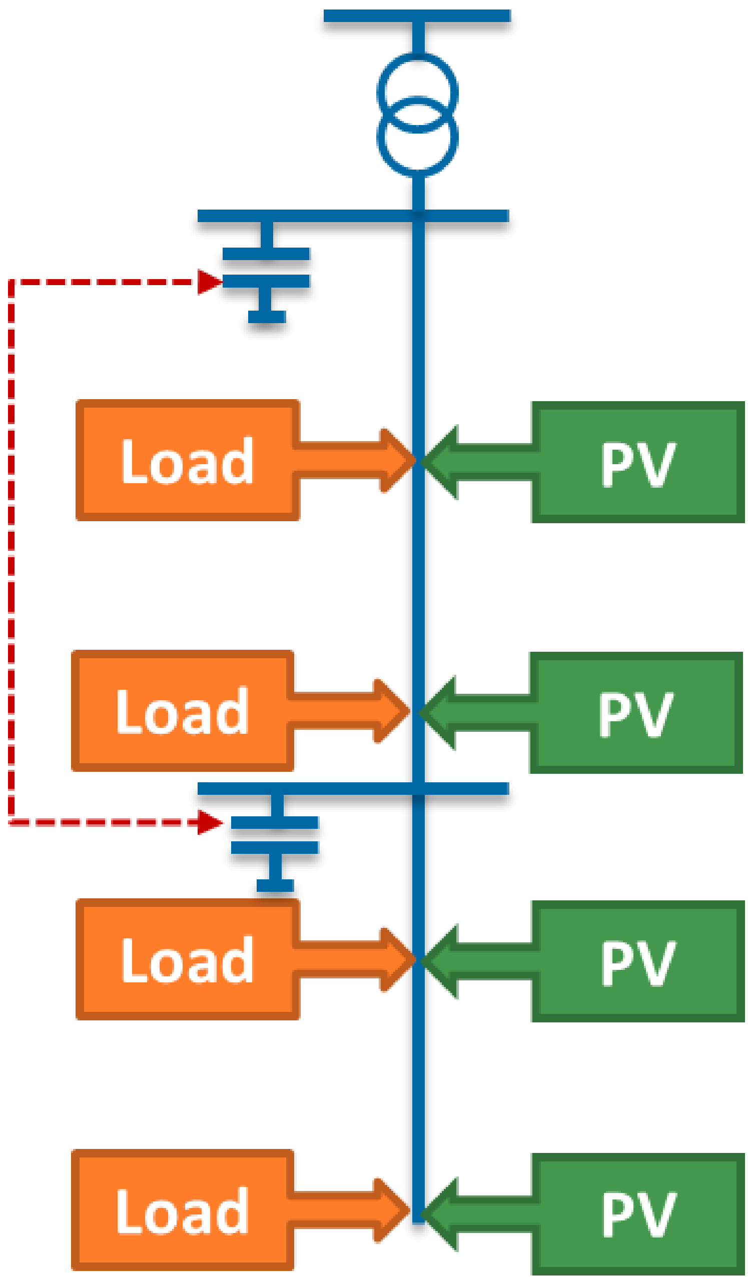


Figure 51: Shunt Compensator for voltage control

7.4.5 PV inverters with fixed non-unity power factor

To reduce the voltage rise at the point of connection that is caused by the injection of active power at the connection point of a PV unit, the inverter can be set to an off-unity, underexcited power factor. It will draw reactive current and thus lower the voltage. As a solution approach, all units are required to operate at a power factor of 0.95 underexcited. Such behavior is required from several German grid operators, for example, and the current German low voltage grid code requires such capabilities from PV inverters. However, the reactive currents will increase line and transformer loading while reducing the voltage.

7.4.6 Active voltage control by PV inverters (Q-V characteristic)

A more advanced version of voltage control by PV inverters is the use of a Q-V characteristic as shown in Figure 52, allowing the unit to actively control the voltage at the connection point. This has the advantage that reactive power is only consumed – and asset loading increased – if the voltage actually rises, while it is not activated in non-critical cases.

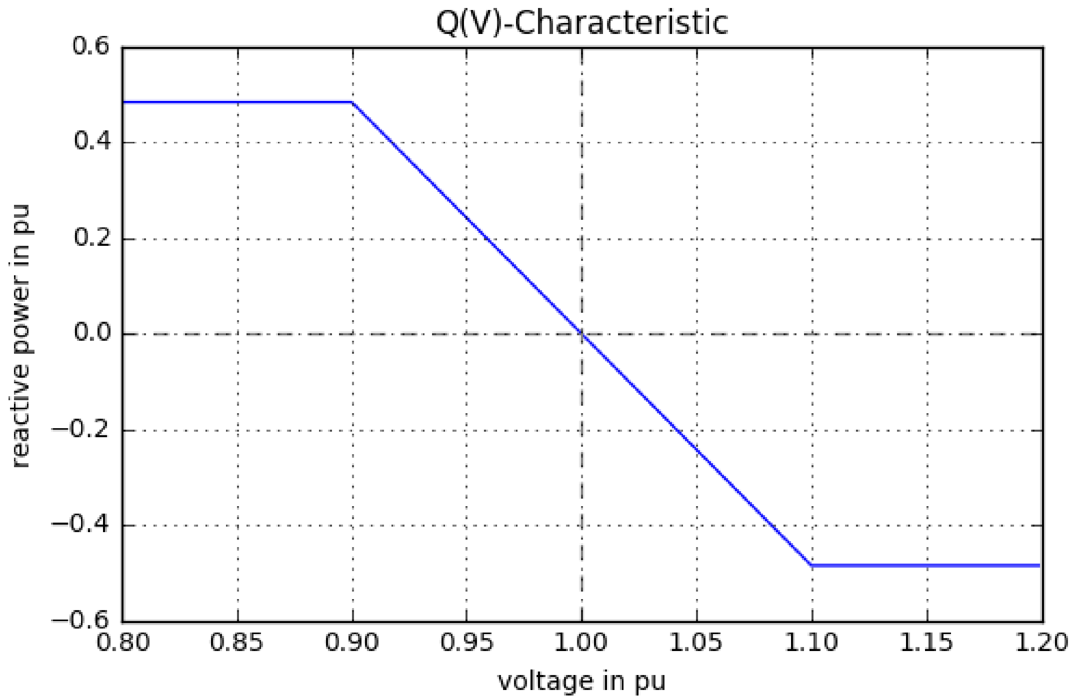


Figure 52: Utilized Q-V-characteristic.

7.4.7 On-load tap changing DT

German and Californian distribution grid operators have started to use automatically controlled on-load tap changing distribution transformers in some grid with high PV penetration. For the Delhi urban grid model, where the LT grid was modelled in detail, this was also considered as a solution option. The on-load tap changing is implemented with a capability to control the voltage at a specific node in the LT network (similar to the wide area management at MV level), since the main voltage rise in this case takes place in the LT network, and just controlling the LT of the distribution transformer would not be very helpful.

7.4.8 PV generation cap at certain percentage of installed panel capacity, remote curtailment of active power

As explained in section 6.3.2, PV panels in India will usually only reach 70 % of their installed capacity as peak power due to heat and dust. In reality, inverter and panel capacity will often be mismatched in both directions, but for this study, it is assumed that the inverters are rated at 70 % of panel capacity, allowing for the expected peak power to be fed into the grid.

Actual peak power is usually reached only a few times a year. If the requirement is set that the grid actually has to be able to absorb the peak power, the impact of PV will be overestimated for much of the year. The peak power of PV units can be capped to 70 to 80 % at relatively low yearly losses of energy, as shown in Table 23 (derived from measured data from two PV units in Gurgaon nearby Delhi, and Indore in the vicinity of Bhopal), to reduce grid impact.

In most European countries, 3 % of annually lost energy is an acceptable value for renewable curtailment and/or capping. Based on the values given in Table 23, a cap of PV feed-in to 70 % (Delhi) and 75 % (Bhopal) inverter capacity is considered.

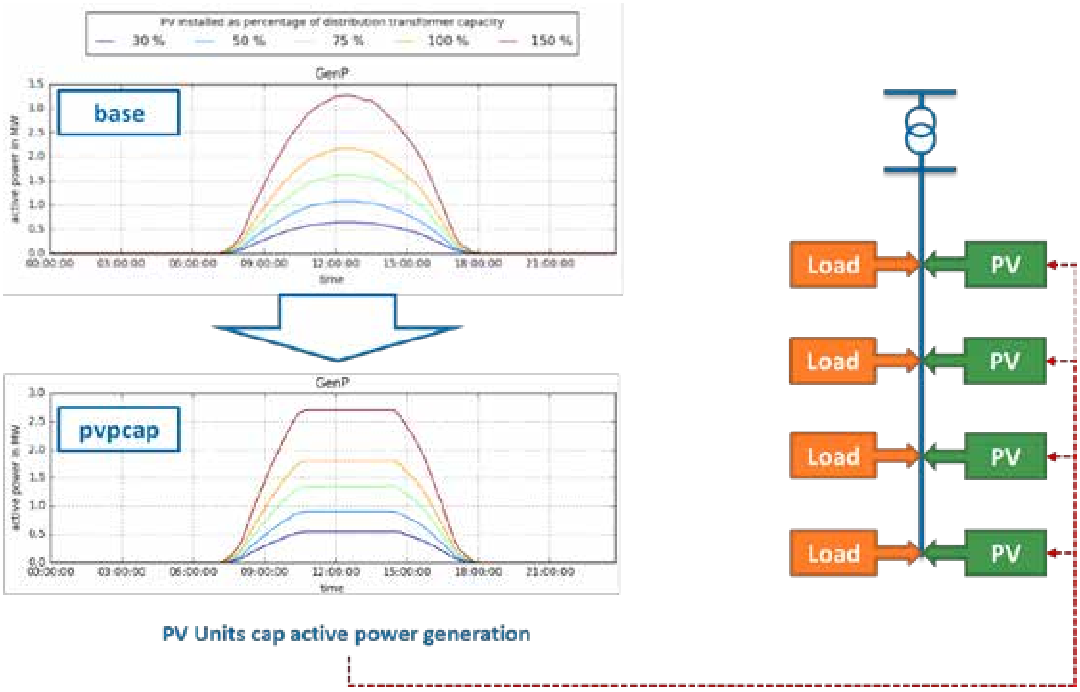


Figure 53: Capping of Photovoltaic plants peak power

Table 23: Energy lost due to PV capping at different percentages of the rated inverter power, assuming that the inverter is dimensioned to the unit's peak power (around 70 % of installed panel capacity.) Data from two PV units at Gurgaon (Delhi) and Indore (Madhya Pradesh.)

	Indore	Gurgaon
Active power percentage cap[12]	Annual energy loss	Annual energy loss
90 %	0.21 %	0.06 %
80 %	1.74 %	0.49 %
70 %	5.67 %	2.31 %
60 %	12.33 %	6.68 %
50 %	21.18 %	13.93 %
40 %	32.09 %	24.57 %
30 %	45.17 %	38.47 %
20 %	60.59 %	55.48 %

7.4.9 PV storage battery deployment

If the correlation between demand peak and PV peak is low, as it is in all analyzed Indian cases, there is a use case for energy storage, to store the excess PV energy generated during the day for the evening peak. The market for small scale battery storage, typically lithium ion batteries, is slowly picking up in Europe and North America, batteries installed directly at the PV unit may thus become a viable solution to minimize the grid impact of distributed PV and maximize self-consumption. In India, there is already a strong incentive for battery use, as frequent power outages require many customers to own a backup battery anyway.

Combined PV-battery units currently offered in India are typically sized at around 1 – 2 kWh storage capacity for each kW of installed PV capacity.[77] As a model case, 1 kWh for 1 kW of PV is considered in this study.

If an incentive is set for batteries for self-consumption, battery owners will usually try to charge their battery as quickly as possible as soon as their PV units starts generating. This leads to the behavior depicted in Figure 54, where the battery charges in the morning, but is already full at the time the PV unit hits its peak power. This has no positive impact on the grid even though self-consumption is maximized.

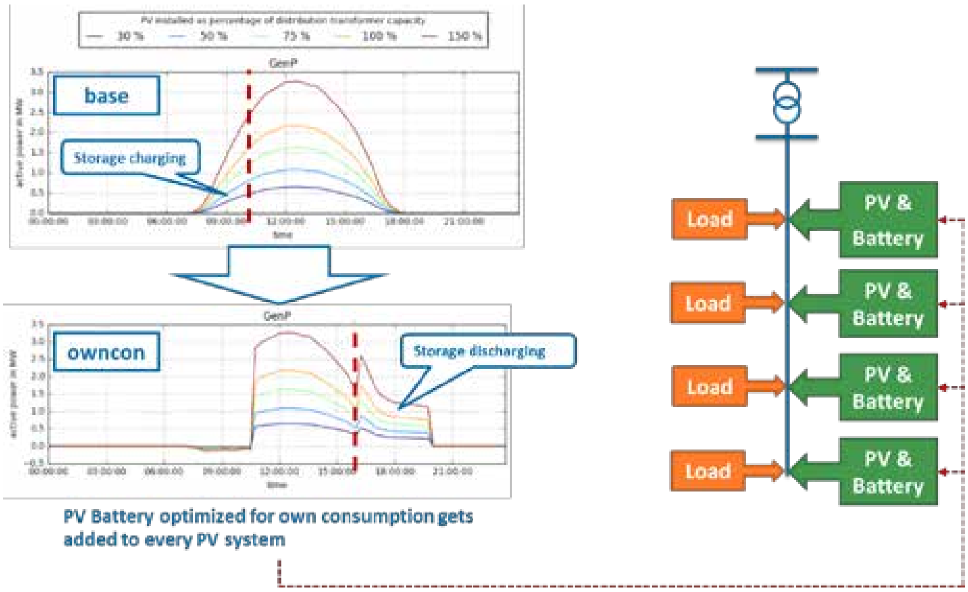


Figure 54: PV Battery implementation with own consumption optimization

To observe a positive impact on grid operation, batteries need to be operated in peak shaving mode, where the battery starts charging some time before mid-day and "shaves" the peak off the PV curve (Figure 55.) Usually, the grid operator will have to set some incentive for this behaviour to be implemented by the system owners.

Both options were included in the solutions, the pure self-consumption option only to show that the use of batteries does not necessarily benefit the grid.

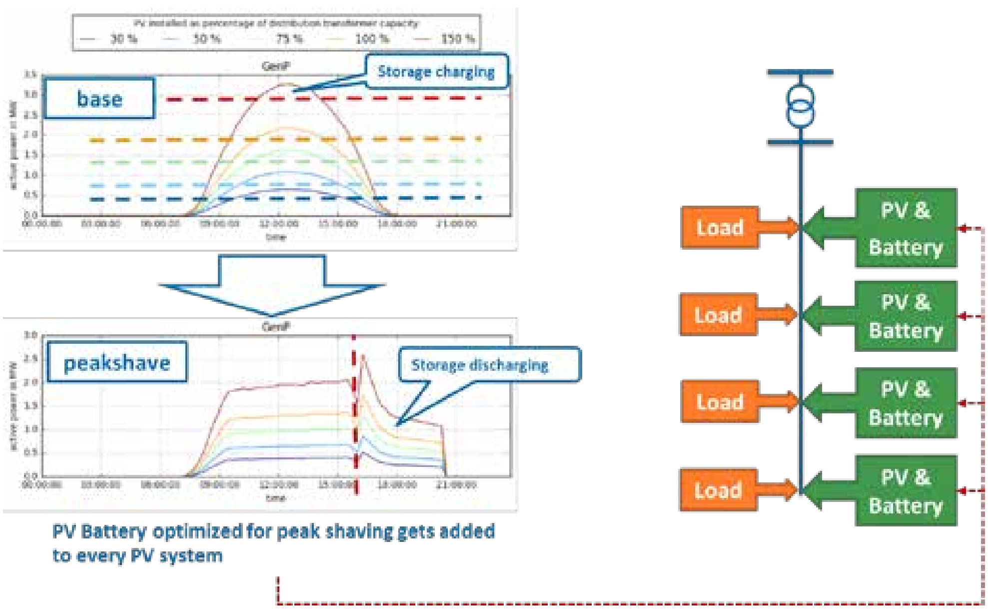


Figure 55: PV Battery implemented with peak shaving optimization

7.4.10 Demand side management

Apart from trying to influence the increased generation, there can be some potential to influence the demand such that the increased demand coincides with the solar plant generation peak and thus consumes as much of the excess energy being produced as possible. This may require a certain communication backbone. Usually the demand from heating and cooling systems may be shifted by forcing higher cooling or higher heating at times when large amounts of solar power is being generated and allowing the temperature to stabilize as time progresses. The peak demand of added A/C-load within the adapted load scenarios described in Section 7.3.3, was shifted towards mid-day to simulate a behavior adjusted to the available PV power. An exemplary load profile is shown in Figure 56.

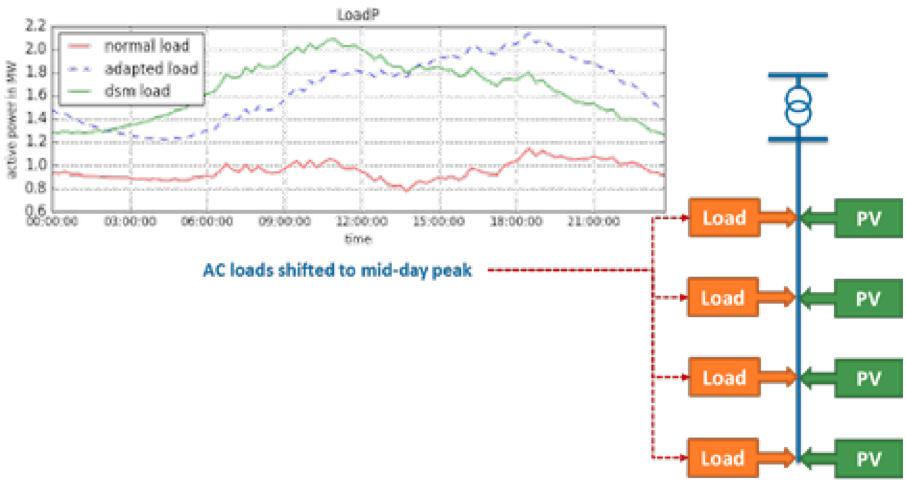


Figure 56: Demand Side Management profile

7.4.11 Reinforcements of lines, cables transformers

Network reinforcement is the simplest and most effective, but also often the most expensive remedy to increase photovoltaic penetration in the network. This solution helps alleviate both voltage and overloading issues. For each scenario, simple reinforcement of overloaded assets was considered. Detailed results are given in the annex.

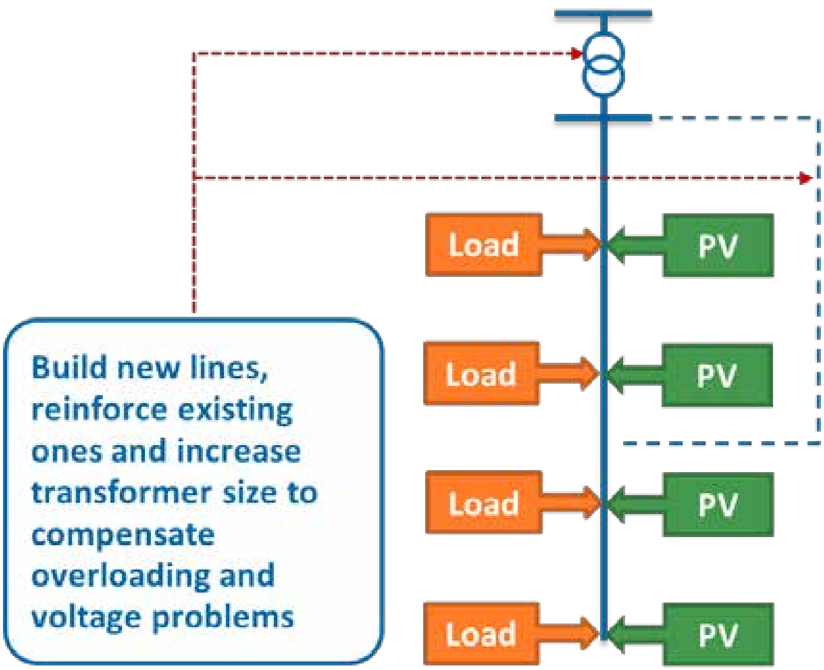


Figure 57: Network Reinforcement

7.4.12 Overview

An overview of the utilized solutions is given in Table 24. For each scenario, simple reinforcement of overloaded assets was considered as well, detailed results are given in the annex.

Table 24: Solutions applied to the urban feeder with LV network.

Measure (Abbrevation)	Description
base	Base case with no additional measures implemented.
oltc	On-load tap changing transformers with automatic voltage control are used between 33 and 11 kV (only Bhopal, part of base case in Delhi)
shunt V control	Existing shunt capacitors present in the network are used for automated voltage control.
wide area control	Voltage control by OLTC based on a wide area monitoring system. Including on-load tap changing DTs for the Delhi urban case.
fixed PF	Distributed PV units operate at a fixed power factor of 0.95 lagging.
qvchar	Distributed PV units are equipped with a Q-V characteristic for voltage control
cap pv	PV output is capped to 70 % (Delhi) or 75 % (Bhopal) of inverter rating (less than 3 % annual energy loss)
storage ownConsumption	Storage batteries are installed at all PV units, with 1 kWh of storage per 1 kWp of PV, operation optimized solely for self-consumption.
storage peakShaving	Storage batteries are installed at all PV units, with 1 kWh of storage per 1 kWp of PV, operation optimized for self-consumption and grid impact.
dsm	Demand side management for all loads.
grid reinforcement	Overloaded assets are reinforced.

8. Detailed Simulation Results

8.1 Visual representation of results

The detailed description of results requires some visual representation, which may not be self-explanatory. In the following, the structure used in presenting the results in this section shall be explained briefly.

The main means of graphic representation of each scenario is a figure like the example given in Figure 58. From the left to the right, PV penetration is increased in the analyzed grid model from 20 or 30 to 150 % of the total capacity of installed distribution transformers. For each value, the maximum asset loading experienced by any asset is given in the upper graph, and the maximum voltage occurring anywhere in the grid model is given on the lower graph. These values are interpolated linearly to show a trend. The conditions in the base case, with the grid "as is," is represented by a black line, while the multiple colored lines represent the conditions under the implementation of different technology options.

The limits allowed during normal operation, both for loading and voltage, are given by dotted red lines. For each scenario, the PV penetration level at which one of the thresholds is crossed and a security or quality constraint thus violated, are given in an additional table, including the values for all different technology options.

For each scenario, simple reinforcement of overloaded assets was considered. Detailed results are given in the annex.

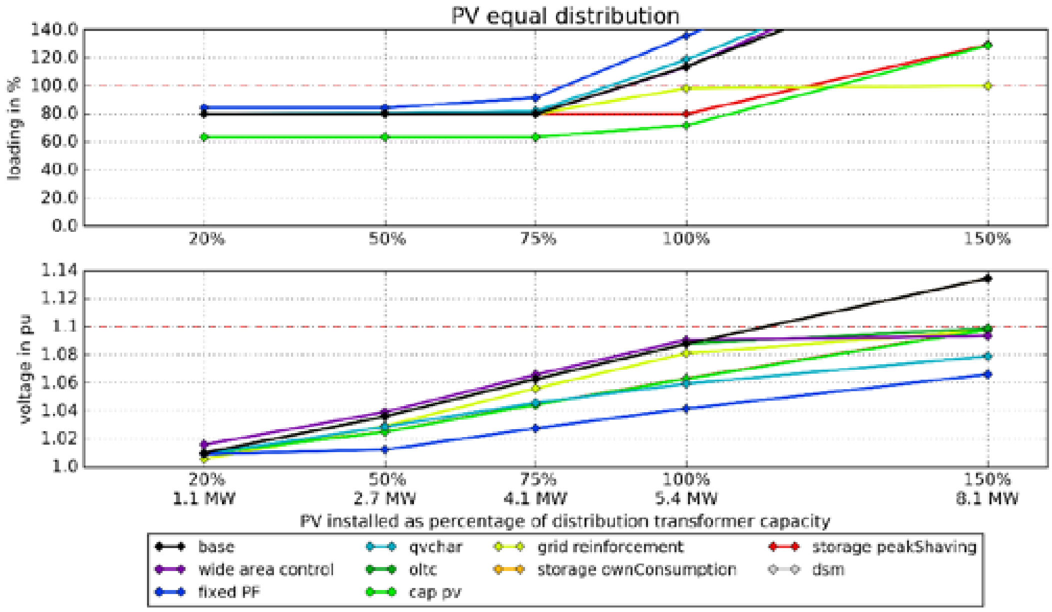


Figure 58: Result example as described in the text.

8.2 Urban feeder Delhi

The urban feeder with a fully modelled generic LV network consisting of eight distribution transformers and a total of 28 LV feeders, has been simulated using five different scenarios. For each of the scenarios, the installed PV capacity as a percentage of the distribution transformer capacity has been increased stepwise. Nine solutions were considered to be appropriate for this network.

8.2.1 Scenario 1: PV equally distributed

Installing PV in an equally distributed manner along each of the LV feeders will likely result in loading issues of either cables or transformers before any voltage issues appear. The outcome of the simulations for equal distribution are depicted in Figure 59.

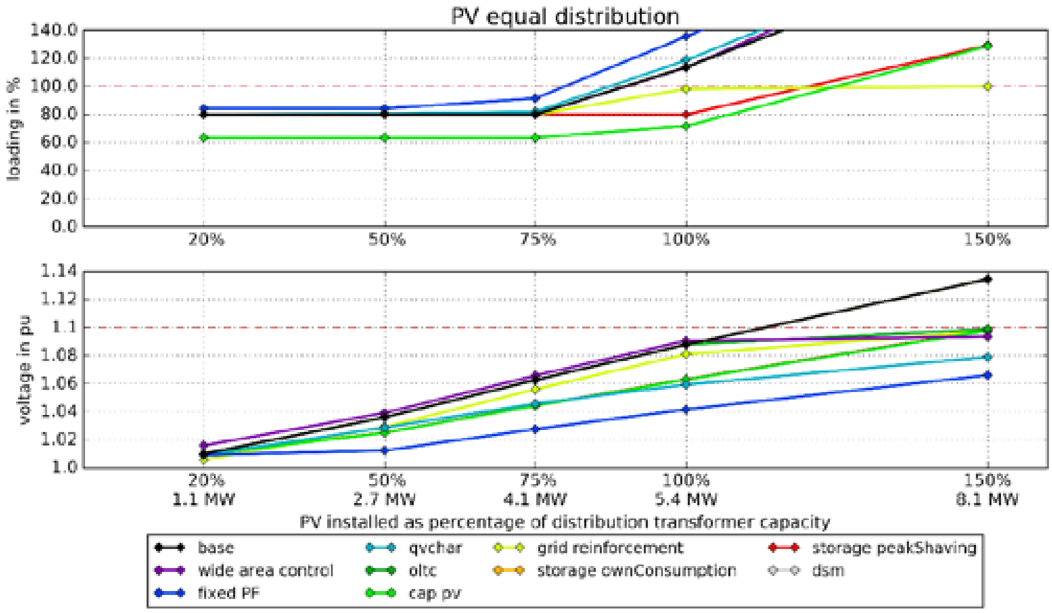


Figure 59: Simulation results for urban feeder with LV network and equal PV distribution.

Up to 90% of installed PV per distribution transformer capacity can be installed without encountering overloading of elements considering an equal distribution in the LV feeders. Loading issues of installed cables can be observed starting at 90%. Due to the equal distribution of PV and generally large cable cross-sections, voltage issues are not an arising issue in the considered LV network. In order to achieve higher installed PV capacities, solutions reducing the loading of the cable can be utilized, while all solutions dealing with voltage issued cannot result in higher PV capacities. Storage utilizing peak shaving can increase the installed PV up to 120%. Afterwards, capping PV at 70% can increase this value up to 125%. An overview of the suitable solutions and their issues can be found in Table 25.

Table 25: Evaluation of measures for urban feeder with LV network and equal PV distribution.

Measure	Max. installed PV	Evaluation / limiting factor	
base	90%	loading issue	
wide area control	90%	not suitable	×
fixed PF	80%	not suitable	×
qvchar	90%	not suitable	×
oltc	90%	not suitable	×
cap pv	125%	suitable, loading issue	✓
grid reinforcement	150%	suitable	✓
storage ownConsumption	90%	not suitable	×
storage peakShaving	120%	suitable, loading issue	✓
dsm	90%	not suitable	×

8.2.2 Scenario 2: PV equally distributed with adapted load

Future load development (demand increase of 5 % per year) is expected to be beneficial to PV integration, as more power generated by PV can be consumed locally. Scenario 2 evaluates the impact of such a load increase. The higher load is based on the addition of A/C units at every LV load. The results of this scenario are shown in Figure 60.

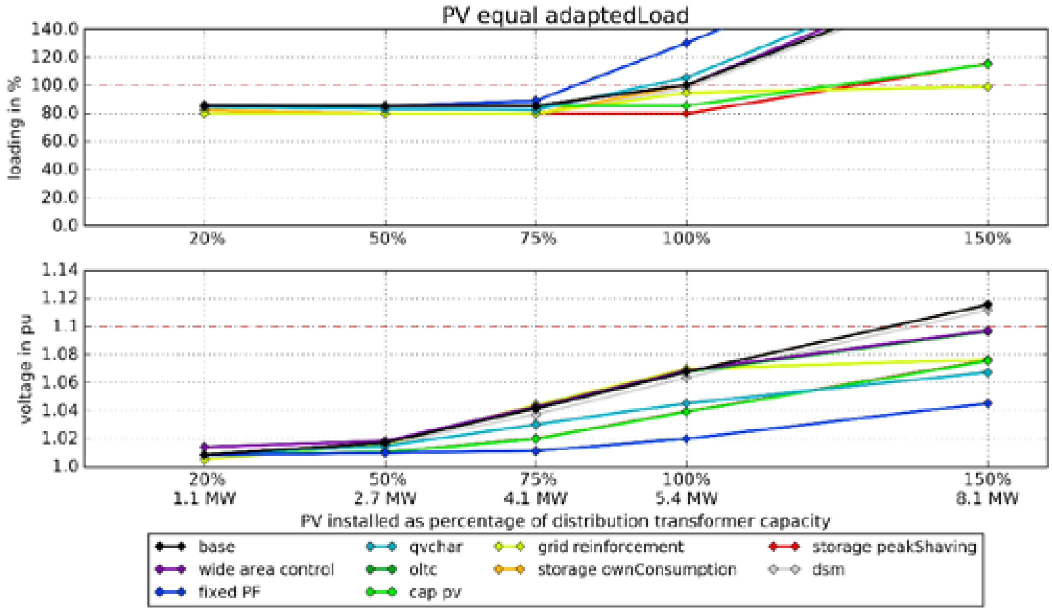


Figure 60: Simulation results for urban feeder with LV network and equal PV distribution with adapted load.

The first cable starts to get overloaded at 100% of installed PV capacity, due to reverse power flow during mid-day. The adapted load allows for an increase of 10% installed PV within the LV network in comparison to the scenario without adapted load. Capping PV at 70% or using storage with peak shaving can help to increase installed PV up to 130% of distribution transformer capacity. An overview of the thresholds for installed PV are listed in Table 26 (. Since voltage is not an issue in this scenario, measures dealing with voltages problems only (reactive power control, wide area management) are neither suitable nor necessary.

Table 26: Evaluation of measures for urban feeder with LV network and equal PV distribution with adapted load.

Measure	Max. installed PV	Evaluation / limiting factor	
base	100%	loading issue	
wide area control	100%	not suitable	×
fixed PF	85%	not suitable	×
qvchar	95%	not suitable	×
oltc	100%	not suitable	×
cap pv	130%	suitable, loading issue	✓
grid reinforcement	150%	suitable	✓
storage ownConsumption	100%	not suitable	×
storage peakShaving	130%	suitable, loading issue	✓
dsm	100%	not suitable	×

8.2.3 Scenario 3: PV at the end of the feeder

Shifting the installed PV capacity to the end of the feeder, bot voltage and overloading issues are expected to occur within the LV network at high penetration levels. This represents a worst case scenario that can happen in some areas as PV development is not always homogeneous. The results of this scenario for each solution and installed PV capacity is shown in Figure 61.

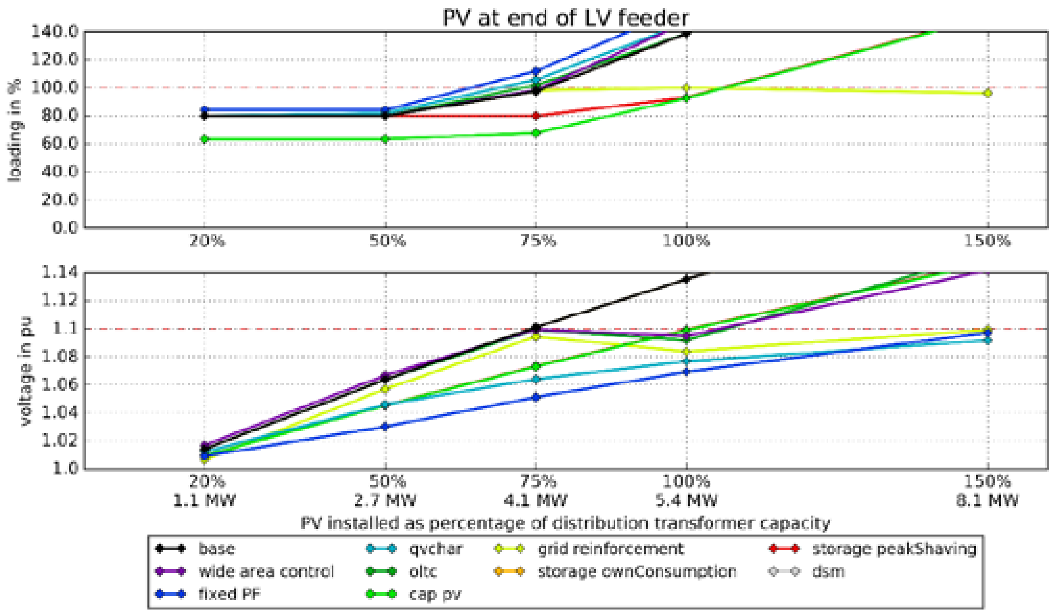


Figure 61: Simulation results for urban feeder with LV network and PV at the end of the feeder.

The base case of the scenario with PV located at the end of the feeder of each LV feeder allows for a maximum of 75 % of installed PV capacity. Afterwards, both voltage and loading issues can be observed in the LV network. Utilizing storage with peak shaving capabilities allows to push this limit up to 100 % until high voltage becomes an issue. Capping PV infeed at 70 % of installed inverter capacity allows for an installed PV size of 100 % of distribution transformer capacity. Higher capacities will lead to overvoltage problems.

Although voltage is the main issue in this case, the grid is also highly loaded. The solutions targeting voltage issues alone are not suitable in this case, as the voltage problems may be alleviated, but grid elements will be overloaded at only very slightly higher installed capacity (see Table 27.) Solutions using reactive power even increase loading of elements and should not be used in this scenario.

Table 27: Evaluation of measures for urban feeder with LT network and PV at the end of the feeder.

Measure	Max. installed PV	Evaluation / limiting factor	
base	75%	loading and voltage issue	
wide area control	75%	not suitable	×
fixed PF	65%	not suitable	×
qvchar	70%	not suitable	×
oltc	75%	not suitable	×
cap pv	100%	suitable, voltage issue	✓
grid reinforcement	150%	suitable	✓
storage ownConsumption	75%	not suitable	×
storage peakShaving	100%	suitable, voltage issue	✓
dsm	75%	not suitable	×

8.2.4 Scenario 4: PV at the end of the feeder with adapted load

Applying the adapted load to the scenario with PV installed at the end of the feeder, it is anticipated that more PV can be installed in comparison to the scenario with just PV at the end of the feeder. The corresponding simulation results of the scenario with adapted load and PV at the end of the LV feeders is presented in Figure 62.

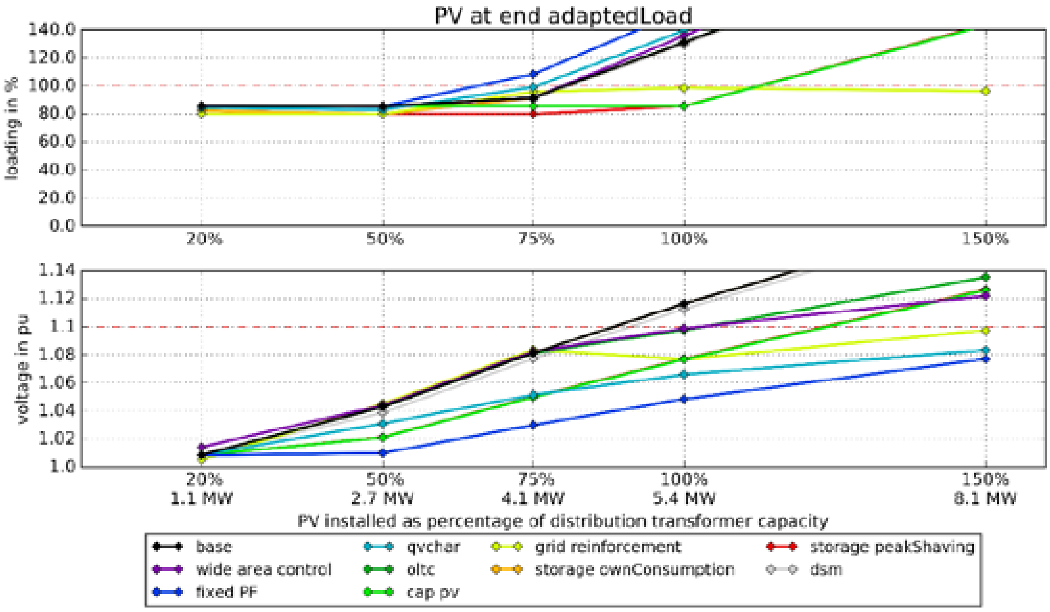


Figure 62: Simulation results for urban feeder with LV network and PV at the end of the feeder with adapted load.

The hosting capacity increases by about 5%, compared to the normal load case with PV at the end of the feeder (Scenario 3). This leads to a maximum of 80% of installed PV without any measures taken. This scenario leads to cables experiencing overloading issues. The overloading occurs within the LV network, when smaller cross-sections are used towards the end of the feeder. In contrast, scenarios with equal distribution exhibit loading problems at cable sections with larger cross-sections close to the distribution transformer. The additional load does resolve the main issue of overloading of network elements. With the voltage being close to the considered limit of 1.1 p.u., it should not be disregarded. Storage with peak shaving allows for an increase of 35% installed PV capacity, reaching a total value of 115%, before cables cross the loading limit of 100%. Similarly, capping PV at 70% manages to allow for up to 115% installed PV capacity. Table 28 provides a comprehensive summary of thresholds for installed PV.

Table 28: Evaluation of measures for urban feeder with LV network and PV at the end of the feeder with adapted load.

Measure	Max. installed PV	Evaluation / limiting factor	
base	80%	loading issue	
wide area control	80%	not suitable	×
fixed PF	70%	not suitable	×
qvchar	75%	not suitable	×
oltc	80%	not suitable	×
cap pv	115%	suitable, loading issue	✓
grid reinforcement	150%	suitable	✓
storage ownConsumption	80%	not suitable	×
storage peakShaving	115%	suitable, loading issue	✓
dsm	80%	not suitable	×

8.2.5 Scenario 5: PV at the end of the feeder with lower cable cross-section

The final scenario of the evaluated urban distribution grid with a fully modelled LV network deviates from the previous the scenarios. The worst case scenario was chosen from the previous four, which was the scenario with PV at the end of the feeder (max. 75% of installed PV without measures). The scenario was then modified by reducing corresponding cable cross sections from 300 mm² to 150 mm². Thereby, loading of cables increased to approximately 100% without PV present. The intention is to present a model case for weaker urban grids. The results of this scenario and all applied measures for each simulated installed PV capacity is displayed in Figure 63.

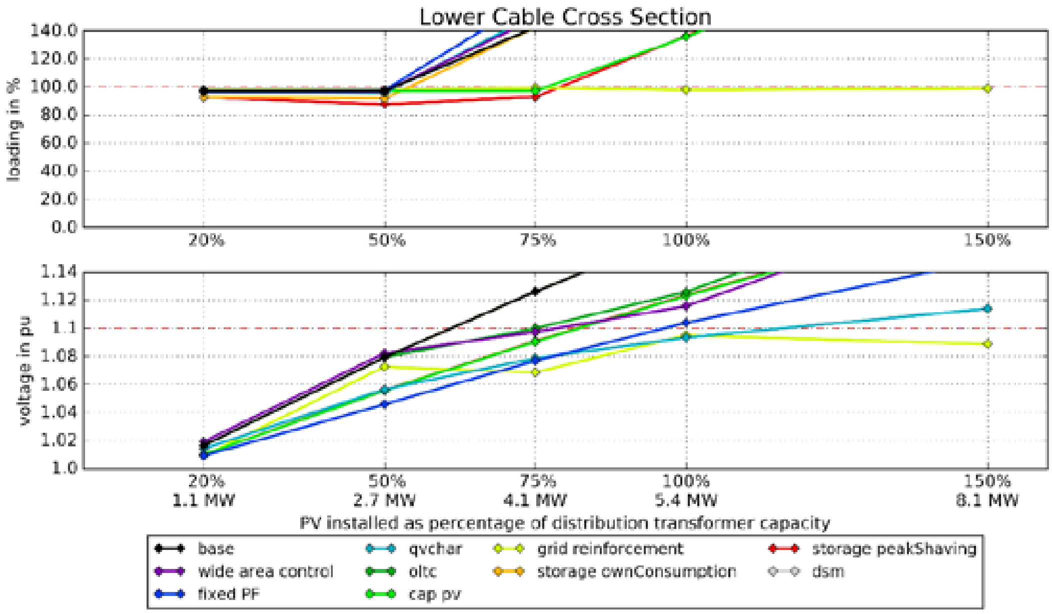


Figure 63: Simulation results for urban feeder with LV network and PV at the end of the feeder with lower cable cross-section.

The maximum installed PV capacity drops significantly to about 55 % of installed distribution transformer capacity. Loading of cables is still the main issue of this network and now gets aggravated by using a lower cross-section for the majority of cables. Storage with peak shaving allows for up to 80% of installed PV capacity. Capping PV at 70 % of installed converter size also increases the maximum installed PV capacity to 80 %. The maximum of installed PV and an assessment of each measure is given in Table 29.

Table 29: Evaluation of measures for urban feeder with LV network and PV at the end of the feeder with lower cable cross-section.

Measure	Max. installed PV	Evaluation / limiting factor	
base	55%	loading issue	
wide area control	50%	not suitable	×
fixed PF	50%	not suitable	×
qvchar	55%	not suitable	×
oltc	55%	not suitable	×
cap pv	80%	suitable, loading issue	✓
grid reinforcement	150%	suitable	✓
storage ownConsumption	55%	not suitable	×
storage peakShaving	80%	suitable, loading and voltage issue	✓
dsm	55%	not suitable	×

8.3 Rural feeder Delhi

8.3.1 Scenario 1: PV power plant

A larger PV power plant is connected to one of the feeders. As a first step, the connection scheme of the PV power plant is decided upon, using three different configurations:

- PV power plant connected to feeder 1
- PV power plant connected to feeder 2
- PV power plant connected to feeder 1 and feeder 2

The network without the PV power plant is also simulated to get a baseline for the simulation results. The results for each of these scenarios are shown in Figure 64

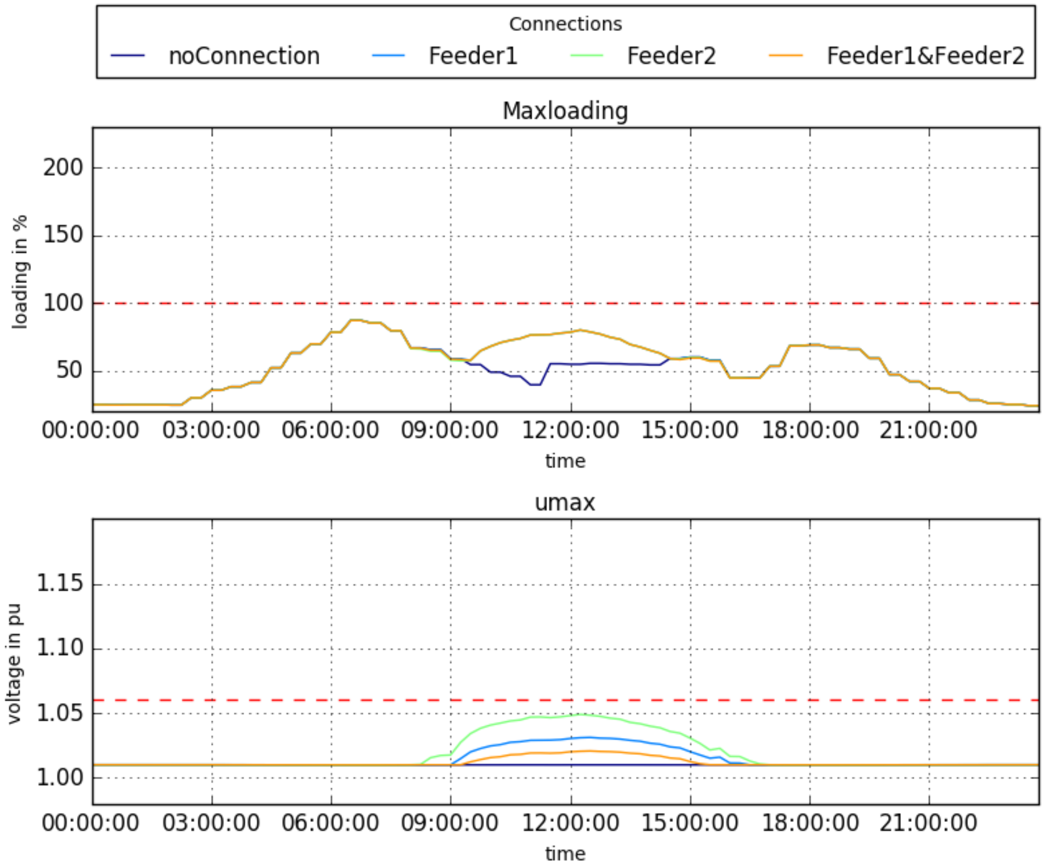


Figure 64: Simulation results of the rural feeder with two parallel MV feeders and a 3.5 MW power plant with different connection schemes.

The connection of the PV power plant to Feeder 2 can be considered as the worst case, due to having the highest observed voltage. Splitting up the PV in-feed onto both feeder is obviously the safest way, but also the most expensive one. The connection to Feeder 1 has the lowest impact on voltage, while only using a single connection to one of the grids. It is therefore good compromise between economical and technical considerations.

Since voltage seems to be the main issue, it is reasonable to introduce voltage control for the PV power plant. A Q-V-characteristic, as described in Section 7.4.6, has been used and the simulation results are shown in Figure 65.

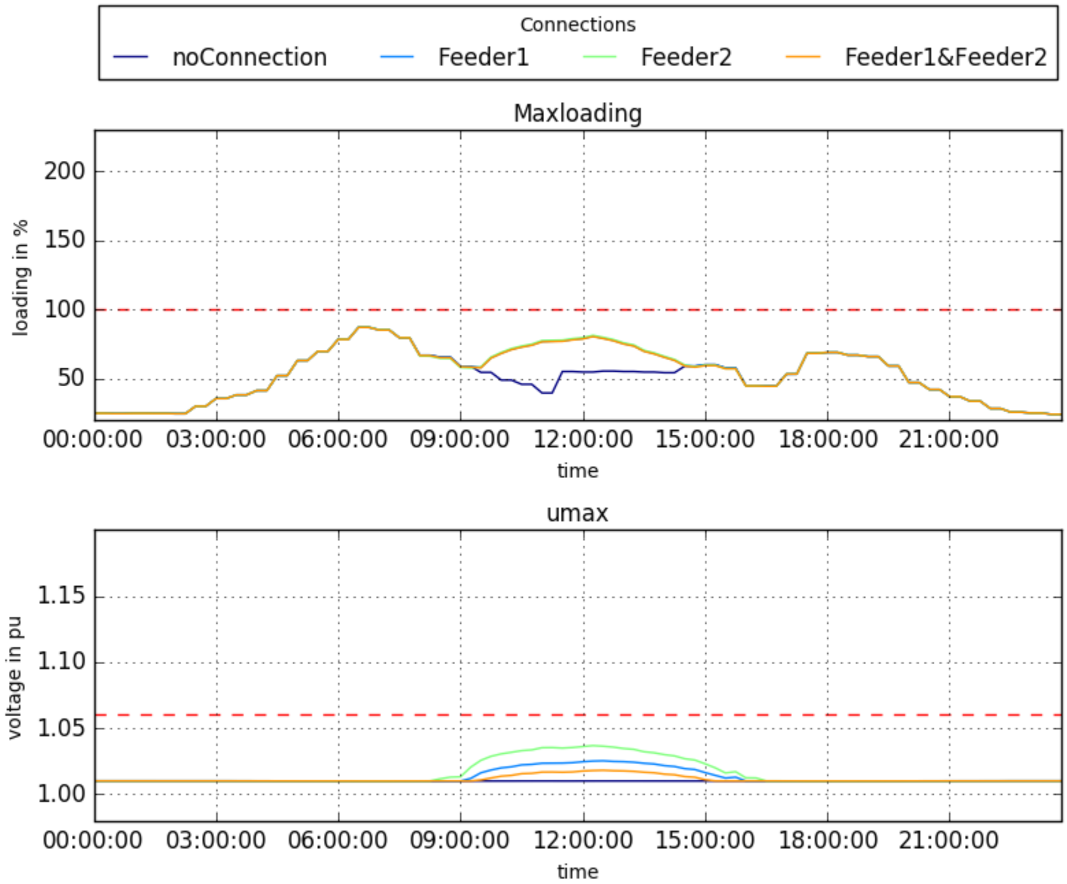


Figure 65: Simulation results of the rural feeder with two parallel MV feeders and a 3.5 MW power plant with different connection schemes and Q-V-characteristic enabled.

The Q-V-characteristic reduces the observed voltage in all connection schemes, without any serious increase of maximum loading. It makes sense to require voltage control capabilities of the PV power plant in this network. Such requirements are international good practice for power plants connected to the MV level.

The connection to Feeder 1 with an activated Q-V-characteristic will be used for future simulations with the PV power plant under consideration, since this will demonstrate the highest possible impact of PV power plant on a rural feeder, while still using the recommended capability of the PV power plant to reduce voltage issues.

8.3.2 Scenario 2: PV equally distributed

The second scenario evaluates an equal distribution of installed PV at each distribution transformer along the MV feeders. Since no LV network is modelled, PV is aggregated and connected at the LV side of the distribution transformer. The scenario can be considered as a typical basis for further investigations and a good assessment of potential problems occurring in the network. Voltage issues are expected to manifest, based on the long lines of the rural topology. The simulation results are shown in Figure 66.

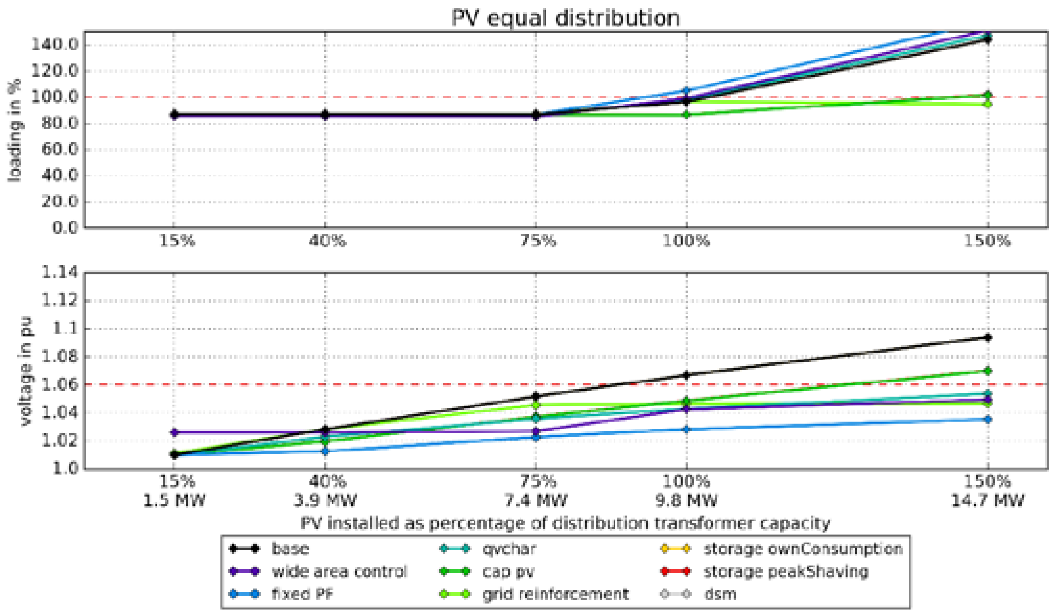


Figure 66: Simulation results of the rural feeder with two parallel MV feeders and equal PV distribution.

The considered rural feeder is able to support a maximum of 90% installed PV capacity if equal distribution is assumed. Voltage becomes an issue, if higher values are supposed to be considered. The voltage problem occurs first on the slightly longer Feeder 2. All measures dealing with voltage issues are therefore applicable to increase the potential of installed PV. Using wide area control of the power transformer or a Q-V-characteristic allows for up to 105%, while running PV inverters at a fixed power factor of 0.95 underexcited only enables 95%. The impact of all three measures is rather low, because once the voltage problem is alleviated, loading issues of network elements become apparent. If storage with peak shaving or a 70 % PV cap is applied more PV can be installed without experiencing the loading problem, while also reducing overvoltages. Both solutions increase the share to 125% of installed DT capacity. A list of the impact on maximum installed PV of all measures applied to the scenario is given in Table 30.

Table 30: Evaluation of measures for the rural feeder with two parallel MV feeders and equal PV distribution.

Measure	Max. installed PV	Evaluation / limiting factor	
base	90%	voltage issue	
wide area control	105%	suitable, loading issue	✓
fixed PF	95%	suitable, loading issue	✓
qvchar	105%	suitable, loading issue	✓
cap pv	125%	suitable, voltage issue	✓
grid reinforcement	150%	suitable	✓
storage ownConsumption	90%	not suitable	×
storage peakShaving	125%	suitable, voltage issue	✓
dsm	90%	not suitable	×

8.3.3 Scenario 3: PV equally distributed with adapted load

Adding A/C load at each distribution transformer will generally reduce reverse power flows and lead to more PV power being consumed locally, increasing hosting capacity. The corresponding results are shown in Figure 67.

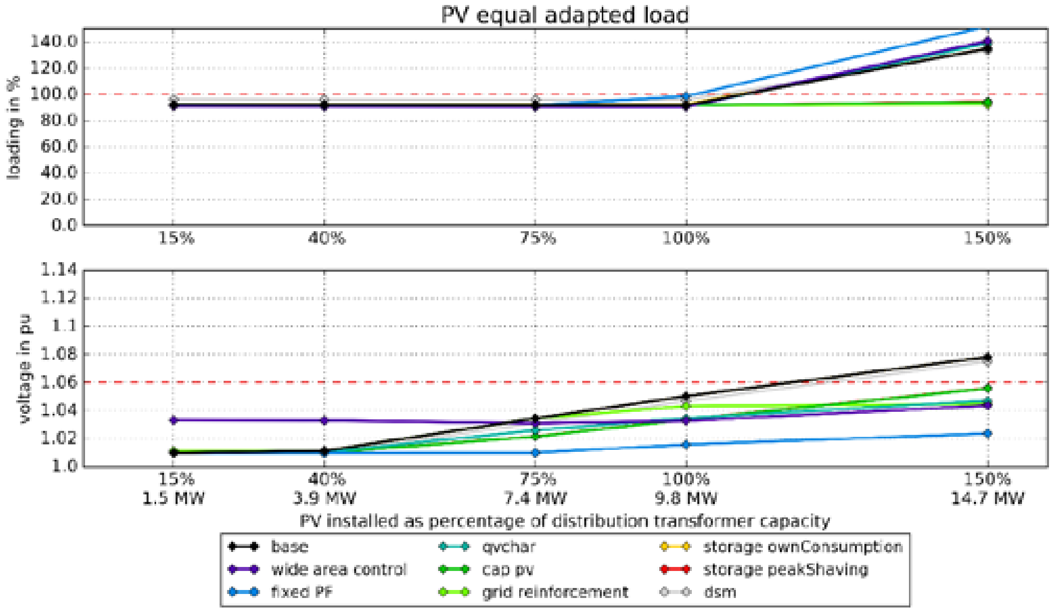


Figure 67: Simulation results of the rural feeder with two parallel MV feeders and equal PV distribution with adapted load.

Considering adapted load increases the maximum installed PV capacity from 90 % up to 110 % compared to the base case of Scenario 2. Starting at 110 %, distribution transformers get overloaded. Capping PV generation and storage with peak shaving can significantly increase hosting capacity. The results are very similar to the base case, albeit with a slightly higher hosting capacity (Table 31.)

Table 31: Evaluation of measures for the rural feeder with two parallel MV feeders and equal PV distribution with adapted load.

Measure	Max. installed PV	Evaluation	
base	110%	loading issue	
wide area control	110%	not suitable	×
fixed PF	105%	not suitable	×
qvchar	110%	not suitable	×
cap pv	150%	suitable	✓
grid reinforcement	150%	suitable	✓
storage ownConsumption	110%	not suitable	×
storage peakShaving	150%	suitable	✓
dsm	110%	not suitable	×

8.3.4 Scenario 4: PV equally distributed with a 3.5 MW PV power plant

Open field PV power plants, typically connected to the MV or HV level, are mostly set up in rural areas where enough open space is available. One such plant is already planned in the example rural grid in Delhi, as described in Scenario 1. The 3.5 MW PV power plant connected to Feeder 2 will also impact the amount of rooftop PV that can be integrated. Results from simulations with the PV power plant along with the equally distributed residential PV is considered in the simulation results depicted in Figure 68.

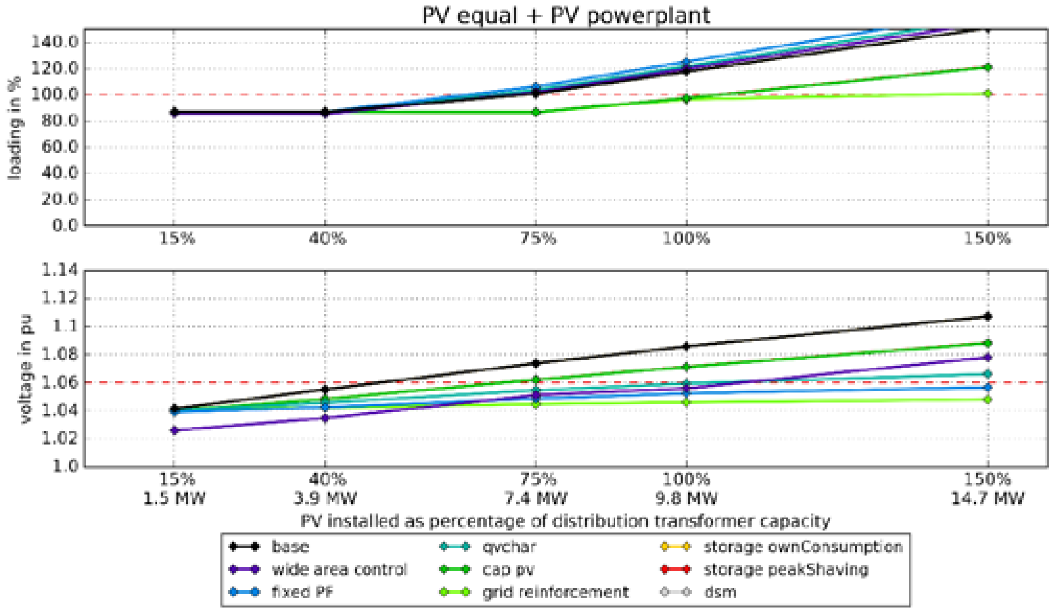


Figure 68: Simulation results of the rural feeder with two parallel MV feeders and equal PV distribution with a 3.5 MW PV power plant.

The maximum voltage increases significantly with the introduction of the PV power plant in this scenario, as could already be anticipated from the results given in Figure 65 on page 171, showing the PV power plant without the addition of equally distributed rooftop PV. The installable amount of residential PV reduces from 90 % in Scenario 2 to 50 % in this scenario.

Capacity can be increased back to 90 % through the introduction of wide area control, alleviating voltage issues without increasing network loading. The other solutions are generally helpful in reducing the maximum voltage, but their effect is limited at an earlier percentage of installed PV capacity ranging from 65% using a fixed power factor at residential PV systems to 70% using either Q-V-characteristic, capping PV or storage with peak shaving. An overview of the maximum installed PV capacity per solution is listed in Table 32.

Table 32: Evaluation of measures for the rural feeder with two parallel MV feeders and equal PV distribution with a 3.5 MW PV power plant.

Measure	Max. installed PV	Evaluation / limiting factor	
base	50%	voltage issue	
wide area control	75%	suitable, loading issue	✓
fixed PF	65%	suitable, loading issue	✓
qvchar	70%	suitable, loading issue	✓
cap pv	70%	suitable, voltage issue	✓
grid reinforcement	150%	suitable	✓
storage ownConsumption	50%	not suitable	×
storage peakShaving	70%	suitable, voltage issue	✓
dsm	50%	not suitable	×

The total PV capacity that can be installed within the entire MV network in each case is listed in Table 33.

Table 33: Sum of maximum installed rooftop and open field PV capacity per scenario.

Measure	Scenario 2 total PV installed	Scenario 4 total PV installed
base	8.8 MW	8.4 MW
wide area control	10.3 MW	10.85 MW
fixed PF	9.3 MW	9.87 MW
qvchar	10.3 MW	10.36 MW
cap pv	12.3 MW	10.36 MW
grid reinforcement	14.7 MW	18.2 MW
storage ownConsumption	8.8 MW	8.4 MW
storage peakShaving	12.3 MW	10.36 MW
dsm	8.8 MW	8.4 MW

8.3.5 Scenario 5: PV equally distributed with the network fully cabled

Different system operators have different philosophies as to whether using overhead lines or underground cables should be preferred. For example, in Germany DSOs are in the process of exchanging older overhead lines for underground cables. In India there might also be regions using more cables than overhead lines within distribution networks. Since both feeders under consideration mostly use overhead lines, the network was equipped with cables with a similar cross-section, in order to assess the difference between both configurations. The observed results can be found in Figure 69

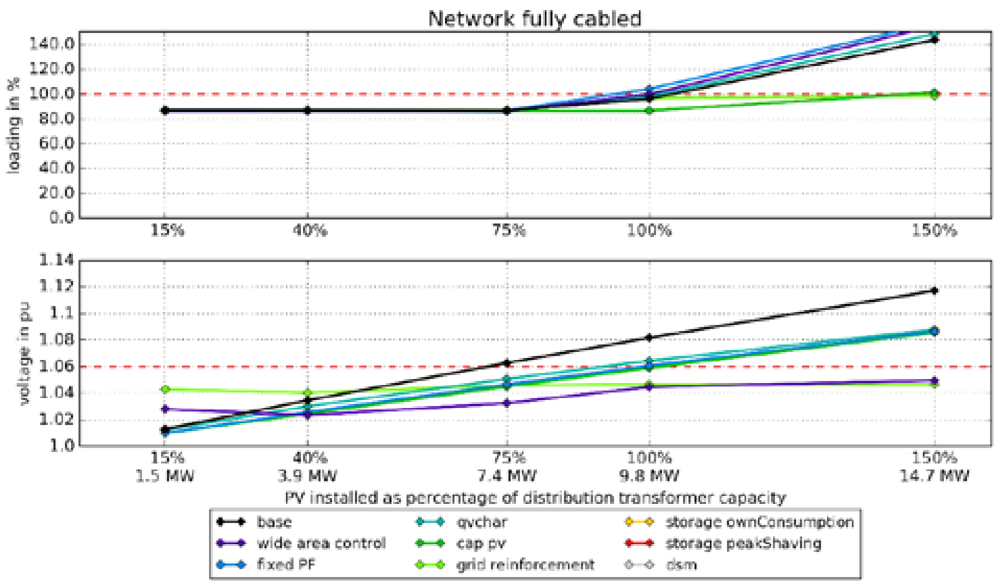


Figure 69: Simulation results of the rural feeder with two parallel MV feeders and equal PV distribution with the network fully cables.

Using cables results in a more pronounced voltage issue compared to Scenario 2. This reduces the maximum installed PV capacity from 90% down to 70% without any measures applied. This can be attributed to the higher capacity of cables compared to overhead lines, which increases voltage by shifting the reactive power balance. Loading of cables is not much different from Scenario 2, since cables with similar ampacity were used. Applying a fixed power factor of 0.95 to all PV units increases hosting capacity to 95 %, at which point both overloading and voltage problems occur. The use of Q-V characteristics is less effective, increasing capacity to only 90 %. The problem here is that PV units will only start drawing reactive power once the voltage at their connection point rises. Units closer to the 11 kV busbar experience lower voltages and will thus not contribute to voltage control.

Once again, wide area control can cope with the voltage problem by fully utilizing the available voltage range, but cannot prevent transformer overloading starting at 100% of installed transformer capacity. Storage with peak shaving or a PV cap at 70 % can handle the loading issue but not the voltage issues starting at 100% PV. A combination of wide area control and active power management (batteries or cap) could be used to increase the hosting capacity further (Table 34 .)

Table 34: Evaluation of measures for the rural feeder with two parallel MV feeders and equal PV distribution with the network fully cabled.

Measure	Max. installed PV	Evaluation / limiting factor	
base	70%	voltage issue	
wide area control	100%	suitable, loading issue	✓
fixed PF	95%	suitable, loading and voltage issue	✓
qvchar	90%	suitable, voltage issue	✓
cap pv	100%	suitable, voltage issue	✓
grid reinforcement	150%	suitable	✓
storage ownConsumption	70%	not suitable	×
storage peakShaving	100%	suitable, voltage issue	✓
dsm	70%	not suitable	×

8.4 Urban feeder Bhopal

8.4.1 Scenario 1: Rooftop PV equally distributed along the feeder with normal load

Installing PV in an equally distributed manner to each distribution transformer on the MV feeder will likely result in loading issues of either lines or transformers before any voltage issues appear. The outcome of the simulations for equal distribution are depicted in Figure 70.

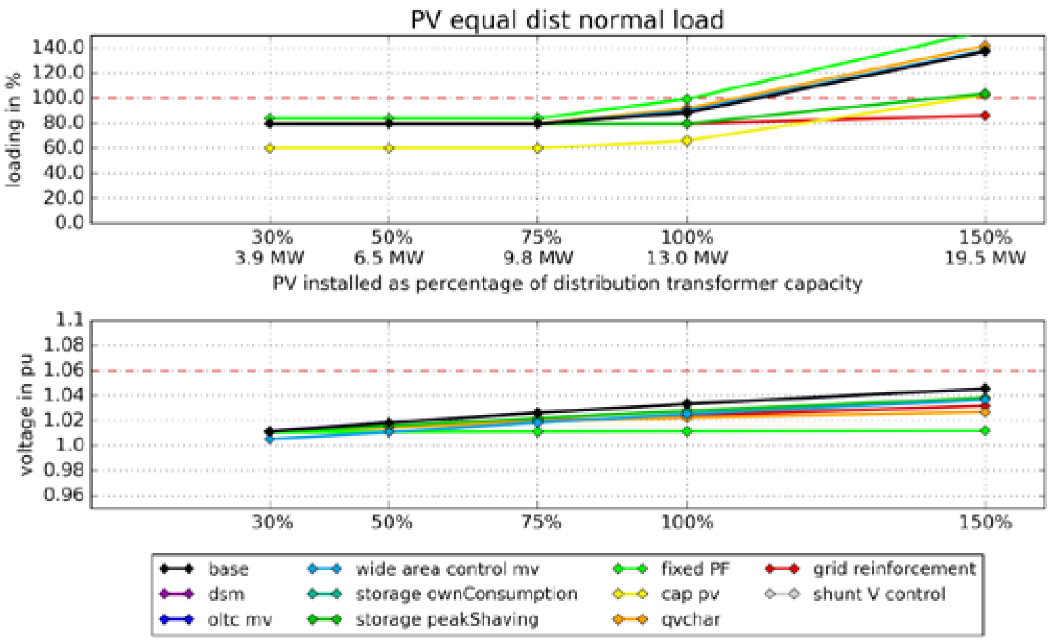


Figure 70: Simulation results for the urban feeder in Bhopal with rooftop photovoltaic plants equally distributed along the feeder with normal load considered

In the urban feeder in Bhopal, the voltage drop and rise along the feeder is insignificant due to the short line length. Thus, no overvoltage issues are found at any of the simulated PV penetration levels, and no corresponding measures have to be implemented. Overloading of transformers and MV lines start at a PV penetration of around 110 % of installed distribution transformer capacity.

To increase the capacity further, active power measurements can be implemented. Using peak shaving batteries as described in section 7.4.9 can increase the penetration level to 140 %, while the less costly option of capping PV at 75 % of inverter size enables a level of 145 %. A comparison of results is listed in Table 35.

Table 35: Rooftop photovoltaic penetrations on the urban feeder at Bhopal for scenario 1 with different solutions

Measure	Max. installed PV	Evaluation / limiting factor	
Base	110 %	Loading	✓
oltc mv	110 %	Loading	✓
wide area control mv	110 %	Loading	✓
shunt V control	110 %	Loading	✓
fixed PF	100 %	Loading	✓
qvchar	110 %	Loading	✓
cap pv	145 %	Suitable, loading	✓
storage ownConsumption	110 %	Loading	✓
stograge peakShaving	140 %	Loading	✓
grid reinforcement	150 %	Suitable	✓

8.4.2 Scenario 2: Rooftop PV equally distributed along the feeder with adapted load

Future load development (demand increase of 5 % per year) is expected to be benefitial to PV integration, as more power generated by PV can be consumed locally. Scenario 2 evaluates the impact of such a load increase. The higher load is based on the addition of A/C units at every LV load as described in section 7.3.3. The results of this scenario are shown in Figure 71.

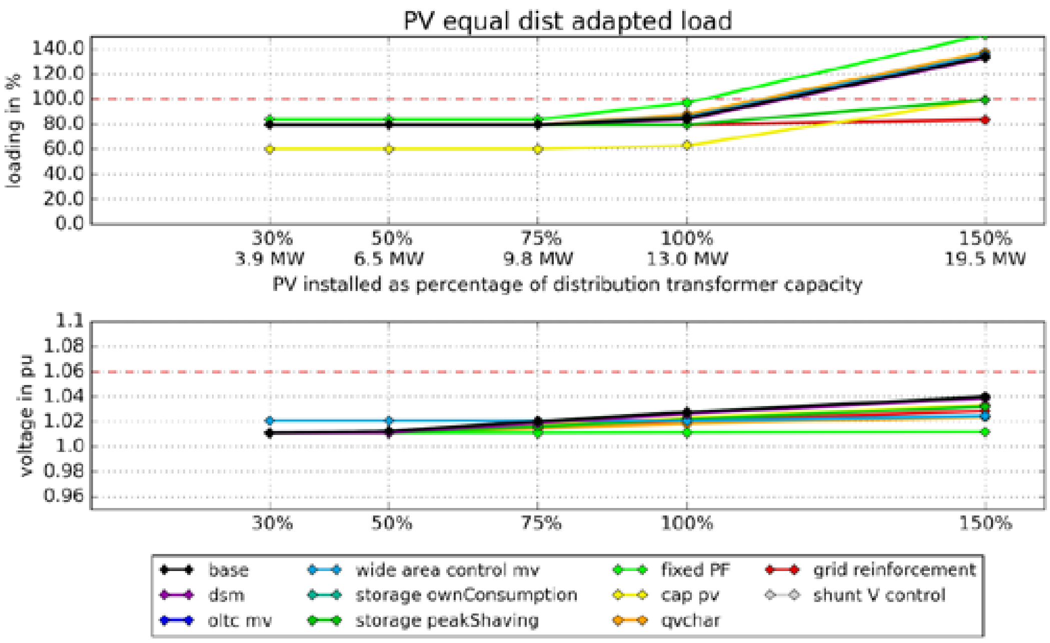


Figure 71: Simulation results for the urban feeder in Bhopal with rooftop photovoltaic plants equally distributed along the feeder with adapted load considered

In the urban feeder in Bhopal, the voltage drop and rise along the feeder is insignificant due to the short line length. Thus, no overvoltage issues are found at any of the simulated PV penetration levels, and no corresponding measures have to be implemented. Overloading of transformers and MV lines start at a PV penetration of around 115 % of installed distribution transformer capacity. This means that with a 25 % demand increase, the PV capacity can only be increased by 5 %, resulting from the fact that high PV feed-in and high load times have little correlation.

To increase the capacity further, active power measurements can be implemented. Using peak shaving batteries as described in section 7.4.9 can increase the penetration level to 150 %, while the less costly option of capping PV at 80 % of inverter size enables a level of 150 % as well. A comparison of results is listed in Table 36.

Demand Side Management (dsm) has only a small impact on the photovoltaic penetration due to low DSM potential in residential consumers. The impact so low that it is not visible in the results comparison in Table 36 as values are rounded to the nearest 5 %.

Table 36: Rooftop photovoltaic penetrations on the urban feeder at Bhopal for scenario 2 with different solutions.

Measure	Max. installed PV	Evaluation / limiting factor	
Base	115 %	Loading	✓
oltc mv	115 %	Loading	✓
wide area control mv	115 %	Loading	✓
shunt V control	115 %	Loading	✓
fixed PF	105 %	Loading	✓
qvchar	110 %	Loading	✓
cap pv	150 %	Suitable, loading	✓
storage ownConsumption	115 %	Loading	✓
stograge peakShaving	115 %	Loading	✓
grid reinforcement	150 %	Suitable	✓

8.4.3 Scenario 3: Rooftop PV with higher PV at the end of feeder with normal load

Shifting the installed PV capacity to the end of the MV feeder presents the case with the highest impact of PV on the voltage. The results of this scenario for each solution and installed PV capacity are shown in Figure 72.

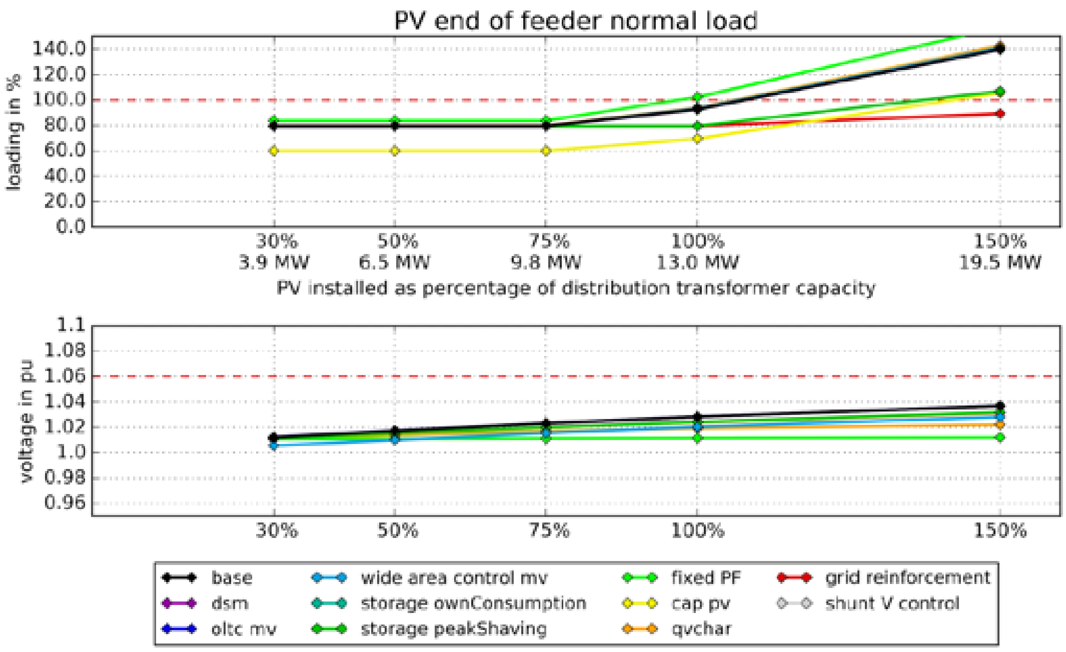


Figure 72: Simulation results for the urban feeder in Bhopal with rooftop photovoltaic plants higher at the end of the feeder with normal load considered

As the impact of PV on voltage in the urban feeder in Bhopal is low due to the grid characteristics, the differences to Scenario 2 are very small. A slight increase in voltage can be observed, but loading remains the limiting factor for PV capacity. Percentage values are given in Table 37 and are in line with scenario 2.

Table 37: Rooftop photovoltaic penetrations on the urban feeder at Bhopal for scenario 3 with different solutions.

Measure	Max. installed PV	Evaluation / limiting factor	
base	110 %	Loading	✓
oltc mv	110 %	Loading	✓
wide area control mv	105 %	Loading	✓
shunt V control	110 %	Loading	✓
fixed PF	90 %	Loading	×
qvchar	105 %	Loading	✓
cap pv	140 %	Suitable, loading	✓
storage ownConsumption	110 %	Loading	✓
storage peakShaving	130 %	Loading	✓
grid reinforcement	150 %	Suitable	✓

8.4.4 Scenario 4: Rooftop PV with higher PV at the end of feeder with Adapted load

The scenario with the PV capacity shifted towards the end of the feeder was also simulated with the expected load increase. The results of this scenario for each solution and installed PV capacity are shown in Figure 73.

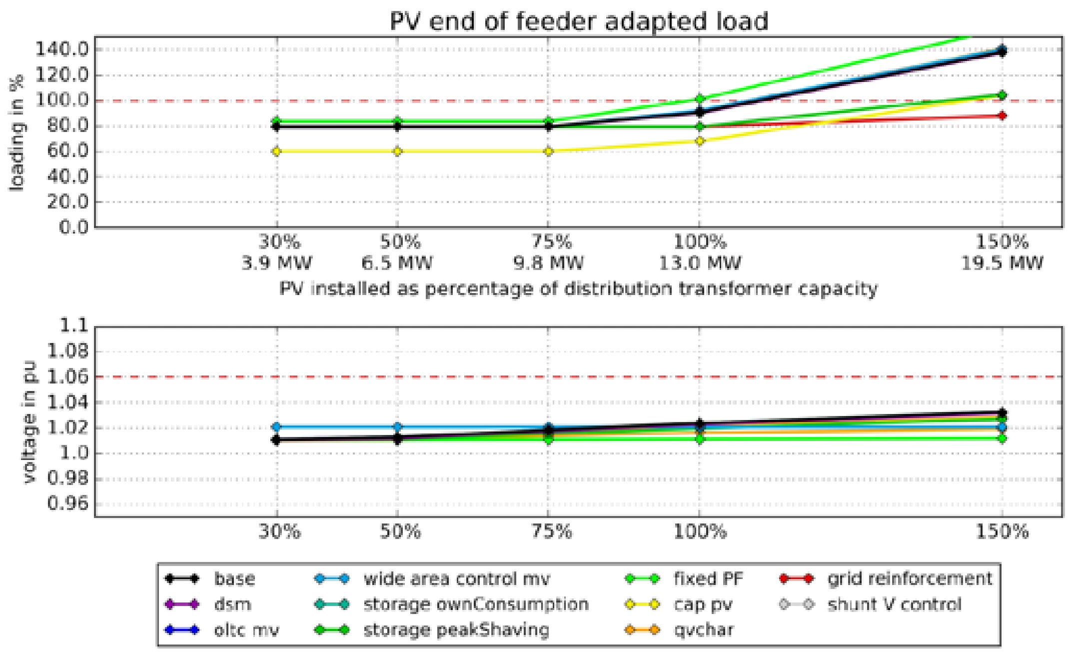


Figure 73: Simulation results for the urban feeder in Bhopal with rooftop photovoltaic plants higher at the end of the feeder with adapted load considered.

As the impact of PV on voltage in the urban feeder in Bhopal is low due to the grid characteristics, the differences to Scenario 3 are very small. A slight increase in voltage can be observed, but loading remains the limiting factor for PV capacity. Percentage values are given in Table 38 and are in line with scenario 3.

Table 38: Rooftop photovoltaic penetrations on the urban feeder at Bhopal for scenario 4 with different solutions.

Measure	Max. installed PV	Evaluation / limiting factor	
base	110 %	Loading issue	✓
oltc mv	110 %	Loading issue	✓
wide area control mv	110 %	Loading issue	✓
shunt V control	110 %	Loading issue	✓
fixed PF	95 %	Loading issue	×
qvchar	110 %	Loading issue	✓
cap pv	145 %	Suitable	✓
dsm	110 %	Loading issue	✓
storage ownConsumption	110 %	Loading issue	✓
storage peakShaving	135 %	Loading issue	✓
grid reinforcement	150 %	Suitable	✓

8.4.5 Scenario 5: Rooftop PV with fully cabled network

Different system operators have different philosophies as to whether using overhead lines or underground cables should be preferred. For example, in Germany DSOs are in the process of exchanging older overhead lines for underground cables. In India there might also be regions using more cables than overhead lines within distribution networks. Since both feeders under consideration mostly use overhead lines, the network was equipped with cables with a similar cross section and ampacity, in order to assess the difference between both configurations. The observed results can be found in Figure 74.

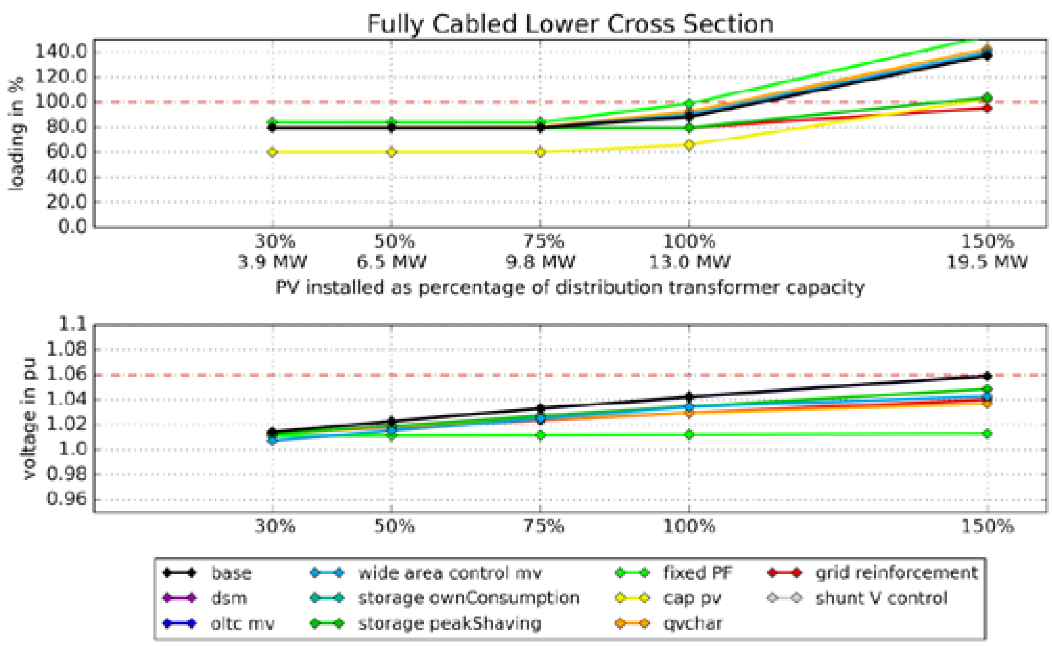


Figure 74: Simulation results for the urban feeder in Bhopal with rooftop photovoltaic plants equally distributed along the feeder with lower cable cross-section considered.

Cables will increase voltage or reduce the voltage drop in the network due to their capacitive behaviour. As the impact of PV on voltage in the urban feeder in Bhopal is low due to the grid characteristics, the differences to Scenario 2 are very small. A slight increase in voltage can be observed, but loading remains the limiting factor for PV capacity. Percentage values are given in Table 39 and are in line with scenario 2.

Table 39: Rooftop photovoltaic penetrations on the urban feeder at Bhopal for scenario 4 with different solutions.

Measure	Max. installed PV	Evaluation / limiting factor	
base	110 %	Loading	✓
oltc mv	110 %	Loading	✓
wide area control mv	110 %	Loading	✓
shunt V control	110 %	Loading	✓
fixed PF	100 %	Loading	✓
qvchar	110 %	Loading	✓
cap pv	145%	Suitable, loading	✓
storage ownConsumption	110 %	Loading	✓
stograge peakShaving	140 %	Loading	✓
grid reinforcement	150 %	Suitable	✓

8.5 Rural feeder Bhopal

8.5.1 Scenario 1: Rooftop PV equally distributed along the feeder with normal load

PV is installed in an equally distributed manner to each distribution transformer on the MV feeder. The outcome of the simulations for equal distribution are depicted in Figure 75.

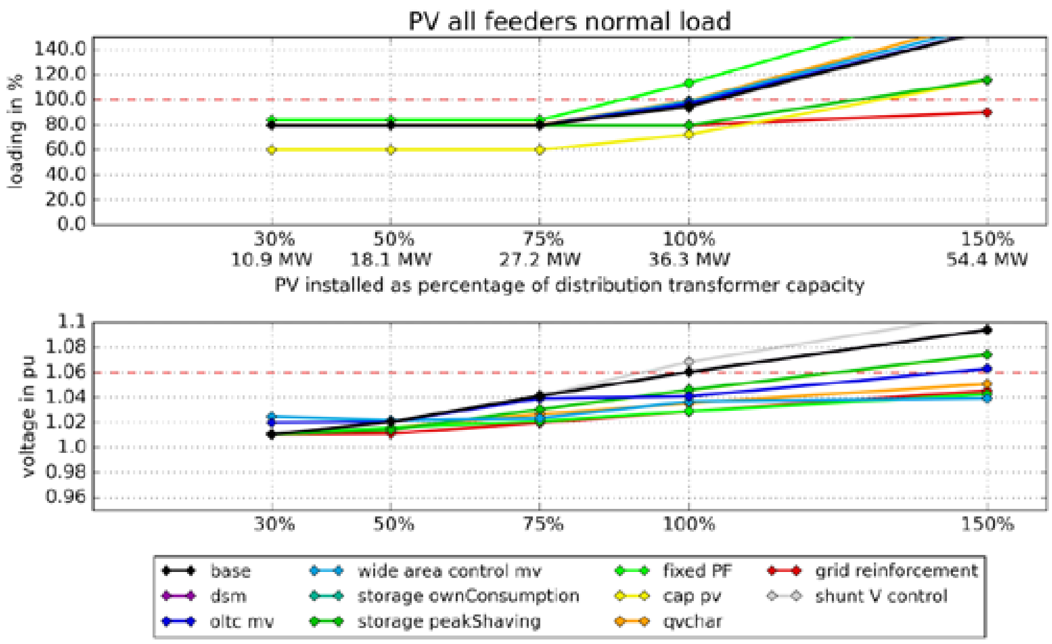


Figure 75: Simulation results for the rural feeder in Bhopal with rooftop photovoltaic plants equally distributed along the feeder with normal load considered

With longer lines in the rural feeder, the impact of PV on the voltage is considerably higher than on the short urban feeder. This makes the case for the use of voltage improving solutions like additional voltage control by MV transformer and shunts, wide area control, reactive power injection based on a Q-V characteristic and fixed non-unity power factor control on inverter.

However, as overloading of some lines and transformers occurs along with the voltage problems at a PV penetration of 105 % of distribution transformer capacity, such measures do improve the voltage, but do not allow for increased PV shares. Active power management solutions such as a PV cap or peak shaving batteries, alleviate both voltage and loading issues and allow for an increase of PV capacity to 130 % (see Table 40.)

Table 40: Rooftop photovoltaic penetrations on the rural feeder at Bhopal for scenario 1 with different solutions.

Measure	Max. installed PV	Evaluation / limiting factor	
base	100 %	Overloading and voltage	✓
oltc mv	105 %	Loading	✓
wide area control mv	100 %	Loading	✓
shunt V control	90 %	Not suitable, loading	×
fixed PF	90 %	Not suitable, loading	×
qvchar	100 %	Not suitable, loading	✓
cap pv	125 %	Suitable, loading	✓
storage ownConsumption	100 %	No impact, loading and voltage	✓
storage peakShaving	125 %	Suitable, loading	✓
grid reinforcement	150 %	Suitable	✓

8.5.2 Scenario 2: Rooftop PV equally distributed along the feeder with adapted load

Future load development (demand increase of 5 % per year) is expected to be beneficial to PV integration, as more power generated by PV can be consumed locally. Scenario 2 evaluates the impact of such a load increase. The higher load is based on the addition of A/C units at every LV load as described in section 7.3.3. The results of this scenario are shown in Figure 76.

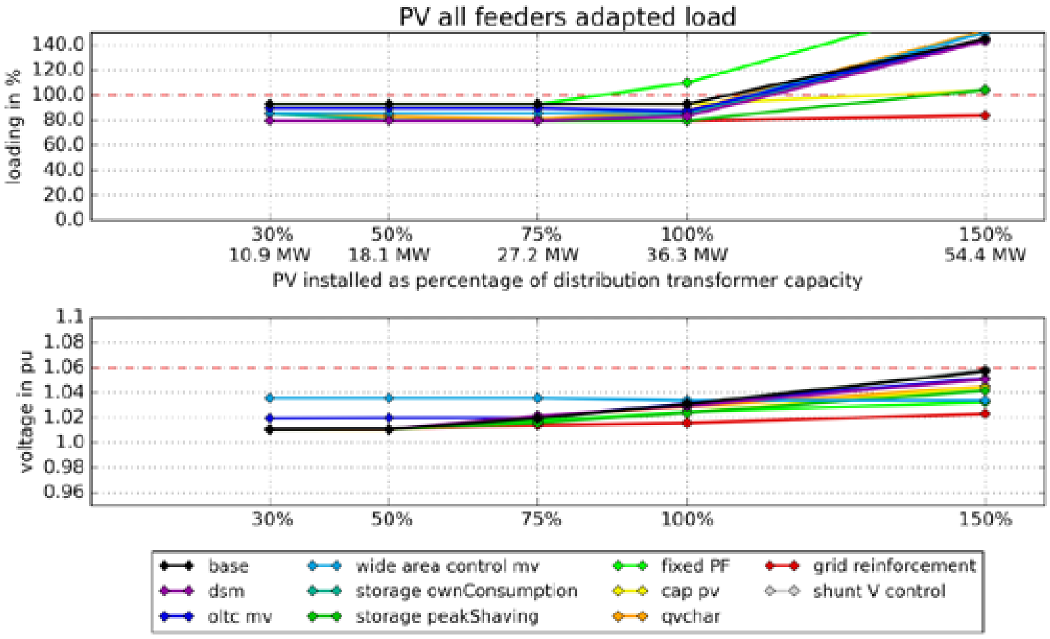


Figure 76: Simulation results for the rural feeder in Bhopal with rooftop photovoltaic plants equally distributed along the feeder with adapted load considered

The impact of the increased daily load is rather low (see Table 41), and the results are largely in line with Scenario 1.

Table 41: Rooftop photovoltaic penetrations on the rural feeder at Bhopal for scenario 2 with different solutions.

Measure	Max. installed PV	Evaluation / limiting factor	
base	105 %	Overloading and voltage	✓
oltc mv	110 %	Loading	✓
wide area control mv	110 %	Loading	✓

shunt V control	105 %	Loading	✓
fixed PF	85 %	Not suitable, loading	×
qvchar	110 %	Small impact	✓
cap pv	130 %	Suitable, loading	✓
storage ownConsumption	115 %	No impact	✓
storage peakShaving	140 %	Suitable, loading	✓
grid reinforcement	150 %	Suitable	✓

8.5.3 Scenario 3: PV power plant and rooftop PV

A. PV power plant specifications

As mentioned, free field PV units of considerable size may be connected to rural 11 kV grids, reducing the hosting capacity of the feeder. For Bhopal, a hypothetical 2.5 MWp power plant is considered. Three different subscenarios are evaluated, in which the power plant is connected to the 11 kV busbar, to a node in the middle of the 11 kV feeder, and to a node at the end of the 11 kV feeder.

As stated in section 8.3.1, it is quite common to require reactive power for voltage control from PV power plants connected to the 11 kV level. However, for the rural feeder in Bhopal, reactive power provision from the PV power plant would actually decrease the amount of rooftop PV that can be installed additionally. The reactive currents lead to increase the grid loading, which in this case is more critical than voltage issues (see Figure 77 through Figure 79.) For all subscenarios, the PV power plant is thus modelled operating at unity power factor.

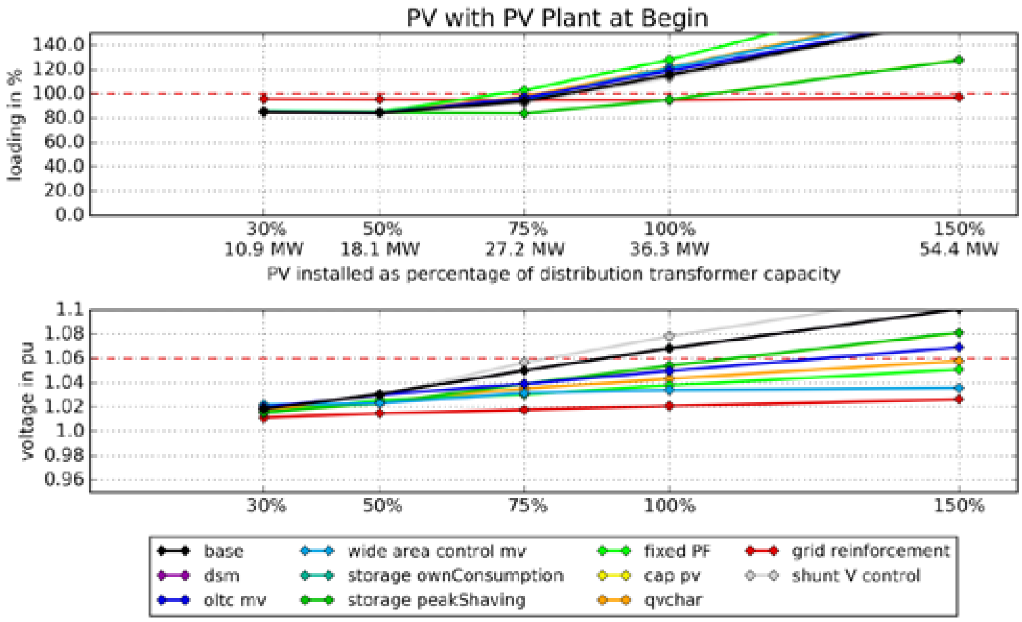


Figure 77: Impact of reactive power injection through the utility scale solar plant at the beginning of the feeder

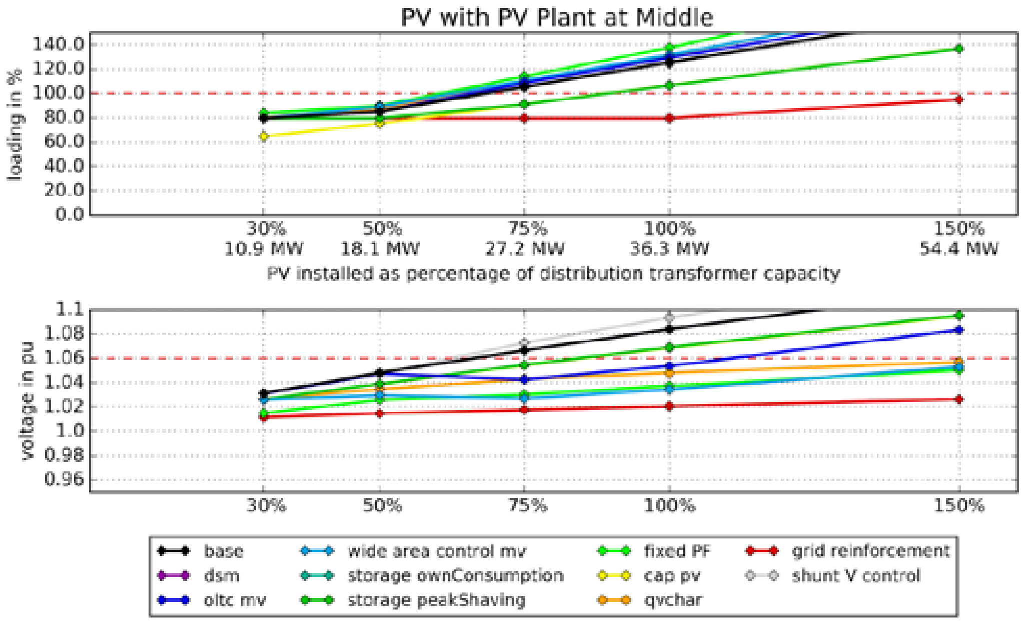


Figure 78: Impact of reactive power injection through the utility scale solar plant at the middle of the feeder

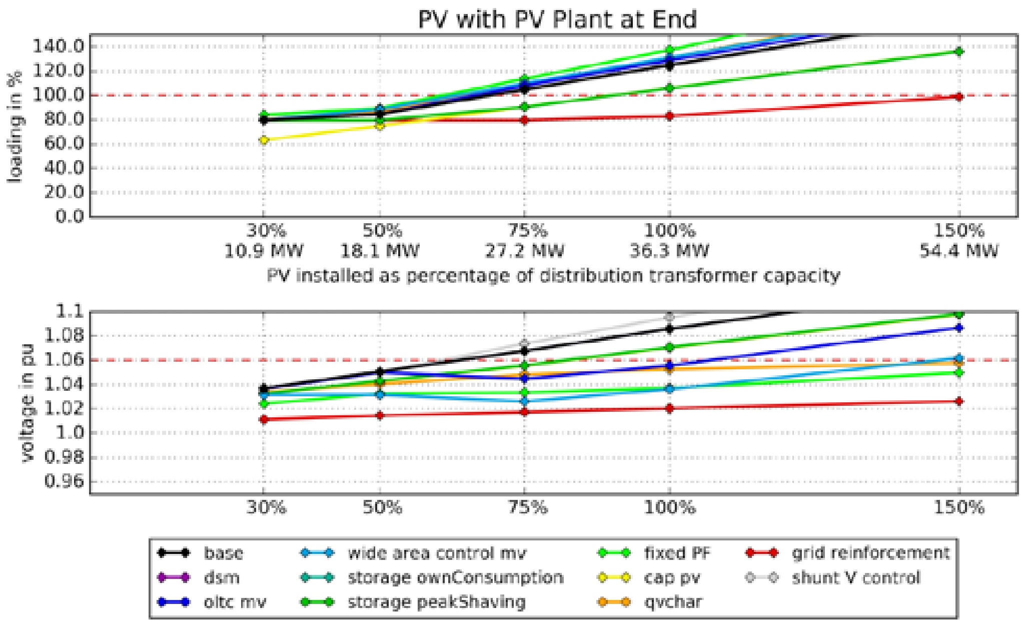


Figure 79: Impact of reactive power injection through the utility scale solar power plant at the end of the feeder

B. Power plant connected at 11 kV busbar

In the first sub-scenario, the power plant is connected directly to the 11 kV busbar of the feeder that is modelled in detail. Rooftop PV is distributed equally, and load is not adapted (2016 data.) Results are shown in Figure 80.

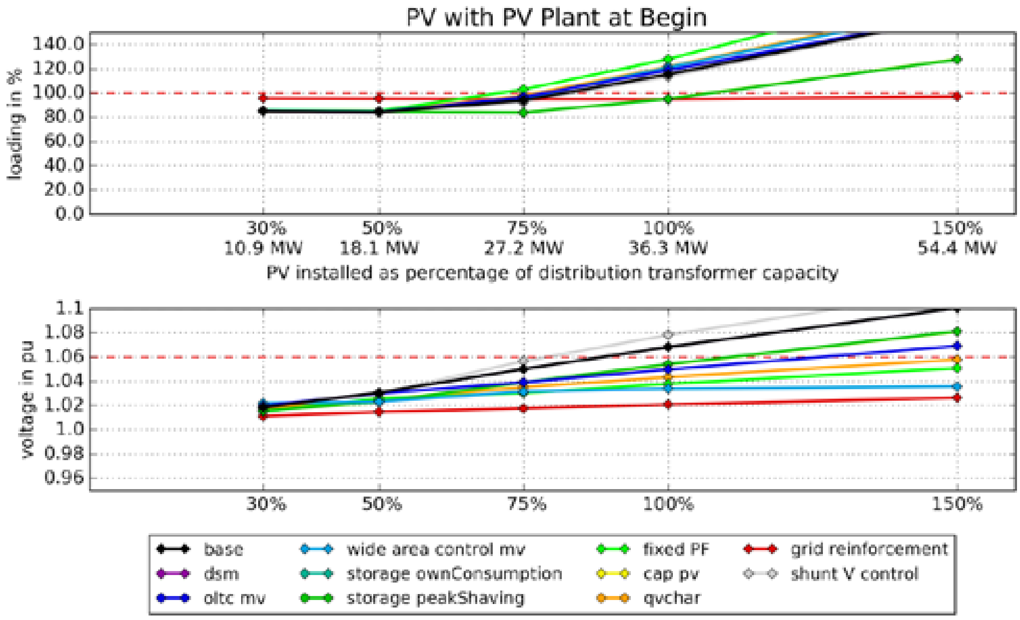


Figure 80: Simulation results for the rural feeder in Bhopal with rooftop photovoltaic plants equally distributed along the feeder with a utility scale solar plant of 2.5 MWp at the beginning of the feeder considered.

The hosting capacity for rooftop PV of the 11 kV feeder is reduced from 105 % in the base case to 80 %, with the bottleneck being the 33/11 kV transformer which is overloaded. Active power management measures (PV cap, peak shaving battery) can significantly increase the hosting capacity, while all other measures are ineffective (see Table 42.)

Table 42: Rooftop photovoltaic penetrations on the rural feeder at Bhopal for scenario 3A with different solutions.

Measure	Max. installed PV	Evaluation / limiting factor	
base	80 %	Loading	×
oltc mv	80 %	No impact	×
wide area control mv	80 %	No impact	×
shunt V control	80 %	No impact	×
fixed PF	70 %	Loading increases	×
qvchar	75 %	Loading increases	×
cap pv	105 %	Suitable	✓
storage ownConsumption	80 %	No impact	×
stograge peakShaving	105 %	Suitable	✓
grid reinforcement	150 %	Suitable	✓

C. Power plant connected to the middle of 11 kV feeder

The PV power plant is connected at a node approximately in the middle of the 11 kV feeder, to the results depicted in Figure 81.

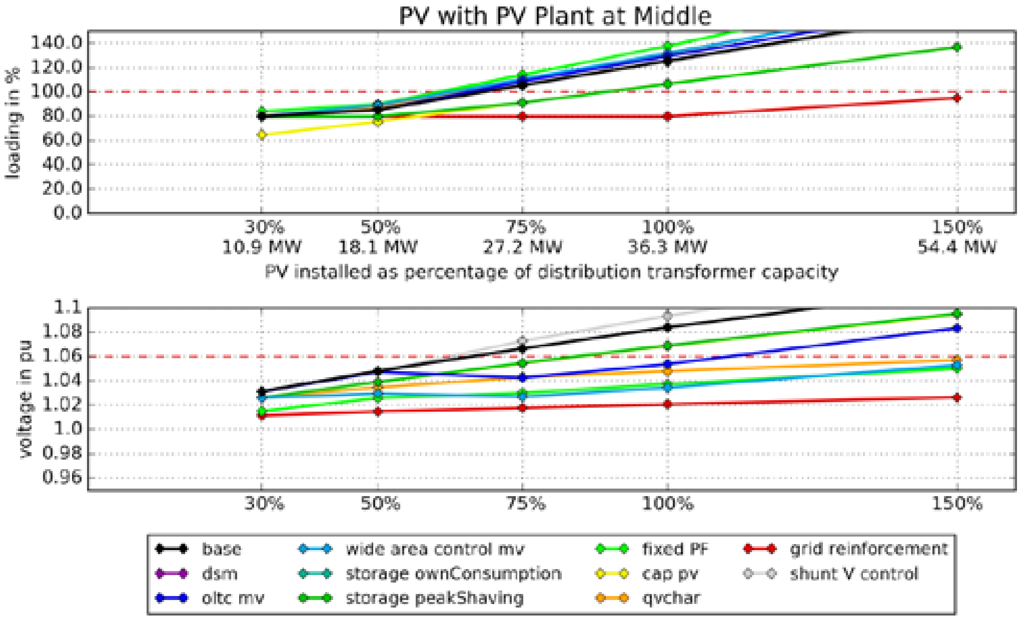


Figure 81: Simulation results for the rural feeder in Bhopal with rooftop photovoltaic plants equally distributed along the feeder with a utility scale solar plant of 2.5 MWp at the middle of the feeder considered

The hosting capacity for rooftop PV is reduced by another 5 % to 70 % of installed transformer capacity. Although voltage issues become more prominent, overloaded 11 kV overhead lines are still the main bottleneck, making active power management the only solution which can significantly increase the hosting capacity (see Table 43.)

Table 43: Rooftop photovoltaic penetrations on the rural feeder at Bhopal for scenario 3B with different solutions.

Measure	Max. installed PV	Evaluation / limiting factor	
base	65 %	Loading issue	×
oltc mv	65 %	Increase in transformer voltage drops	×
wide area control mv	65 %	Increase in transformer voltage drops	×
shunt V control	60 %	No Impact	×
fixed PF	60 %	Loading increases	×
qvchar	65 %	Loading increases	×
cap pv	85 %	Suitable	✓
storage ownConsumption	65 %	No impact	×
stograge peakShaving	85 %	Suitable	×
grid reinforcement	150 %	Suitable	✓

D. Power plant connected at the end of the 11 kV feeder

As a worst case scenario, the PV power plant is connected to a node at the end of the 11 kV feeder, to the results given in Figure 82.

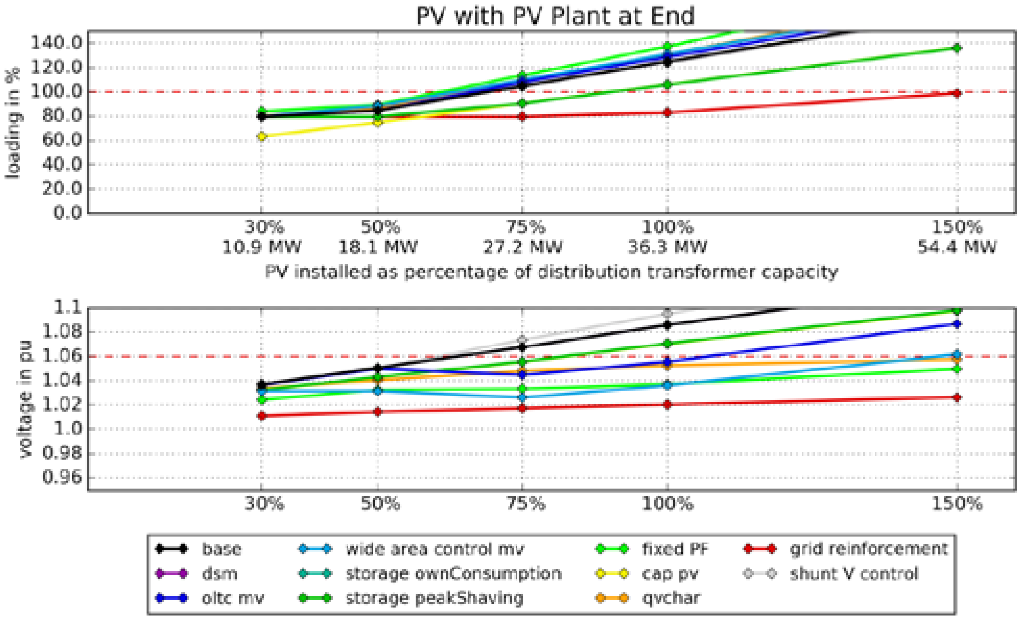


Figure 82: Simulation results for the rural feeder in Bhopal with rooftop photovoltaic plants equally distributed along the feeder with a utility scale solar plant of 2.5 MWp at the end of the feeder considered

With the power plant at the end of the feeder, the hosting capacity for rooftop PV is reduced to 50 %. In this case, the voltage problems prevail, while overloading does occur only slightly earlier than in the previous cases. As can be seen in Table 44, voltage control measures that do not increase grid loading through reactive power – voltage control by transformers or wide area control – can increase the hosting capacity back to 65 %. Voltage rises can also be mitigated by active power management, but it is not more effective than the voltage control strategies. Controlling the voltage by reactive power is insufficient, as it alleviates the voltage problem and replaces it with an overloading problem.

Table 44: Rooftop photovoltaic penetrations on the rural feeder at Bhopal for scenario 3C with different solutions.

Measure	Max. installed PV	Evaluation / limiting factor	
base	65 %	Voltage	×
oltc mv	65 %	Suitable, loading	×
wide area control mv	65 %	Suitable, loading	×
shunt V control	60 %	No Impact	×
fixed PF	60 %	Small impact, loading	×
qvchar	65 %	Suitable, loading	×
cap pv	85 %	Suitable	×
storage ownConsumption	65 %	No impact	×
stograge peakShaving	80 %	Suitable, loading	×
grid reinforcement	150 %	Suitable	✓

8.5.4 Scenario 4: Rooftop PV with fully cabled network

Different system operators have different philosophies as to whether using overhead lines or underground cables should be preferred. For example, in Germany DSOs are in the process of exchanging older overhead lines for underground cables. In India there might also be regions using more cables than overhead lines within distribution networks. Since both feeders under consideration mostly use overhead lines, the network was equipped with cables with a similar cross section and ampacity, in order to assess the difference between both configurations. The observed results can be found in Figure 83.

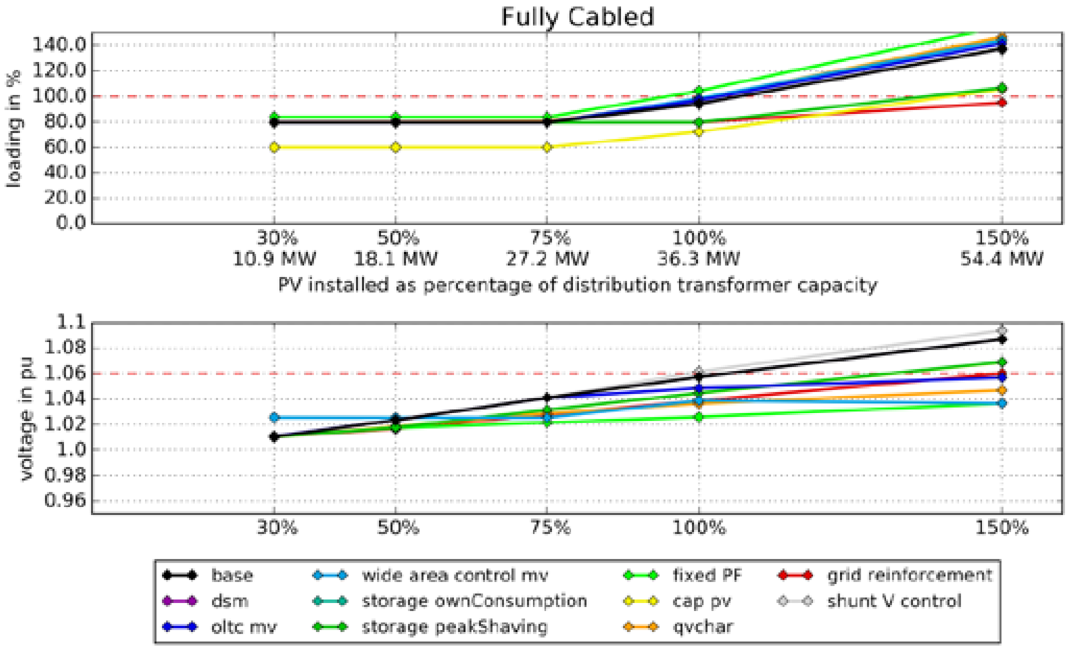


Figure 83: Simulation results for the rural feeder in Bhopal with rooftop photovoltaic plants equally distributed along the feeder with overhead lines replaced with cables considered

Cables will increase voltage or reduce the voltage drop in the network due to their capacitive behaviour. As the impact of PV on voltage in the urban feeder in Bhopal is low due to the grid characteristics, the differences to Scenario 1 are very small. A slight increase in voltage can be observed, but loading remains the limiting factor for PV capacity. Percentage values are given in Table 45 and are in line with scenario 1.

Table 45: Rooftop photovoltaic penetrations on the rural feeder at Bhopal for scenario 4 with different solutions.

Measure	Max. installed PV	Evaluation / limiting factor	
base	105 %	Loading issue	✓
oltc mv	105 %	Loading issue	✓
wide area control mv	100 %	Loading issue	✓
shunt V control	100 %	No impact	✓
fixed PF	95 %	Loading increases	×
qvchar	100 %	Loading increases	✓
cap pv	130 %	Suitable	✓
storage ownConsumption	105 %	No impact	✓
stograge peakShaving	130 %	Suitable	✓
grid reinforcement	150 %	Suitable	✓

9. Consolidated simulation results

9.1 Representation of results

In this summary report, the figures are only given for the base case scenario for each feeder, while the results of the other scenarios are given in a table, with the coding used explained in Table 46. A more detailed presentation of results can be found in section 8. Some of the implemented technology options did not have any effect on PV hosting capacity and can thus be considered to be unsuitable. As all options were simulated for all feeders, these are also included in the results for clarity.

Table 46: Symbols used in results tables.

Impact	Symbol
Measure increases hosting capacity from base case, above 100 %	↑↑
Measure increases hosting capacity from bas case but stays below 100 %	↑
Measure has no effect	O
Measure reduces hosting capacity from base case	↓

9.2 Urban feeder Delhi

All simulation results in Delhi's urban network with a fully modelled generic LV network indicate loading problems to either occur first or occur at the same time as PV induced overvoltage becomes an issue. The loading issues mostly occur in cables reaching their maximum current carrying capacity. This results in only two solutions - apart from the common approach of grid reinforcement - being viable to increase the installed PV capacity beyond the individual limits observed in each scenario. From Table 47 it becomes evident that only capping PV infeed or utilizing storage with peak shaving can increase the maximum of installed PV capacity without reinforcing grid assets.

Table 47: Overview of the maximum installed PV capacity as a percentage of the distribution transformer capacity for all scenarios and applied solutions of the urban network of Delhi.

Measure	Scenario 1: PV equally distributed with normal load		Scenario 2: PV equally distributed with adapted load		Scenario 3: PV at the end of the feeder with normal load		Scenario 4: PV at the end of the feeder with adapted load		Scenario 5: PV at the end of the feeder with lower cable cross-section	
base	90%		100%		75%		80%		55%	
oltc	90%	o	100%	o	75%	o	80%	o	55%	o
wide area control	90%	o	100%	o	75%	o	80%	o	50%	↓
fixed PF	80%	↓	85%	↓	65%	↓	70%	↓	50%	↓
qvchar	90%	o	95%	↓	70%	↓	75%	↓	55%	o
cap pv	150%	↑↑	150%	↑↑	140%	↑↑	150%	↑↑	105%	↑↑
storage own Consumption	90%	o	100%	o	75%	o	80%	o	55%	o
storage peakShaving	120%	↑↑	130%	↑↑	100%	↑↑	115%	↑↑	80%	↑↑
dsm	90%	o	100%	o	75%	o	80%	o	55%	o
grid reinforcement	150%	↑↑	150%	↑↑	150%	↑↑	150%	↑↑	150%	↑↑

However, results also show a generally high potential to incorporate residential PV systems in this rather well developed network. With an estimated maximum rooftop potential of approximately 100% of distribution transformer capacity and a capability to include between 75% and 100% based on the selected scenario, the network should be able to handle the maximum amount of PV that can reasonably be expected to be installed without any measures taken. Capping PV or using batteries may become necessary if unfavorable placement of PV systems takes place or the projected load increase does not meet expectations.

9.3 Rural feeder Delhi

The rural network tends to have voltage issues in most scenarios, except when considering load increases. In these cases, distribution transformers that are already highly loaded in the base case are overloaded first. A summary of results for each scenario and solution is shown in Table 48. All solutions coping with loading issues (capping PV, storage with peak shaving) can be helpful in Scenario 3, while the solutions dealing with voltage issues are not helpful here. Scenarios 2, 4 and 5, with the penetration being limited by voltage issues, offer a much higher variety of suitable solutions. Especially wide area control of the 66 kV/11 kV transformers allows for a significant increase of installed PV capacity, because of the expanded use of the full voltage bandwidth. A combination of wide area control and a solution to reduce loading of network elements (either capping PV or storage with peak shaving) can probably be an effective way to include high amounts of PV, without the necessity of grid reinforcement. As an intermediate solution, using reactive power (either fixed power factor or Q-V-characteristic) could be an easy to implement and effective solution to increase the networks capability to handle residential PV installations.

Table 48: Overview of the maximum installed PV capacity as a percentage of the distribution transformer capacity for all scenarios and applied solutions of the rural network of Delhi.

Measure	Scenario 2: PV equally distributed with normal load		Scenario 3: PV equally distributed with adapted load		Scenario 4: PV equally distributed with 3.5 MW PV power plant		Scenario 5: PV equally distributed with network fully cabled	
base	90%		110%		50%		70%	
wide area control	105%	↑↑	110%	o	75%	↑	100%	↑↑
fixed PF	95%	↑	105%	↓	65%	↑	95%	↑
qvchar	105%	↑↑	110%	o	70%	↑	90%	↑
cap pv	150%	↑↑	150%	↑↑	70%	↑	145%	↑↑
storage own consumption	90%	o	110%	o	50%	o	70%	o
storage peak shaving	125%	↑↑	150%	↑↑	70%	↑	100%	↑↑
dsm	90%	o	110%	o	50%	o	70%	o
grid reinforcement	150%	↑↑	150%	↑↑	150%	↑↑	150%	↑↑

9.4 Urban feeder Bhopal

The networks in the urban feeder in Bhopal were simulated with models of the 11 kV and 33 kV level with the low voltage networks represented by load / generation equivalents. With a short feeder length and the feeder being directly attached to the voltage controlling substation, the Bhopal urban feeder experiences no overvoltage problems even at very high PV penetration levels. However, distribution transformers and some lines can eventually be overloaded if PV capacity exceeds transformer capacity. This may be addressed by simply reinforcing transformers and lines. To avoid costly reinforcements, alternative measures can be taken to control the active power feed-in of PV.

Curtailment of PV or a peak cap at a certain percentage of capacity may, if set up reasonably, prevent some of the overloading issues while losing only a small percentage of PV energy. This can in the long run still be cheaper than reinforcing the grid.

Deployment of PV storage batteries can also alleviate some of the issues, if an adequate charging strategy is chosen. If batteries are optimized for own consumption only, they will usually not reduce the mid-day PV peak and thus have no positive impact on grid loading. Setting PV batteries up to shave the PV peak on the other hand will reduce grid loading and overvoltage problems.

Table 49: Overview of the maximum installed PV capacity as a percentage of the distribution transformer capacity for all scenarios and applied solutions of the urban network of Bhopal.

Measure	Scenario 1: PV equally distributed normal load		Scenario 2: PV equally distributed adapted load		Scenario 3: PV at the end of the feeder normal load		Scenario 4: PV at the end of the feeder adapted load		Scenario 5: PV equally distr., cabled network	
base	110 %		115 %		110 %		110 %		110 %	
oltc	110%	o	115%	o	110%	o	110%	o	110%	o
shunt V control	110%	o	115%	o	110%	o	110%	o	110%	o
wide area control	110%	o	115%	o	105%	↓	110%	o	110%	o
fixed PF	100%	↓	105%	↓	90%	↓	95%	↓	100%	↓
qvchar	110%	o	110%	↓	105%	↓	110%	o	110%	o
cap pv	145%	↑↑	150%	↑↑	140%	↑↑	145%	↑↑	145%	↑↑
storage ownConsumption	110%	o	115%	o	110%	o	110%	o	110%	o
storage peakSh.	140%	↑↑	150%	↑↑	130%	↑↑	135%	↑↑	140%	↑↑
grid reinf.	150%	↑↑	150%	↑↑	150%	↑↑	150%	↑↑	150%	↑↑

9.5 Rural feeder Bhopal

The networks in the rural feeder in Bhopal were simulated with models of the 11 kV and 33 kV level with the low voltage networks represented by load / generation equivalents. The lines are longer but have a lower average cross section in comparison to the urban feeder, and there is a higher number of smaller transformers instead of a few large ones. Both overvoltage as well as overloading problems occur with rising PV penetration, depending on the scenario.

All issues can be resolved with simply reinforcing the network. If this is to be avoided, there are several different alternative solutions that can mitigate the problems. As in the urban feeder, active power control measures such as a cap of the PV peak or peak shaving batteries are suitable to alleviate both overvoltage and overloading problems. Only in the scenario with a large PV plant at the end of the feeder does it make sense to implement measures that directly control the voltage by reactive power feed-in of PV inverters.

Table 50: Overview of the maximum installed PV capacity as a percentage of the distribution transformer capacity for all scenarios and applied solutions of the rural network of Bhopal.

Measure	Scenario 1: PV equally distributed normal load		Scenario 2: PV equally distributed adapted load		Scenario 3C: PV equ. dist. with PV plant at end of feeder[13]		Scenario 4: PV equally distributed, fully cabled network	
base	100 %		105 %		65 %		105 %	
oltc	105%	↑↑	110%	↑↑	65%	o	105%	o
shunt V control	90%	↓	105%	o	60%	↓	100%	↓
wide area control	100%	o	110%	↑↑	65%	o	100%	↓
fixed PF	90%	↓	85%	↓	60%	↓	95%	↓
qvchar	100%	o	110%	↑↑	65%	o	100%	↑
cap pv	125%	↑↑	130%	↑↑	85%	↑	130%	↑↑
storage ownConsumption	100%	o	115%	↑↑	65%	o	105%	o
storage peakShaving	125%	↑↑	140%	↑↑	80%	↑	130%	↑↑
grid reinforcement	150%	↑↑	150%	↑↑	150%	↑↑	150%	↑↑

10. Conclusions and recommendations

10.1 Conclusions

10.1.1 General conclusions

Simulation results from the four feeders show that PV penetration levels of 75 % of distribution transformer capacity and higher can be implemented without having to undertake any measures to contain voltage problems or overloading. This is significantly higher than the limits of usually 30 – 60 % prescribed by regulators in most Indian states today. Hosting capacity may be lower in other, weaker grids, or if additional free field PV power plants are connected.

In most cases, penetration levels of slightly above 100 % can be realized. As the minimum daily load is low on all of the analyzed grids, lines and transformers will get overloaded at penetration levels typically above 110 %, as little PV power is consumed locally during the simulated worst case days. To push installed capacity higher, active power control measures have to be implemented. These may include a fixed cap on 70 – 80 % of rated capacity, PV curtailment based on grid loading, or the use of peak shaving PV batteries.

10.1.2 Most relevant technical issues

As expected, the problems observed in the analyzed distribution feeders at high penetration levels of rooftop PV are somewhat different from the experiences in Germany and California due to the grid characteristics. Generally, the following can be stated:

- The urban grids are short and strong, enabling high penetration levels of rooftop PV. At shares above 100 % of distribution transformer capacity, some assets, mostly transformers, can be overloaded. The impact of PV on the voltage is low.
- The rural grids consist of weaker lines and are more highly loaded. With an unfavorable distribution of rooftop PV or the addition of free field PV units connected to the 11 kV level, overvoltage problems can occur at penetration levels of above 50 % already. With normal distribution, overloading becomes relevant at levels of 90 – 100 %.

All these results were obtained under the assumption that voltage control at the 66/11 or 33/11 kV (Delhi) or 132/33 kV (Bhopal) substations is adequate, and the voltage at the distribution grid busbar is no higher than 1.01 p.u. This is currently not always the case in Indian distribution grids. BSES is currently upgrading all transformers stepping down to 11 kV to automatic voltage control, making the assumption valid for the future. In Bhopal, voltage control at the 132/33 kV transformers is done manually and by the transmission company, leading to large voltage swings at the 33 kV busbar especially in the rural grid. Under current conditions, this could severely limit PV penetration. For the urban grid, this issue is less pressing as PV has very little impact on voltage due to the short line lengths.

10.1.3 Performance of technical solutions

As the model grids were able to absorb quite high penetration levels of PV, in most cases, there is no need for advanced technical solutions to avoid loading or voltage problems. However, at very high penetration levels, it could be observed that the active power management strategies of either capping PV feed-in at 70 or 75 % of inverter capacity or the use of peak shaving batteries performed best in resolving both voltage and loading issues. This is true for both rural and urban grids, as the mechanisms are the same. Both overvoltage and overloading are caused by active power feed-in, and if that is limited or shifted, problems are alleviated. However, both solutions have costs attached to them, both of which may be either be borne by the DISCOM or by the client – either way, it will somewhat increase the cost of power from rooftop PV.

A. **Peak shaving batteries**

Battery storage needs to be procured and installed by the customer at their facility. Prices for lithium ion and lead acid batteries have reduced by more than 40 % since 2013, keeping the price for a kWh of storage capacity in the same range as the price for a kWp of rooftop solar PV. [78][79] This means that the installation of 1 kWh of battery capacity for each kWp of installed solar capacity would roughly double the price of the installation. Currently, there is no grid parity for such a system, meaning that it would not work without an additional incentive scheme. However, as prices for PV and storage drop, this may be a feasible future scenario. Moreover, many Indian homes are already equipped with batteries that could be used for PV storage. The current backup battery boom in India also has the effect of reducing battery costs by economics of scale. In any way, an incentive has to be set for batteries to operate in peak shaving mode, instead of optimizing purely for own consumption, which may conflict with their use for backup during power outages.

B. **Capping of inverters**

The cheaper solution, having almost the same grid impact during extreme situations[25], is the capping of PV inverters. As shown in section 7.4.8, it is possible to cap PV feed-in at 70 – 75 % of the maximum value without losing more than 3 % of energy annually, while significantly increasing the hosting capacity of the grid. With an average increase of 3- 4 % in generation cost for retrofitted systems, and less than that for new systems due to cost savings in a smaller inverter[26], this is an effective, but much cheaper solution than the use of PV storage batteries. This solution is also currently used for small rooftop PV units in Germany.

The impact of demand side management in grids with primarily residential customers is low due to the low potential for DSM in private households. However, the strategy should be given more attention when analysing grids with a high share of industrial or commercial customers.

C. **Voltage control measures**

For cases in which only voltage problems (overvoltage) can be expected – long lines, low load and unfavourable PV distribution – some voltage control solutions are applicable and feasible. Voltage control by the power transformers can be enhanced by a wide area control system, measuring the voltage on each feeder and setting the transformer taps accordingly. This solution requires some additional investments in communication, but will have multiple positive effects on grid operation, extending beyond PV integration:

- Voltage rises induced by PV are detected and alleviated.
- Voltage drop issues caused by high loading during evening and night can be detected and alleviated as well.
- The general quality of supply will be improved by improving the voltage profile.
- As continuous measurements have to be made at multiple points in each grid, the operator is supplied with a constant stream of operational data, can manage quality of supply more efficiently, and detect possible operational problems early on.

Wide area control is used in distribution grids in different countries already and is a generally accepted tool to improve voltage quality. It requires investments in communication infrastructure and will only be applicable if automatic on-load tap changing transformers

25 PV batteries will always reduce the active power output of the system and thus have additional value to distribution grid and power system operation. The PV cap will only reduce it in situations of very high feed-in and has no impact during most of the year.

26 Inverters may be sized to a smaller rating if output is capped at 70 % anyways, but the software side has to be set up to reduce power at the DC side of the inverter already, to prevent overloading the inverter.

are available. The distribution grid study for the German state of Rhineland Palatinate [38] estimated the cost at 50,000 € per 110/20 kV transformer[27], but the actual cost depends on the local conditions and used equipment and must be assessed for each project individually.

On-load tap changing transformers with automatic voltage control at least at the connection between transmission or subtransmission level (220 or 132 kV) and the distribution grid should be considered in all cases – otherwise, voltage problems may occur already without any PV installed, as can be observed on the rural feeder in Bhopal (see sections 6.2 and 7.2.3.) Besides facilitating PV integration, this will improve voltage quality significantly and alleviate current load-induced undervoltage issues.

D. Voltage control from PV inverters

Voltage control from the PV units themselves, on the other hand, cuts both ways. Reactive power from PV inverters can effectively control voltage, and can be obtained via a simple grid code requirement that most inverters on the market can fulfill already, but at the cost of increasing grid loading through reactive currents. In already highly loaded grids, caused either by high load or high PV feed-in, it may actually have a negative impact. In any way, requiring the capability for reactive power and voltage control from rooftop PV inverters is sensible, as it will give the operator an additional means of voltage control, that could also be used to alleviate pre-existing voltage issues (for example in cases where no automatic voltage control from power transformers is available.) The actual regime for activation of reactive power provision should be decided based on the characteristics of each individual grid. In the simulations for this study, the following could be observed:

- In already highly loaded grids, using a Q-V characteristic for inverters connected to the 0.4 kV level provides better results, as reactive power provision is only activated when it is really needed, reducing the probability of overloading caused by reactive currents.
- In grids with no loading issues, a fixed power factor of 0.95 lagging performed better than a Q-V characteristic in alleviating overvoltage problems. With Q-V characteristics implemented, the units closer to the 11 kV substation that do not "see" the full voltage rise at the end of the feeder will not contribute to voltage control, while with a fixed power factor, their reactive power behavior contributes to containing the voltage increase.
- If a large amount of PV power is injected into one node in the grid, either by inhomogeneous distribution of rooftop PV, or by a PV power plant, a Q-V characteristic performs better, if the grid is not prone to overloading.

Theoretically, PV inverters operating at leading power factors could also be used to alleviate low voltage problems during high load – this is, however, not a common use case, and was not investigated in detail in this study.

E. Reversed power flows and protection

The only direct impact of a reversal of power flow with a moderate flow that can be observed concerns the protection settings. Especially with the overcurrent protection typically used at medium and low voltage levels, the short circuit current contribution of the units feeding in between the protection relay and the location of the fault have to be considered. For PV, the short circuit current is no larger than the rated current of the inverter, leading to a moderate contribution that should nevertheless be considered in the calculation of protection settings.

The easy way around this problem would be to require the units on a feeder protected by an overcurrent relay to immediately disconnect at detection of a voltage drop (which indicates

27 Power transformers used in Germany, role comparable to 66/11 or 132/33 kV transformers in India.

a short circuit nearby), or stay connected but not provide any short circuit current. If this requirement collides with low voltage ride through that may be required for other reasons, the short circuit current of all units on a feeder should be limited to

$$\sum I_{sc,unit} \leq I_{sc,max} - I_{sc,trigger}$$

10.2 Recommendations

10.2.1 Studies

The results from the four analyzed distribution grids show a great variety in results, but all of them, even the rural Bhopal feeder which is much weaker and much more inadequately controlled than the others, display a high hosting capacity for rooftop PV. However, this can by no means be generalized. Each grid area needs to be analyzed on its own and checked for possible problems with rising PV shares. This does not necessarily require extensive simulation studies like those conducted in this study – some simple estimation approaches are given in section 1.1.1..

Simulation studies at least for some example feeders are recommended to be conducted by each DISCOM anyway, to develop a better understanding of the dynamics of distributed generation and their impact on grid operation.

10.2.2 General technical requirements

Independent of expected or achievable PV penetration level, a number of technical requirements should always be fulfilled by PV units. Like all power electronics, PV inverters are potential sources of harmonics and DC currents that are generally undesirable to the power system. Grid codes applicable to PV should thus set limits on such emissions. Modern inverters emit very little distorting currents and are often compliant with international standards that limit emissions, such as IEEE 519 or IEC 61000-3-2. Typical voltage quality requirements include the following:

- Limits on voltage rise induced by connection of the unit (typically 2 – 3 %);
- Limit on voltage steps induced by switching operations (typically 2 – 3 %);
- Limits on flicker (example: $P_{lt} \leq 0.5$ with the definition according to standard IEC 61000-3-3 and -3-11);
- Limits of harmonic current infeed (defined in IEC 61000-3-2, limits from 3 % for the third order harmonic, descending with ascending harmonic order);
- Limits on asymmetrical loading (example: 4.6 kVA difference in Germany.)

None of the countries in the study cases from section 2.3 have experienced any wide spread voltage quality problems due to inverter emissions. Requirements to comply with international standards have been in place in all of them since the beginning of PV development in the 1990s.

PV units also have to be equipped with adequate generator protection to avoid damage to the unit in case of a nearby fault as well as to prevent unintentional islanding.

Moreover, the compatibility of the fault behavior of PV units with the local protection settings should be checked, see section 1.1.1A.

10.2.3 Technology options to enable high PV penetration levels

Specific technical solutions need to be assessed for each grid area separately, but some recommendations can be drawn from the model cases analyzed in this study. Concerning voltage control, these are the following:

- Automatic voltage control by tap changing transformers at 132/33, 220/66 or 220/33 kV should be implemented in all distribution grids regardless of PV development, this is international good practice to ensure good voltage quality.
- Automatic voltage control by tap changing transformers at 66/11 or 33/11 kV level is very beneficial to voltage quality regardless of PV penetration, but not strictly required if the voltage control above is adequate.
- Voltage problems in the distribution grid, caused by both load (undervoltage) and PV (overvoltage) can be efficiently eliminated by the use of a wide area voltage control, measuring the voltage at multiple points in the grid and operating the voltage control by transformers accordingly.
- The capability for voltage control by rooftop PV inverters by provision of reactive power can easily be required by the grid code, and such a requirement is highly recommended and international good practice. The actual set points of the voltage control or fixed power factor, or the decision whether it is engaged at all, must be determined by the operator based on grid loading. If loading is low, reactive power for voltage control is beneficial. If loading is high, reactive currents may cause overloads. Generally, Q-V characteristics perform better in highly loaded grids and offer more control, while fixed offset power factors alleviate voltage problems in lightly loaded grids more effectively.
- PV power plants connected to the 11 or 33 kV level should be equipped with active voltage control by Q-V characteristic. If the grid experiences severe overloading issues, the grid operator may choose to disable the controls and run the unit at a fixed power factor, unity or offset.

Active power management of PV units will also play a large role in the future, leading to the following recommendations:

- Some degree of active power management and controllability should be required from all PV units, regardless of size and connection level.
- Centralized PV power plants connected to 11 kV and above should be remotely controllable so the grid operator can curtail active power in case of grid congestion. The exact conditions under which the operator may curtail must be clearly defined and subject to energy legislation and regulation.
- Rooftop PV units connected to the low voltage grid should either be capped at 70 to 75 % of their maximum expected output, or be remotely controllable, or be equipped with a peak shaving storage. A cap is the cheapest and least complicated option.[28]
- If PV batteries are introduced, there should be an incentive to use them in peak shaving mode (see 7.4.9) to maximized positive grid impact.

10.2.4 Legal and regulatory framework

Technical development needs to be supported by an adequate legal and regulatory framework. Most Indian states have a net metering scheme in place and specific regulations for application, installation and metering. For a large scale roll-out of rooftop PV and with regard to the technical solutions developed within this report, the following points need to be addressed in legal and regulatory development:

- The distribution grid codes should be updated to require voltage control capability from PV inverters, with the grid operator being in charge of the actual reactive power regime. It is recommended to align the requirements with the German low voltage grid code, as many

28 The German grid code requires a 70 % cap for non-controlled units below 13.8 kWp, and controllability for larger units. In India, communication infrastructure in the disitribution grid may be weaker, so the cap could also be the easier solution for larger rooftop units.

inverters available on the market are compliant with that already.

- The capping of PV at 70 or 75 %, if implemented, must be specified in grid code and net metering scheme, and must be checked for legal complications.
- For PV batteries, incentives have to be set by energy legislation, both for installation of batteries and for running them in peak shaving mode.
- If PV units can be remotely controlled by the grid operator, it needs to be specified in legislation and regulatory documents under which circumstances the operator is actually allowed to do so. For the case of active power curtailment, remuneration of lost energy must be agreed on[29].
- The high share of rooftop PV expected to be installed in India will also impact power system operation above the distribution level. Grid code requirements should be developed in coordination with the entities responsible for the operation and stability of the transmission system. As an example, frequency response of PV units will neither impact the distribution grid nor is it required for distribution grid operation, but will considerably impact transmission system operation.

10.2.5 Specific recommendations for Delhi

Based on the analyzed cases, once the 66/11 and 33/11 kV transformers are upgraded to automatic voltage control, there are no specific recommendations that deviate from the previously stated.

The PV power plant should either be connected to feeder 1, or split and connected to both feeders, if a technically optimal solution is required. A connection to feeder 2 will impact the feeder's hosting capacity for rooftop PV, but is still a technically feasible solution.

10.2.6 Specific recommendations for Bhopal

For Bhopal, especially concerning the rural feeder, an improvement in voltage control will be necessary. Currently, the 132/33 kV on-load tap changing transformers are manually controlled by the subtransmission company. To improve voltage quality and facilitate PV integration, the DISCOM should have more control over the voltage control regimes. This would either require the 132/33 kV transformers to be retrofitted with automatic tap changing to regulate the voltage at the 33 kV side, or the 33/11 kV transformers to be equipped with on-load tap changers. This should be the first priority. Even if it is not possible to retrofit all transformers, on-load tap changing models with automatic voltage control should at least be used in new projects or when replacing old or damaged units.

29 Example from Germany: If the unit is not capped, the operator can curtail up to 3 % of energy yearly without remuneration, for any reason. Additional curtailment must be remunerated. Curtailment due to emergencies in the grid is not remunerated.

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Annex: Grid Reinforcements

For Delhi urban, the necessary grid reinforcements are given in Table 51. The reinforcements for a higher penetration level have to be added to the previous reinforcements. Transformers are given as quantity by type. In case of overloading, transformers were upgraded with a parallel transformer of the same type.

Table 51: Grid reinforcements per scenario and penetration level, Delhi urban.

Case	PV	Sheet	OHL Dog / km	50mm² / km	150mm² / km	300mm² / km	630 kVA	990 kVA
01_PV_equal_distribution	100%	01_100	0.000	0.000	0.000	0.052	0	0
01_PV_equal_distribution	150%	01_150	0.073	0.000	0.000	0.850	2	7
02_PV_at_end_of_LV_feeder	100%	02_100	0.409	0.000	0.231	0.316	0	0
02_PV_at_end_of_LV_feeder	150%	02_150	0.761	0.030	0.723	1.318	2	7
03_PV_equal_adaptedLoad	100%	03_100	0.000	0.000	0.000	0.052	0	0
03_PV_equal_adaptedLoad	150%	03_150	0.271	0.000	0.231	0.617	2	6
04_PV_at_end_adaptedLoad	100%	04_100	0.000	0.000	0.000	0.129	0	0
04_PV_at_end_adaptedLoad	150%	04_150	0.765	0.030	0.437	1.474	2	6
05_Lower_Cable_Cross_Section	75%	05_075	0.247	0.000	0.511	0.000	0	0
05_Lower_Cable_Cross_Section	100%	05_100	0.409	0.000	1.501	0.000	0	0
05_Lower_Cable_Cross_Section	150%	05_150	1.186	0.060	3.327	0.000	2	7

For Delhi rural, the necessary grid reinforcements are given in Table 52. The reinforcements for a higher penetration level have to be added to the previous reinforcements. Transformers are given as total capacity that needs to be installed additionally. Transformers were upgraded to the next larger available transformer.

Table 52: Grid reinforcements per scenario and penetration level, Delhi rural.

case	PV	Sheet	OHL Panther / km	300 XLPE / km	Transformers [MVA]
02_PV equal distribution	100%	02_100	2.059	2.391	14.37
02_PV equal distribution	150%	02_150	6.364	7.584	
03_PV equal adapted load	150%	03_150	5.354	2.391	13.74
04_PV equal + PV powerplant	75%	04_075	3.104	2.391	
04_PV equal + PV powerplant	100%	04_100	5.354	2.391	
04_PV equal + PV powerplant	150%	04_150	8.991	7.584	14.37
05_Network fully cabled	75%	05_075	0	3.565	
05_Network fully cabled	100%	05_100	0	5.874	
05_Network fully cabled	150%	05_150	0	15.217	14.37

For Bhopal urban, the necessary grid reinforcements are given in Table 53. Transformers are given as total capacity that needs to be installed additionally. Distribution transformers were upgraded to the next larger available transformer. Power transformers were upgraded by installing a parallel transformer of the same type.

Table 53: Grid reinforcements per scenario and penetration level, Bhopal urban.

case	PV	Sheet	Power transformers [MVA]	Distribution transformers [MVA]	Lines
01_PV equal distribution	150%		8	2.10	-
02_ PV equal adapted load	150%		8	1.58	-
03_PV_at_end_of_feeder	150%		8	2.10	-
04_PV_at_end_adapted	150%		8	1.58	-
05_Network fully cabled	150%		8	2.10	-

For Bhopal rural, the necessary grid reinforcements are given in Table 54 for the 11 kV feeder that was modelled in detail only Table 52. Transformers are given as total capacity that needs to be installed additionally. Distribution transformers were upgraded to the next larger available transformer. Power transformers were upgraded by installing a parallel transformer of the same type.

Table 54: Grid reinforcements per scenario and penetration level, Bhopal rural, 11 kV.

case	PV	Sheet	Power transformers [MVA]	Distribution transformers [MVA]	Line Dog [km]	Line Panther [km]
01_PV equal distribution	150%		5	3.3	0.35	1.35
02_ PV equal adapted load	150%		5	3.3	0.35	1.35
03a_PV_plant_at_11kV_SS	150%		10	3.3	0.35	1.35
03b_PV_plant_at_middle	150%		10	3.3		2.30
03c_PV_plant_at_end	150%		10	3.3	0.20	2.60
04_ Network fully cabled	150%		5	3.3	0.15 (cable 120XLPE)	0.65 (cable 240XLPE)

As PV penetration was also ramped up in all other 11 kV feeders in the 33 kV network, some reinforcements in the 33 kV grid were also necessary, 10.63 km of 33 kV overhead line and eight 33/11 kV power transformers (5 – 8 MVA) need to be reinforced.

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