Solva

Evaluate the value of distributed solar and storage

Documentation

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Contents

1. Introduction

Solva is an open-source python-based toolbox for simulating and analyzing the technical and economic benefits of modern power systems with distributed renewable energy sources. The Solva web tool allows users to:

- Undertake a feeder/DT/substation level power flow analysis.
- Evaluate the network benefits and social benefits for distributed solar and energy storage.
- Identify system sizes and dispatch strategies to optimize the value of distributed solar and energy storage.

Solva tool helps to accelerate integration of distributed solar energy and storage systems interconnected at the distribution network and support electricity utilities in identifying opportunities for interconnection of distributed solar and energy storage systems.

Power flow analysis gives

The reports generated in Solva give a detailed analysis on the active power and voltage distribution. The report features graphical representations of power flow, load profile, voltage and DER power balance etc. The results displayed show the power flow analysis and the numerical benefits i.e. network and social benefits that are computed under the value of distributed energy resources (VODER).

Power flow analysis gives

- Active power
- Voltage

Value of distributed energy resources (VODER) gives

- Avoided network costs
- Avoided social and environmental costs

Value of distributed energy resources (VODER) gives

- Avoided cost of energy (ACE)
- Avoided transmission capacity costs (ATCC)
- Avoided distribution capacity cost (ADCC)
- Avoided generation capacity cost (AGCC)

Social benefits include

- Avoided cost of energy (ACE)
- Avoided transmission capacity costs (ATCC)
- Avoided distribution capacity cost (ADCC)
- Avoided generatio capacity cost (AGCC)

2. Power Flow Simulation

The power-flow analysis is a numerical analysis of the flow of electric power in an interconnected power system. It analyzes the power systems in normal steady-state operation. Power flow studies are important in determining the best operation of existing systems as well as for planning future expansion of power systems. It determines the magnitude and phase angle of the voltage at each bus and the real and reactive power flowing in each line for a given load, generation, and network conditions.

For given inputs (load and generation), power flow ensures that the following equation is satisfied for each bus i:

$$S_i = P_i + jQ_i = V_i I_i^* = V_i \left(\sum_j Y_{ij} V_j \right)^*$$

where $V_i = |V_i|\, e^{j\theta_i}$ is the complex voltage, whose rotating angle is taken relative to the slack bus.

Y_{ij} is the bus admittance matrix, based on the branch impedances and any shunt admittances attached to the buses.

For the slack bus $i = 0$ it is assumed $|V_0|$ is given and that $\theta_0 = 0$; P and Q are to be found.

For the PV buses, P and $|V|$ are given; Q and θ are to be found.

For the PQ buses, P and Q are given $|V|$ and θ are to be found.

Solva uses PyPSA (Python for Power System Analysis), an open-source python environment to run the power flow.

2.1 Distribution Transformer (DT) level analysis

All the loads under a DT are aggregated and the system under a DT is modelled as a four-bus system. The load is distributed in the middle and tail end of the LT feeder. The user can select the location of DER as starting, middle or receiving of the feeder. A new DT with the same capacity is added when the capacity limit of the current DT is exceeded. The load can be distributed among the two DTs if a new DT is added (by default 50% but it is a variable).

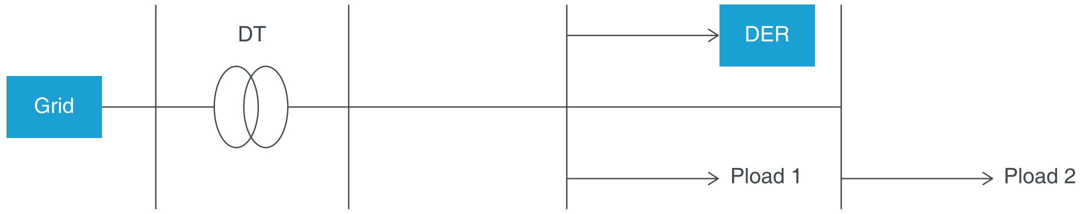

Figure 1: DT with DER located in the middle of the LT feeder.

2.2 HT Feeder level analysis

The HT feeder is modelled as a three-bus system. Load is distributed in the middle and tailend of the feeder. The user can select the location of the distributed energy resources (DER) as starting, middle or receiving of the feeder. A new feeder is added when the feeder capacity limit is exceeded, the load can be distributed among the two feeders (by default 50% but it is a variable).

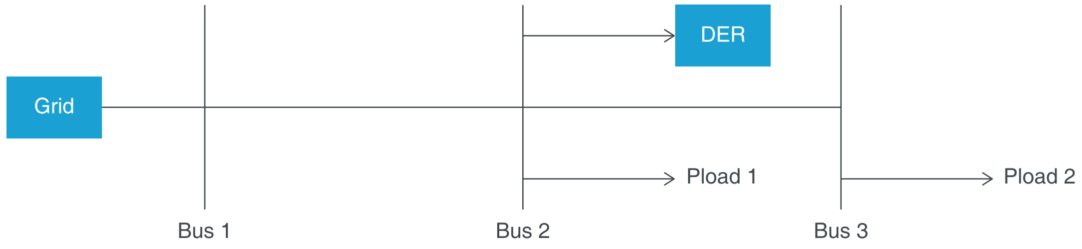

Figure 2: An HT feeder with DER located in the middle of the feeder.

2.3 Substation level analysis

The load of all feeders pertaining to a substation are aggregated and modelled as a four-bus system. All the feeders under a substation are modelled as a single representative feeder with maximum capacity is taken as the total capacity of all the feeders. The load is distributed in the middle and tail end of the feeder. The user can select the location of DER as starting, middle or receiving of the feeder. When maximum substation capacity is violated, a new substation with the same capacity is added and the load is distributed among the two substations. (by default 50% but it is a variable).

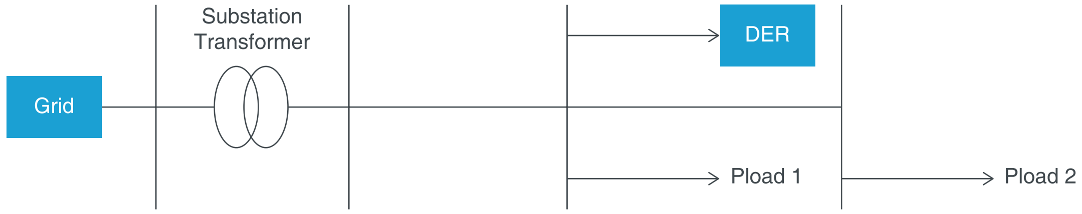

Figure 3: Substation model with DER located middle of the HT feeder.

3. Value of Distributed Energy Resources Methodology

The value of distributed energy resource or VODER methodology takes a systems approach to establishing the value of the electricity generated by DER. DER generation has some unique features: power generation occurs close to the point of consumption, no marginal cost of generation (no fuel cost) and significant environmental advantages over conventional generation based on coal. These characteristics allow the utilities to reduce their energy costs, and avoid generation, transmission and distribution capacity costs. In addition, there are avoided social and environmental externalities of fossil fuel-based generation. Adapting a VODER methodology represents an opportunity for states and utilities across the country to begin to assess the benefits of distributed generation and better plan for energy investments that provide maximum network and societal benefits. The VODER methodology can be made a part of:

- Integrated resource planning of utilities
- Determination of feed-in tariffs for distributed solar
- Demand response and demand side management

3.1 Energy and Capacity Values

3.1.1 Avoided cost of energy (ACE)

We calculate ACE based on the following:

- In order to meet the electricity demand in the state, the system operator schedules the generation fleet contracted or owned by the distribution utility, subject to limitations such as transmission system congestion or generation ramp-up. Distributed generation helps in meeting the demand locally and displaces energy from the marginal generator – the highest cost centralised generator at the top of the dispatch stack in any given hour.
- PV generation in every hour of the lifetime estimated using PVWatts.

Appendix I lists different approaches in the literature to calculate ACE.

For the hosting capacity tool, we will ask the user to enter hourly marginal energy cost values. ACE can then be determined as:

$$ACE = \sum_{t=0}^{n} \frac{\sum_{1}^{8760\ hr} \frac{Marginal\_generator\_cost * \ DER\_generation}{(1 - dl\%) * (1 - tl\%)}}{(1 + i)^{t}}$$

Here, Marginal_generator_cost is the marginal cost of energy to be replace in INR/kWh, DER_generation is the actual energy generated in kWh, n is the analysis period, dl% is the distribution loss percentage, tl% is the transmission loss percentage and i is the discount factor.

A utility can buy energy from the exchange if it is unable to meet the demand due to constraints on its contracted/own capacity (such as outages, higher than expected demand.) Hence, the exchange prices are a good proxy for the hourly marginal cost of energy. Alternatively, the use can upload an hourly energy cost as per merit dispatch or enter a single value for the avoided energy cost.

3.1.2 Avoided distribution capacity cost (ADCC)

To calculate the avoided distribution capacity cost, we calculate the distribution capacity upgrade cost with and without the solar PV and storage (BAU case and DER case). For our tool, the upgrade cost will include the cost of adding a new HT feeder/DT/Substation.

To determine the year in which a distribution capacity upgrade for HT feeder level is required, the following steps are taken:

- Calculating the line flow for each period in Year 1 in the feeder. For each season, the period corresponding to peak line flow for every hour is calculated (hence 96 hours).
- Every year, r power flow for the same 96 periods is run and the peak line flow is determined.
- The peak line flow with the threshold is compared. If the threshold is exceeded more than 5 times (out of the 96 values) of the time, feeder upgrade is considered. The threshold of 5 can be a parameter in the backend database.
- Cost for a new feeder with the same capacity and feeder length will be considered for the upgradation cost.

To calculate the year of distribution capacity upgrade for DT level analysis:

- The power flow through DT for each period in Year 1 is calculated. For each season, the period corresponding to peak line flow for every hour is determined (hence 96 hours).
- Every year, r power flow for the same 96 periods is run and the peak power flow through DT is determined,
- The peak power flow through DT with the threshold is compared. If the threshold is exceeded more than 5 times (out of the 96 values) of the time, DT upgrade is considered. The threshold of 5 can be a parameter in the backend database.
- Cost for a new DT with the same capacity will be considered for the upgradation cost.
- Similarly for substation level analysis, the same procedure is followed, and capacity violation is checked. If it exceeds more than 5 times (out of the 96 values), substation upgrade is considered. Cost for a new substation with the same capacity will be considered for the upgradation cost.

Solva will assume 50% load will be transferred to the new feeder/DT/substation as default value. The upgradation cost will be an advanced input, which will have a default value stored in the database.

Note that both in the BAU case and in the DER case, the power flow models will have to be updated in the upgrade years, and there can be multiple update years. After the upgrade, we continue our analysis for existing feeder using the updated model.

The avoided distribution capacity cost is calculated as

ADCC = Cost_upgradation* $(1 - \frac{1}{e^{rate*t_k}})$

t_k = year of upgradation with DER – year of upgradation without DER

rate = real interest rate

Cost_upgradation = It is the total cost of upgradation

3.1.3 Avoided transmission capacity cost (ATCC)

DER meets the load locally and helps in reducing the need for contracting transmission capacity during peak transmission load periods. Solva calculates the avoided transmission capacity cost as:

$$ATTC = \sum_{t=0}^{n} \frac{Transmission\_capacity\_cost * DER\_capacity * (1 - degradation\_factor_t) * CC}{(1 - tl\%) * (1 - av\_dl\%) * (1 + i)^t}$$

Here, transmission_capacity_cost is in INR/kW. n is the analysis period (default is 25 years), CC is the capacity credit for the DER, which is the output of the distributed resource as a fraction of the total capacity (i.e., the capacity factor) during top N transmission load hours, degradation_factor_t is the factor accounting the decrease in performance of the DER system over the years, avg_dl% is the average distribution loss during the N hours (avg_dl% will have to be calculated all years using power flow.) , and i is the discount factor.

CC can be calculated as:

$$CC = \frac{\sum_{t=1}^{N} \frac{DER\_output}{DER\_capacity}}{N}$$

Here, the capacity credit is calculated over the N top net load hours in Year 1. N can be taken as 100 hours.

3.1.4 Avoided generation capacity cost (AGCC)

In order to meet the electricity demand during all hours, the distribution utility enters into long-term contracts with GENCOS and pays fixed costs for the contracted capacity. It can also contract capacity through medium or long-term open access. These fixed costs cover the cost of equity, O&M costs, interest on debt and depreciation.

The value of avoided generation capacity depends on when in future the net demand exceeds the total contracted capacity, and the distribution utility must contract new capacity. Depending on the analysis horizon the need for contracting new power purchase agreements may not arise and the avoided generation capacity cost benefit is insignificant.

The avoided generation capacity cost can be calculated as:

$$AGCC = \sum_{t=m}^{n} \frac{Generation\_capacitycost * DER\_capacity * (1 - degradation\_factor_t) * CC}{(1 - tl\%) * \ (1 + i)^t}$$

m is the future year where a new power purchase agreement is needed. Generation_capacitycost is the fixed cost in the power purchase agreement INR/kW that the utility will have to pay for the operation period of the generator, degradation_factor_t is the factor accounting the decrease in performance of the DER system over the years, tl% is the transmission losses and i is the discount factor.

3.2 Environmental and Health Value (EHV)

3.2.1 Avoided CO2 emissions / avoided NO2/SO2/PM2.5 emissions

The environmental and health value for the pollutants that are emitted from burning fossil fuels represent their external cost to the economy. DER can be assigned an environmental value based on these emissions they help to avoid.

In recent years, a lot of work has been done to understand the cost of various pollutants emitted from fossil fuel burning. For example, it is estimated that sustained exposure to additional ambient concentration of10 µg of PM10 reduces life expectancy by 0.64 years (see reference in EPIC 2018). By linking this loss in expectancy with the Gross Domestic Product per capital, the value of particulate matter's externalities can be calculated. In the case of CO2, as compared to the local environmental cost of particulate matter, a social cost of carbon can be determined.

Note that deriving monetary cost in the above way is useful in setting environmental regulation in place. Such market-based environmental taxes on polluting fuels is one way to transition to cleaner energy. For CO2, no such market is in place in India.

In our tool, the environmental and health value will be determined as follows:

$$EHV = \sum_{t=0}^{n} \frac{\sum_{1}^{8760\ hr} \frac{env\_health\_value * \ DER\_generation}{(1 - dl\%) * (1 - tl\%)}}{(1 + i)^t}$$

Here env_health_value (INR/kWh) is the multiplication of

- the emissions rate for a typical marginal generator (say, a coal plant) (kg/kWh), and
- the value of avoided emissions (INR/kg).

We assume coal to be the marginal generator and use emission rate based on average heat rate India's coal fleet. In reality, there will be times when a hydropower or other plants are on the margin. However, given coal still dominates the Indian power system, this is a reasonable assumption to make.

Parameter : Social cost of carbon / value of CO2 emissions

Value : ~ INR 3.54/kg

Source : Ricke et al. (2021)

Notes : In general, a lower estimate of the value appears to be in the ballpark of $0.44-0.55/kg. In the given source, the country-wise cost of carbon value is derived by using future carbon pathways (more sustainable vs less sustainable ones) along with an assumed climate model sensitivity. That makes it a very multidisciplinary and complex modeling exercise. Based on the values derived for different pathways in the given source, we can assume roughly $0.50/kg. This matches the rough estimate indicated in EPIC (2018).

Note that the lower bound and upper bound values assumed in the NREL analysis for Gujarat and Jharkhand (Bowen et al. 2021) is very low (~INR1–2/kWh). Their source is Gujarat Pollution Control Board.

Parameter : Environment/health value of SO2 emissions

Value : ~ INR 400/kg

Source : Bowen et al. (2021), EPIC (2018)

Notes : We are going with a mid-value here based on estimates. The upper bound given in the NREL analysis for Gujarat and Jharkhand is INR355/kg. However EPIC (2018) puts a value in US$ 2007 terms as $5.35/kg – but this is in 2007 terms. Putting it in 2020 terms after considering inflation and currency conversion only (this would be a rough calculation), the value would be close to INR550/kg.

Parameter : Environment/health value of NOx emissions

Value : ~INR 500/kg

Source : Bowen et al. (2021), EPIC (2018)

Notes : NREL analysis comes up with an upper bound of INR500/kg. On the other hand EPIC goes with a lower value of <INR400/kg. We can go with the higher estimates observed here.

Parameter : Environment/health value of PM2.5 emissions

Value : INR 5000/kg

Source : EPIC (2018)

Notes : This is the value estimated by EPIC (2018) particularly for emission from coal plants. This is 50 times higher than the upper bound in Bowen et al. (2021) of INR100/kg. This could be because of the fact that EPIC is accounting for all unseen benefits, leading to an increase in life expectancy of an average Indian by abatement of these emissions.

Emission rates for different pollutant can be picked up directly as the average of the upper and lower bounds given in Bowen et al. (2021) – they source the values based on works by Environment Ministry, ICF and Shakti Foundation:

Pollutant	Value (kg/MWh)
CO2	980
SO2	7.05
NO2	4.30
PM2.5	1.15

Appendix I

A single function power_flowfeedermodel_fedupg is defined to run the power flow.
power_flowfeedermodel_fedupg(sn, pload, psol, pstor, loc_sol, loc_stor, len_line, Rperkm, Xperkm, Snom, voltkv,realld)

Inputs

sn - No of hours of the analysis based on the load data (it can be 8760, 96, 16 etc based on the requirement. Assign the required value to the variable)

pload – load profile for the power flow calculations (it can be 8760, 96, 16 etc based on the requirement. Assign the required profile to the variable)

psolar – solar generation profile for the power flow calculations (it can be dataframe with 8760, 96, 16 rows based on the requirement. Assign the required profile to the variable). For BAU case, assign psolar as “0”

pstorage – storage charging/discharging profile for the power flow calculations (it can be dataframe with 8760, 96, 16 rows based on the requirement. Assign the required profile to the variable). For BAU case, assign pstorage as “0”

loc_solar – location of solar system (assign the value based on the user input data - ‘0’ if near to substation, ‘1’ if middle of the substation, ‘2’ if near to tail end of feeder)

loc_stor – location of storage unit (assign the value based on the user input data - ‘0’ if near to substation, ‘1’ if middle of the substation, ‘2’ if near to tail end of feeder)

lenline – assign the value for feeder length (fed_len) from the user input

Rperkm, Xperkm -Based on the type of conductor fetch the data either from the database or from user

Snom – Fetch the value from the database

voltkv – fetch the value from the user input for feeder voltage (fed_vol)

realld – it is the re allocated load to the new feeder. Fetch the data from the advanced input section

Output

Output of the function is a data frame with following data representing each column. The data frame can be exported into a csv file if needed. The output values are with respect to the actual feeder (not upgraded feeder except for grid power). The output data frame includes

Load - load values for the respective hours of analysis of actual feeder

line_flow – Net power flow through the actual feeder for the respective hours of analysis

grid_power – Total grid power at the starting of feeder for the respective e hours of analysis (of both the feeder)

solar_power – Solar power at the respective hours of analysis

store_power – Storage power (charging/ discharging) at the respective hours of analysis. Value is negative if charging and positive if discharging

line_loss – Distribution loss of actual feeder in kW for the respective hours of analysis

line_lossper – Distribution loss of actual feeder in percentage of load for the respective hours of analysis

voltage – tailend voltage of actual feeder in per unit for the respective hours of analysis. Per unit value * feeder voltage will provide the actual voltage value at a particular hour.

Appendix II

In cases of multiple methods available to calculate a value, the method selected for our tool is indicated by ✓

1. Avoided cost of energy (ACE)

From the literature (Denholm et al. 2014, Bowen et al. 2021), we identified three different approaches to find the avoided cost of energy:

Method	Arguments / Special Considerations
Calculation using one typical marginal generator	• Uses one typical generator that is often on the margin or an average of marginal generators • Benefit: no data requirement; if data is not available for below approaches, user can calculate using this method • If you use the APPC value, the transmission capacity cost may needs to be also deducted from it (we are yet to analyse how to deal with transmission cost – next week)
✓Calculation using exchange (IEX) prices (per KWh)	• IEX has publicly available 15-min and hourly energy price data for each "bid area". This data can be directly used. • The IEX energy prices can be assumed a good approximation of for the energy value of solar generated. • Disadvantage: If the utility is able to meet all the demand from the generators, then the IEX price is not the accurate avoided energy cost.
Determine the marginal generator	• Using granular hourly demand data for the State (TN), dispatch data, and solar PV, this finds the avoided cost of marginal generation every hour. • A simpler way of using this method: assume three periods: high demand, medium demand and low demand periods. For each period, using the dispatch stack, calculate the marginal generator. • The hourly demand data for the State would be available from the State Load Dispatch Center.

2. Avoided distribution energy losses

Different methods of dealing with energy losses (for more details see Denholm et al. 2014):

Method	Arguments / Special Considerations
Publicly available average T&D loss rates	• Inaccurate. The publicly available loss also includes commercial losses. • For example, if the distributed generation coincides with the peak demand, then the actual avoided losses will be much higher. • In reality, the solar generation will avoid the marginal loss rate – dependent on time and location/feeder. (losses has two parts: fixed, irrespective of load/no load; and marginal losses)
Marginal loss rates	• Marginal loss rate for a feeder can be found by by multiplying a polynomial loss-rate function with the net load of the feeder • Still doesn't give accurate losses for the complex meshed distribution networks in India • Also doesn't capture differences in avoided losses for different solar PV location – whether BtM or connected to the feeder.
✓Loss rate using power flow models	• Most accurate

4 Avoided transmission energy losses

Method	Arguments / Special Considerations
✓Publicly available average transmission loss rate	• Inaccurate. Higher marginal losses occur during peak load periods can be up to 2 times higher.
Marginal loss rates	• Marginal loss rate for a feeder can be found by by multiplying a polynomial loss-rate function with the system net load time series (so requires system load data). • However, it doesn't capture spatial variation due to location of PV, generators, etc.
Loss rate using power flow models	• Most accurate

Appendix III

Tool Inputs

Page	Input fields	Advanced inputs
Feeder profile	Feeder load profile	
	Name of substation	
	Pincode	
	Name of feeder	
	Feeder type (Overhead/ Underground)	
	Feeder voltage (kV)	
	Feeder length (km)	
	Sanctioned load (MW)	
	State level load profile	
	Power factor	
Substation profile	Substation profile	
	Name of substation	
	Pincode	
	Name of DT	
	Total capacity (MVA)	
	Incoming feeder voltage (kV)	
	Outgoing feeder voltage (kV)	
	Feeder type (Overhead/ Underground)	
	Number of feeders	
	Feeder length	
	Sanctioned load (MW)	
	Power factor	
	State level load profile	
DT profile	DT profile	
	Name of substation	
	Pincode	
	Name of DT	
	DT capacity (kVA)	
	DT tapping	
	Primary voltage (kV)	
	Secondary voltage (kV)	
	Feeder type (Overhead/ Underground)	
	Feeder length (km)	
	Power factor	
	State level load profile	
		Yearly change in load (%)
		Type of conductor
		Resistance (ohms/km)
		Reactance (ohms/km)
		Peak current carrying capacity (Amps)
Technology	Solar Capacity (MW)	
	Interconnection location solar	
	Inverter capacity for storage (MW)	
	Storage capacity (MWh)	
	Interconnection location storage	
	Storage charging/discharging strategy	

Page	Input fields	Advanced inputs
VODER	Marginal cost of energy to be replaced (INR/kWh)	
	Average transmission losses (%)	
	State level load profile	
		Analysis period(years)
		Upper limit of capacity upgradation (%)
		Percentage of load shifted after upgradation
		Transmission capacity cost (INR/kW)
		Generation capacity cost (INR/kW)
		Cost of Upgradation (INR/km)
		cost of carbon (INR/tonne)
		cost of NO2(INR/tonne)
		cost of SO2 (INR/tonne)
		cost of PM2.5 (INR/tonne)

Solva Input parameters

General assumptions

Description	Input variable	Value
Yearly change in load (%)	load_var	5%
Instances of peak violation for capacity upgradation	nviol	5
Minimum acceptable voltage deviation	vol_min	-10%
Maximum acceptable voltage deviation	vol_max	6%
peak load hours time factor (hours)	M	5
Yearly solar degradation factor (%)	sol_var	1%
Yearly storage degradation factor (%)	stor_var	1%
Storage round trip efficiency (%)	st_eff	97%
Depth of discharge (%)	dod	80%
Inverter efficiency (%)	inv_eff	98%
Storage cycle life (cycles)	cycles	3285
Marginal cost of energy to be replaced (INR/kWh)		
Analysis period (years)	nyr	25
Discount Factor	i	5%
Upper limit for capacity upgradation (%)	diffcap_per	90%
Percentage of load shifted after upgradation	ld_shift	50%
Transmission capacity cost (INR/MW)	trcap_cost	1108614.50
Generation capacity cost (INR/MW)	gencap_cost	6800000.00

Conductor details

Conductor name	Resistance (ohms per km) - rperkm	Reactance (ohms per km) - xperkm	Peak current carrying capacity of conductor (Amps) (ipk_cap)
Raccoon	0.371	0.241	300
Rabbit	0.587	0.383	200
Wheasel	0.985	0.392	140

Emission cost of pollutants

Emission costs CO2 (INR/kg)	3.54
Emission costs SO2 (INR/kg)	400
Emission costs NO2 (INR/kg)	500
Emission costs PM2.5 (INR/kg)	5000

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