Very large-scale planning tools for electrical distribution networks

Computational modeling for promoting low-carbon electricity

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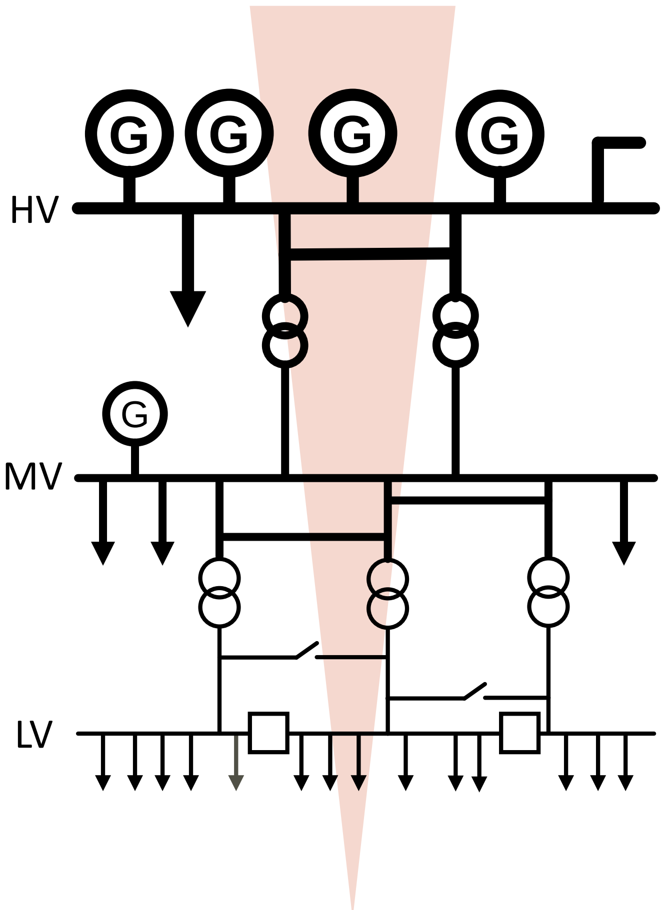
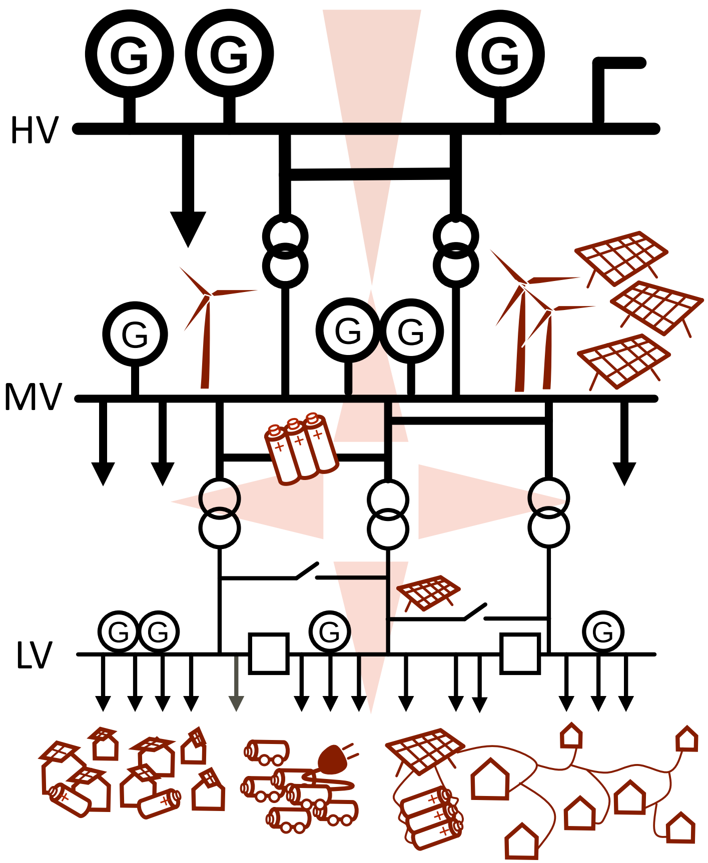
Power systems have been operated in a centralized, top-down manner



- Large utilities dominate the landscape
- Generation at high-voltage level
- Almost negligible distributed generation
- Power flows from high- to medium-voltage levels
- Reduced number of active nodes facilitates operation
- Millions of passive nodes in a service area

Distributed technologies are driving the power system transformation

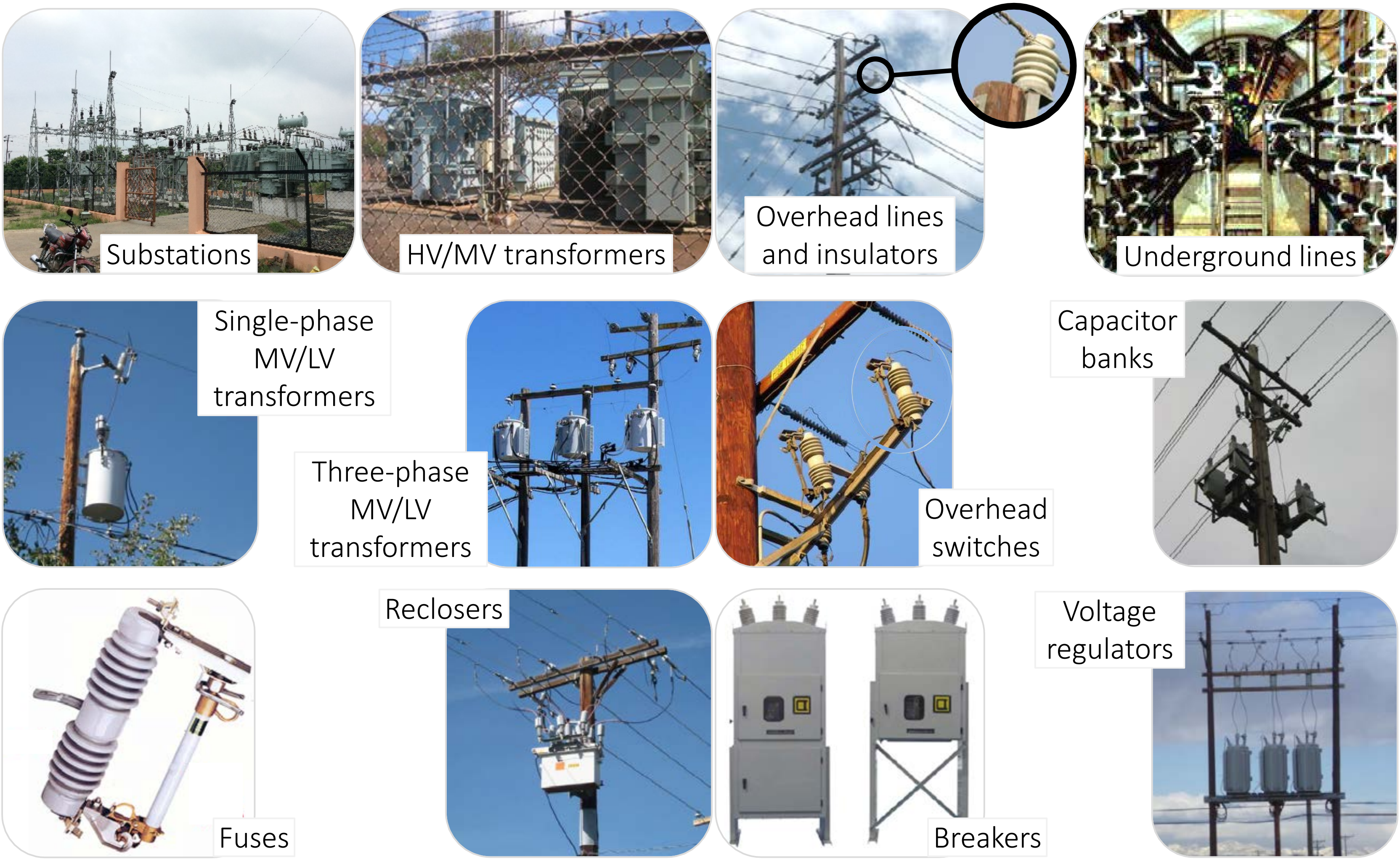


- Empowerment of consumers
- Declining, at least in share, large generation at high-voltage level
- Reverse power flows are possible, and may create difficulties
- Distributed generation at medium- and low-voltage levels
- And batteries, and smart devices, and electric vehicles…
- Potentially, millions of active nodes in a service area

Distributed technologies are sprinkled in the old landscape of passive loads

Countless active nodes at distribution level bring in complexity to network operation and planning, and resources integration

Yet, new distributed technologies will coexist with traditional equipment



The Reference Network Model (RNM) produces real distribution networks

- The objective is to find the most **cost-efficient** –minimum operation and investment costs– solution that covers the demand and connects the distributed generation

- Subject to **technical constraints** (current and voltage limits), **geographical constraints** (street map and geographical features), and **reliability targets** (SAIDI and SAIFI).

- Originally, RNM was used to remunerate distribution network operators
  - The **gold standard** that reveals the perfect distribution network
    - Greenfield mode: planning from scratch
  - And **dynamically** adapts it to arriving technologies and social transformations
    - Brownfield mode: expanding an existing network

Leveraging extensive input information and offering comprehensive results

Inputs

Equipment catalog

Utility specific
Rural | Urban
Underground | Overhead

Geospatial information

Service drops
Distributed generation
Existing network
Rights of way

Demand estimation

Land use
Load archetypes
Weather data

Reference Network Model

Outputs

GIS, plain text, ODSS, Matpower, CYME...

Power lines
Transformers
Substations
Switchers
Capacitors
Regulators

Summary of main results

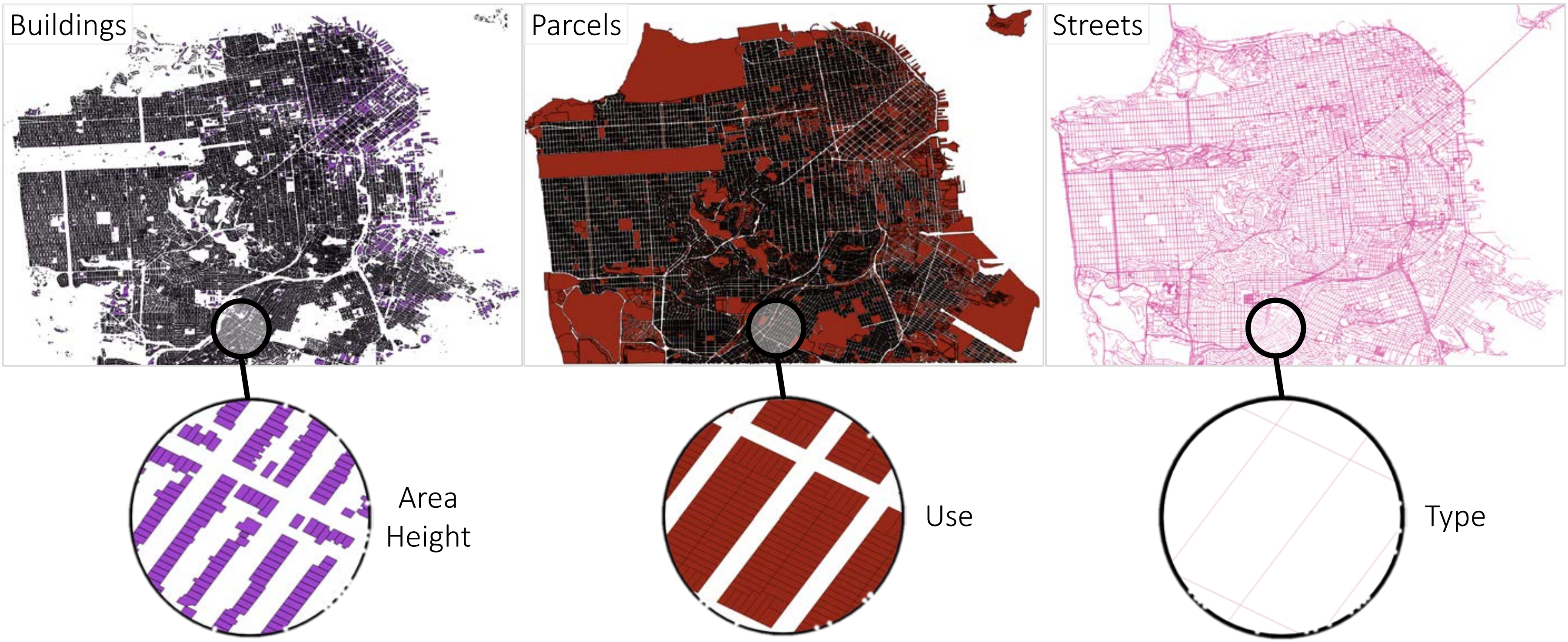
Equipment list
Equipment costs
Line lengths
Energy losses
Reliability
Maintenance

First input. The catalog of equipment

Lines	Transformers and substations	Voltage regulators	Capacitors	Switching devices
Overhead Underground Resistance Reactance Voltage level Amperage Failure rate Investment cost Maintenance costs Repair time Maintenance time Number of phases	Overhead Underground Installed power Primary Secondary voltage No load losses Resistance Reactance Maximum number of outputs Investment cost Failure rate Maintenance costs Maintenance time Repair time	Voltage level Investment cost Maintenance costs Useful life Failure rate Resistance Reactance Minimum tap Maximum tap Number of phases Steps	Voltage level Capacity Investment cost Maintenance costs Number of phases	Investment cost Maintenance costs

- Reliability targets and underground/overhead ratios

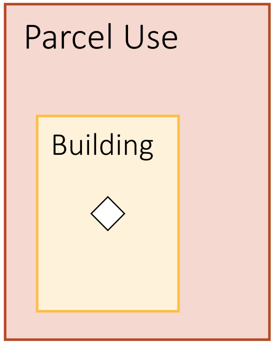
Second input. Geospatial and demand information



A database of reference buildings is needed to estimate the demand

For example, NREL/DOE: https://openei.org/datasets/files/961/pub/

Input preprocessing for RNM – Determine building types and estimate the load



Infer type of user

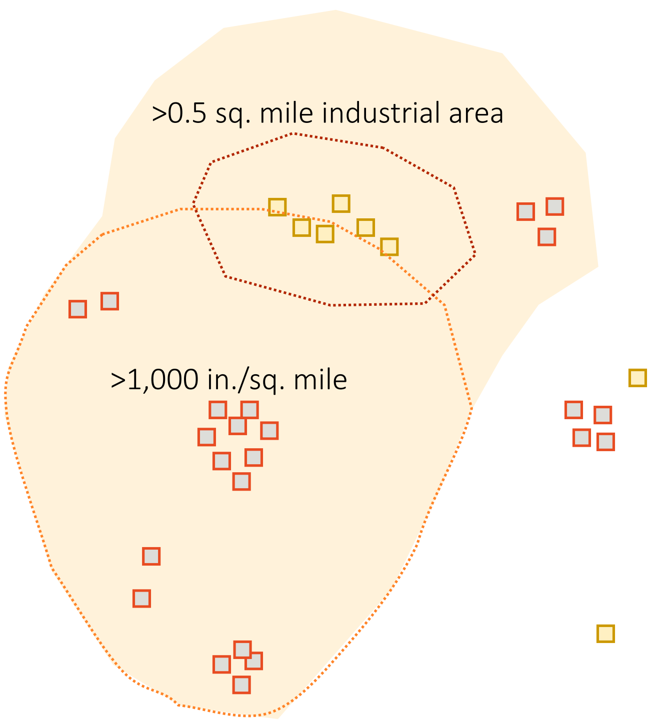
- Locate centroid building in parcel
- Assign parcel category
  1. Single-family
  2. Multi-family
  3. Stand-alone retail
  4. Strip mall
  5. Supermarket
  6. Warehouse
  7. Hotel
  8. Education
  9. Office
  10. Restaurant
  11. Outpatient healthcare
  12. Hospital
  13. Industry

Estimate demand of building

- Linear interpolation w.r.t. volume
- Maximum consumption of largest in area
- Minimum power connection design

Input preprocessing for RNM - Classify rural/urban and underground/overhead

Urban vs Rural



1.5 mile area of influence

Underground vs Overhead

Forbidden paths
- Bridleway
- Cycle way
- Footway
- Steps

Always overhead
- Motorway
- Track
- Trunk
- Service

Always underground
- Pedestrian
- Living street
- 3-ph. LV areas

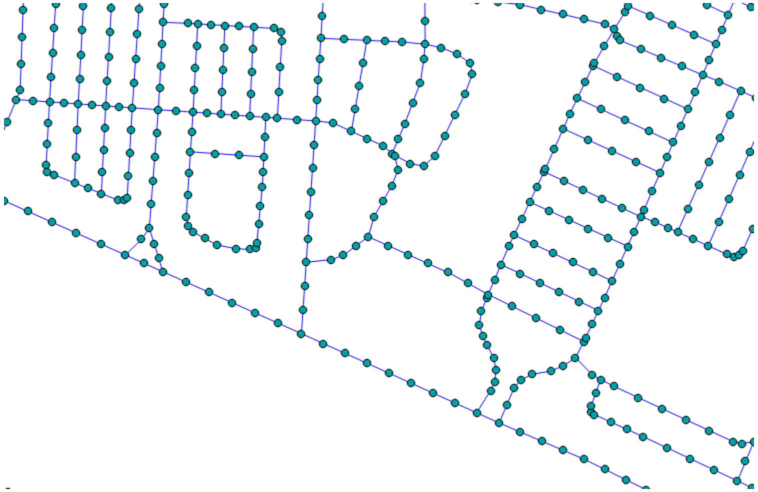
Mixed paths
- Residential

Create meshed grid
Calculate aggregated building height
Sort squares of grid
Set urban/rural underground threshold

Input preprocessing for RNM - Determine rights of way and service drops

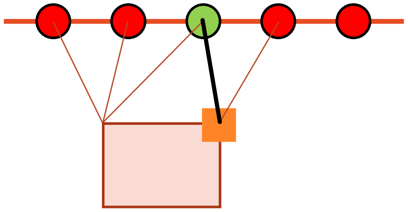
Determine rights of way

- Maximum distance (e.g., 50 ft.)
  - Underground vs overhead
- Wiring routes along paths

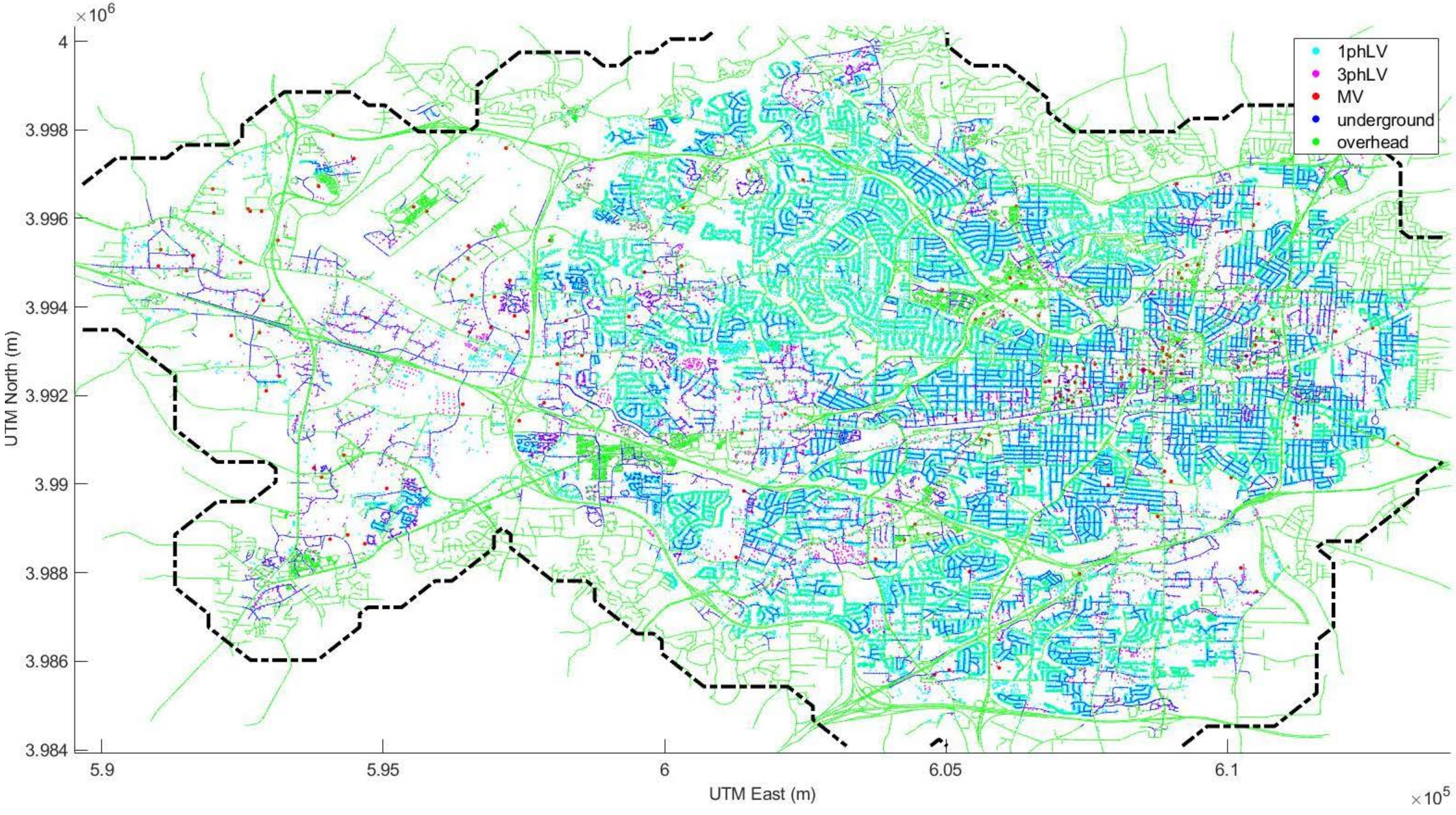


Determine service drops

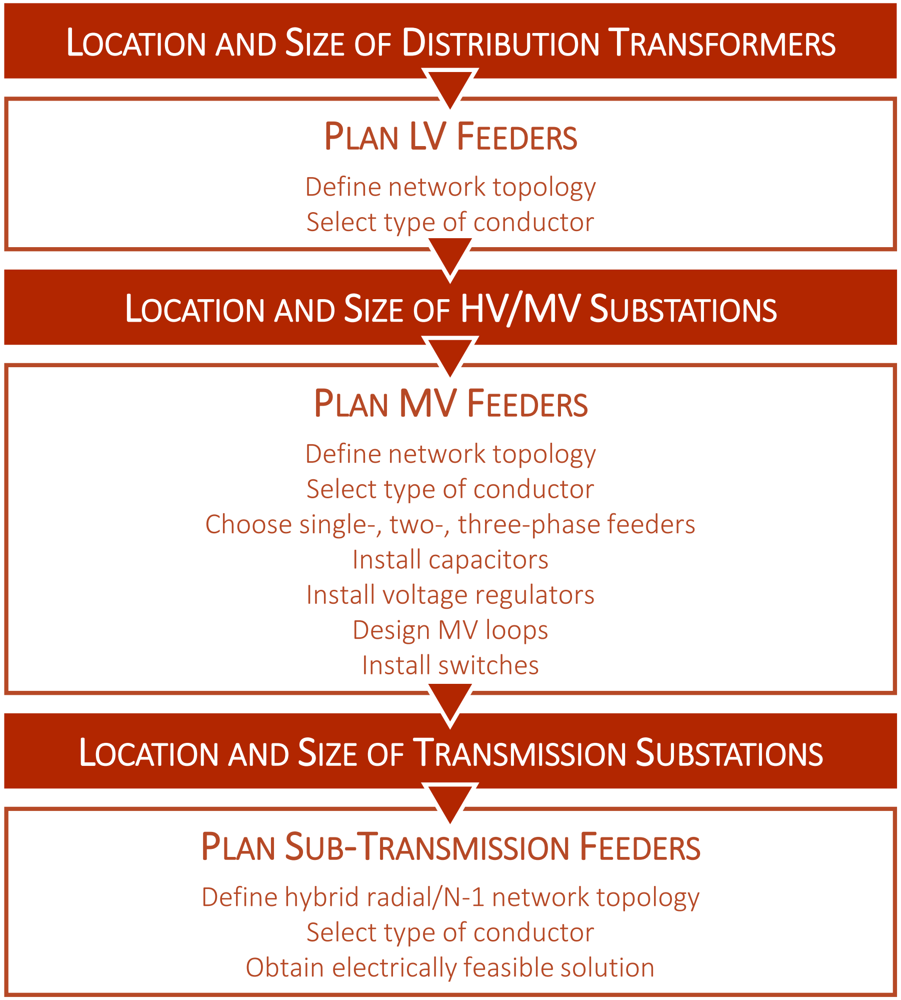
- Closest building point to right of way



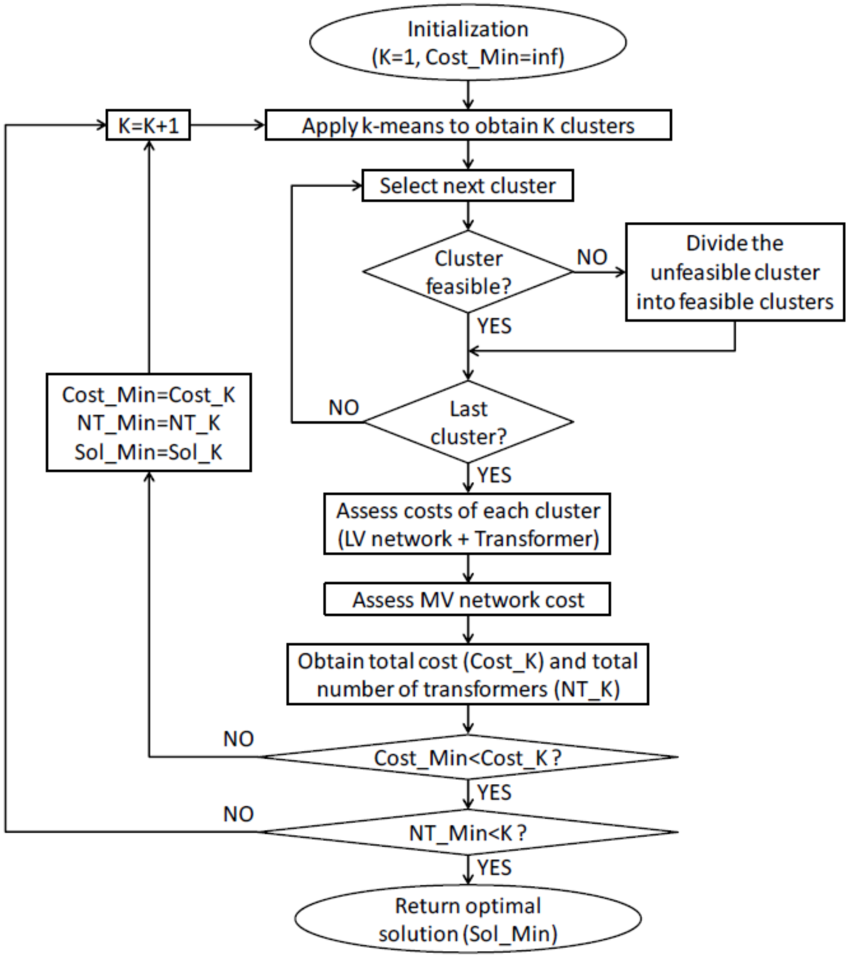
Example of input preprocessing for RNM in Greensboro (NC)

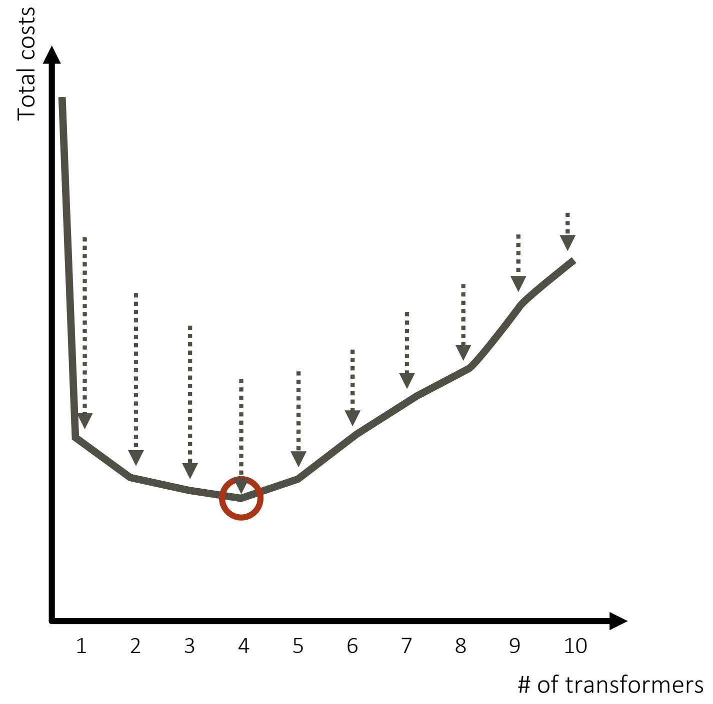


The process flow diagram behind RNM to produce distribution networks

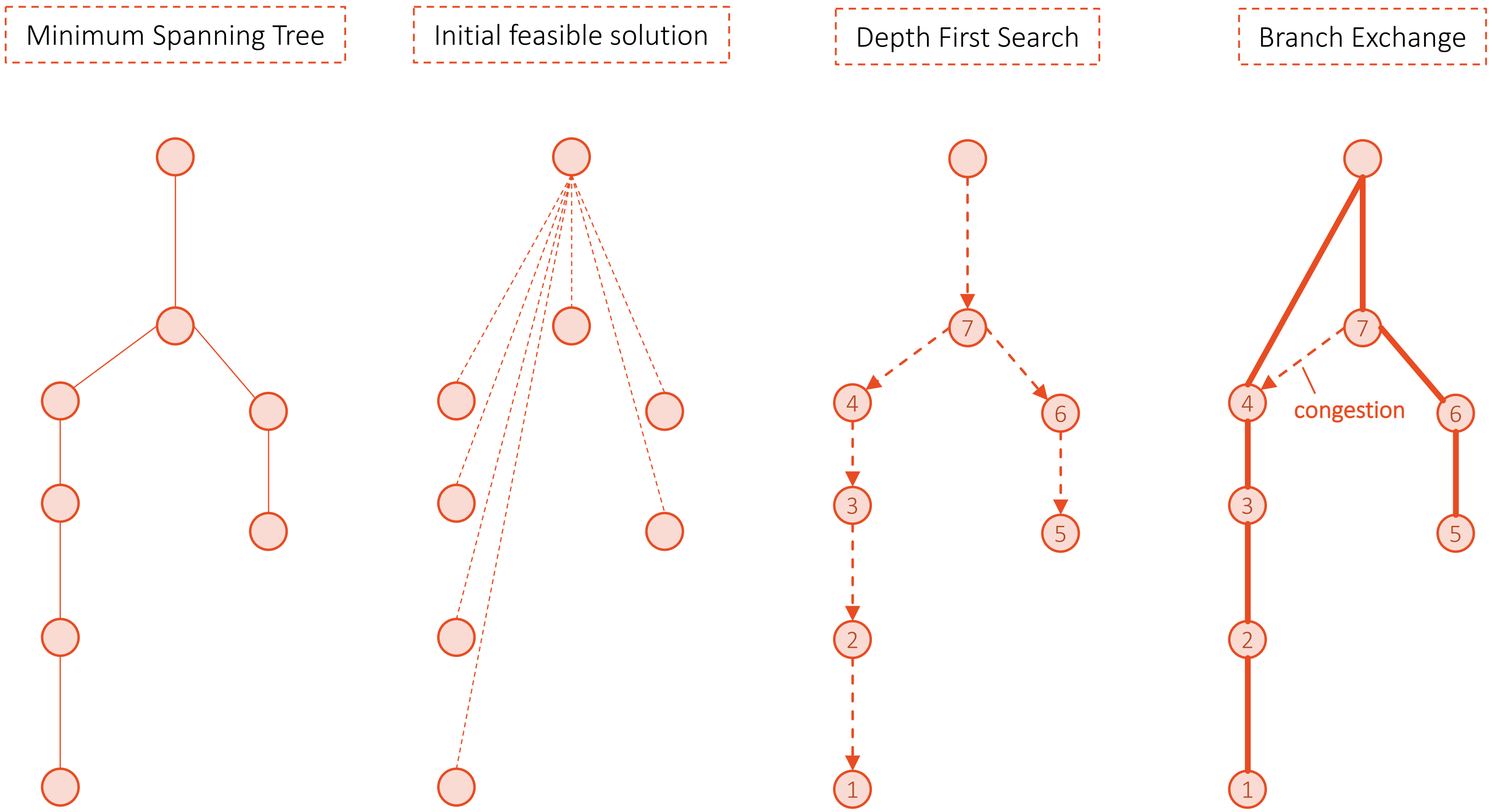


The transformers location and size depend on their number and capacity

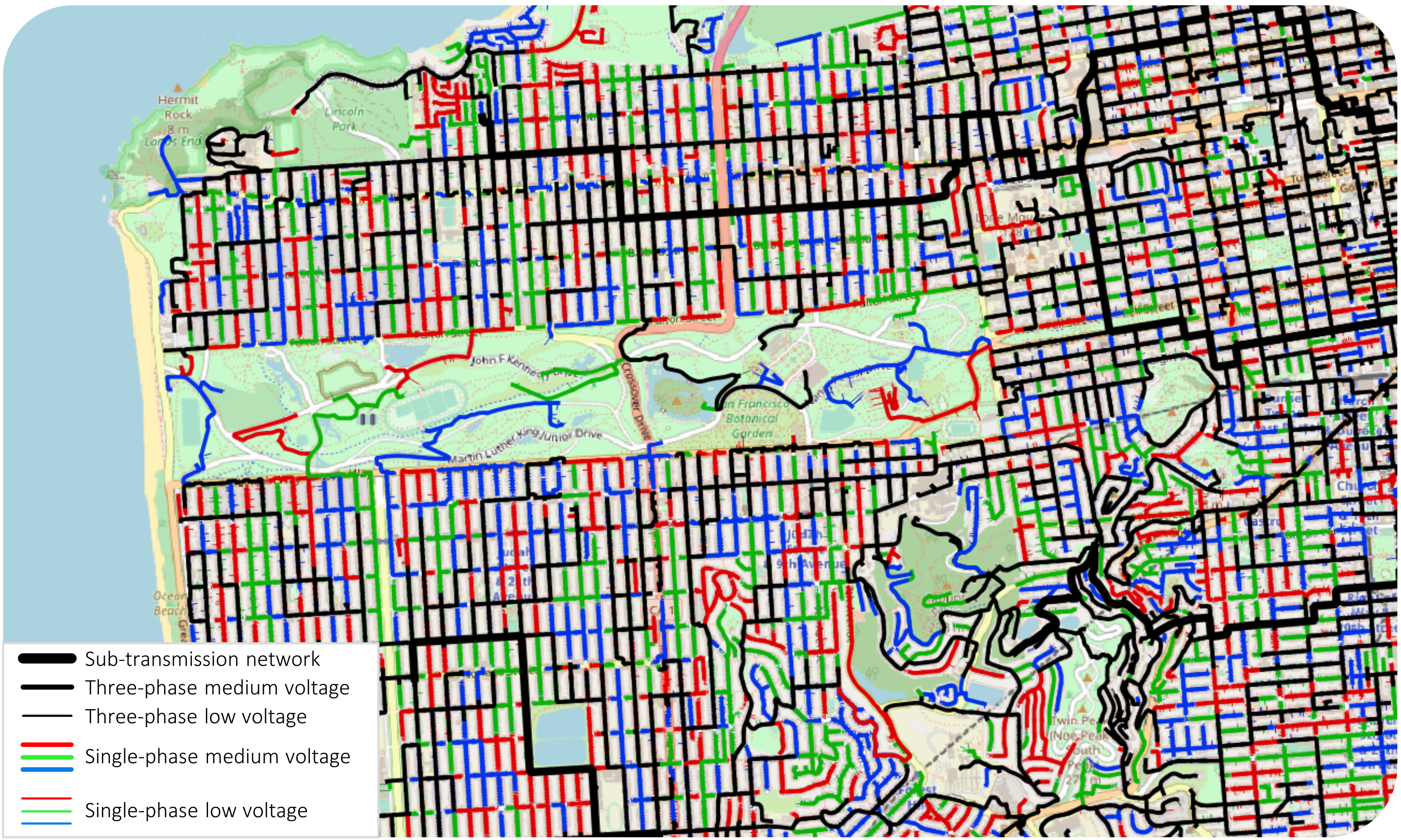




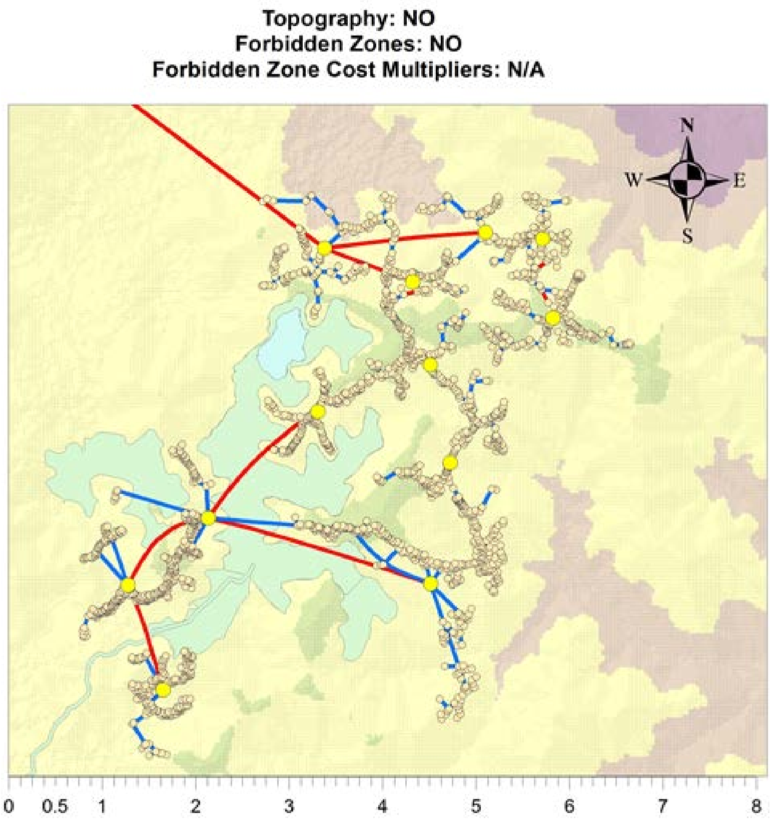
The wiring depends on the minimum distance, considering congestions

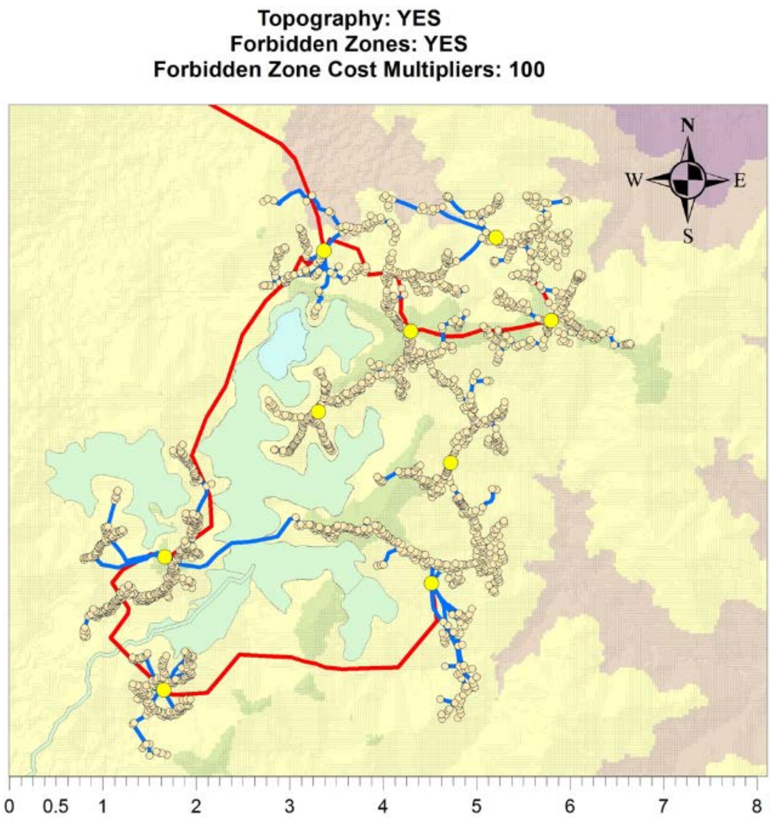


RNM follows streets and roads when wiring connections



RNM respects protected or forbidden areas and geographical features





Let’s build a distribution network for an existing area in Greensboro (NC)

- Electrical node
  - Consumer
  - Producer
  - Prosumer

Street

RNM decides on the location and size of each distribution transformer

• Electrical node
Consumer
Producer
Prosumer

Street

Distribution transformer

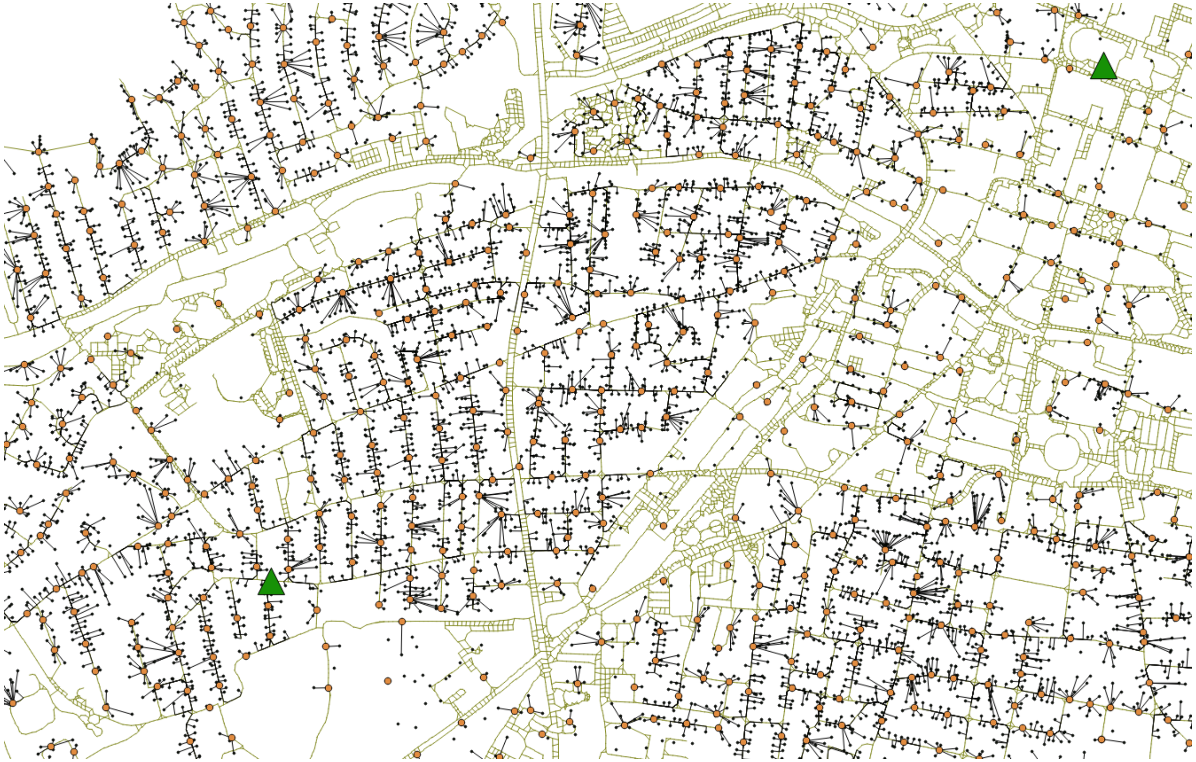
RNM places LV lines from distribution transformers to consumers

- Electrical node
  - Consumer
  - Producer
  - Prosumer
- Street

Distribution transformer

Three-phase low voltage

RNM decides on the location and size of each HV/MV substation



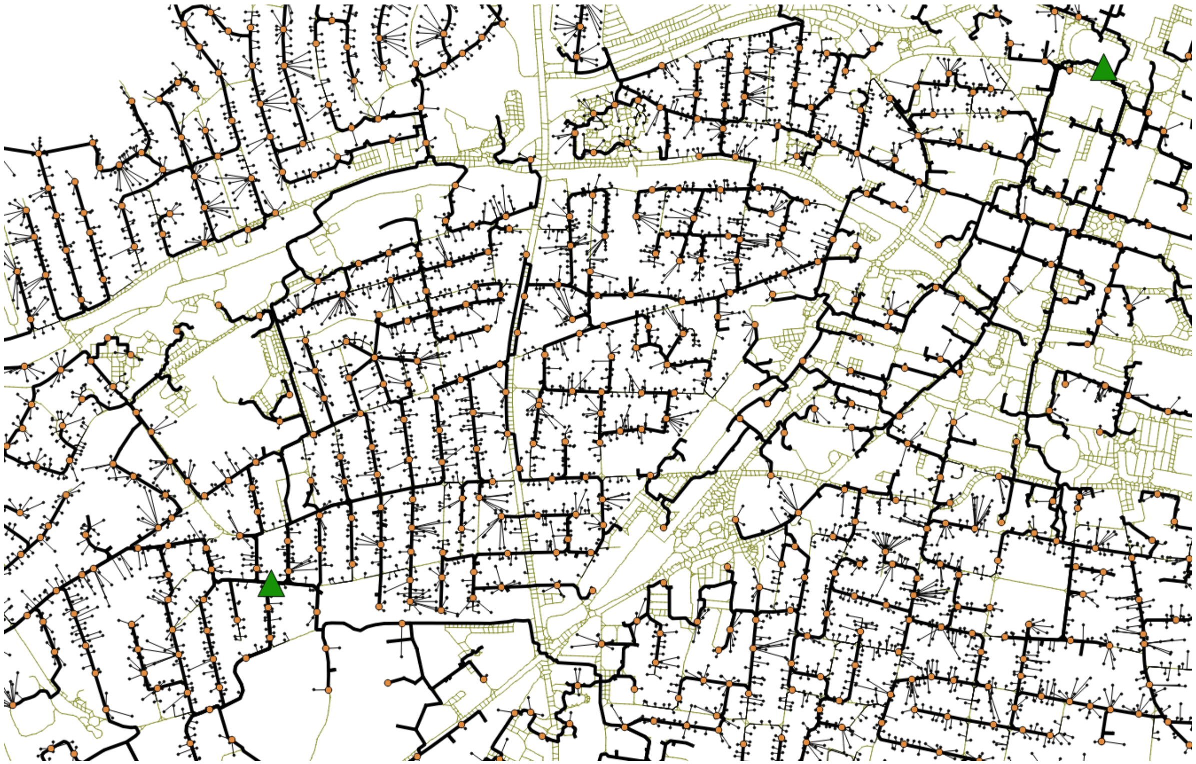
- Electrical node
  - Consumer
  - Producer
  - Prosumer
- Street

HV/MV Substation

Distribution transformer

Three-phase low voltage

RNM places MV lines from HV/MV substations to distribution transformers



- Electrical node
  - Consumer
  - Producer
  - Prosumer

Street

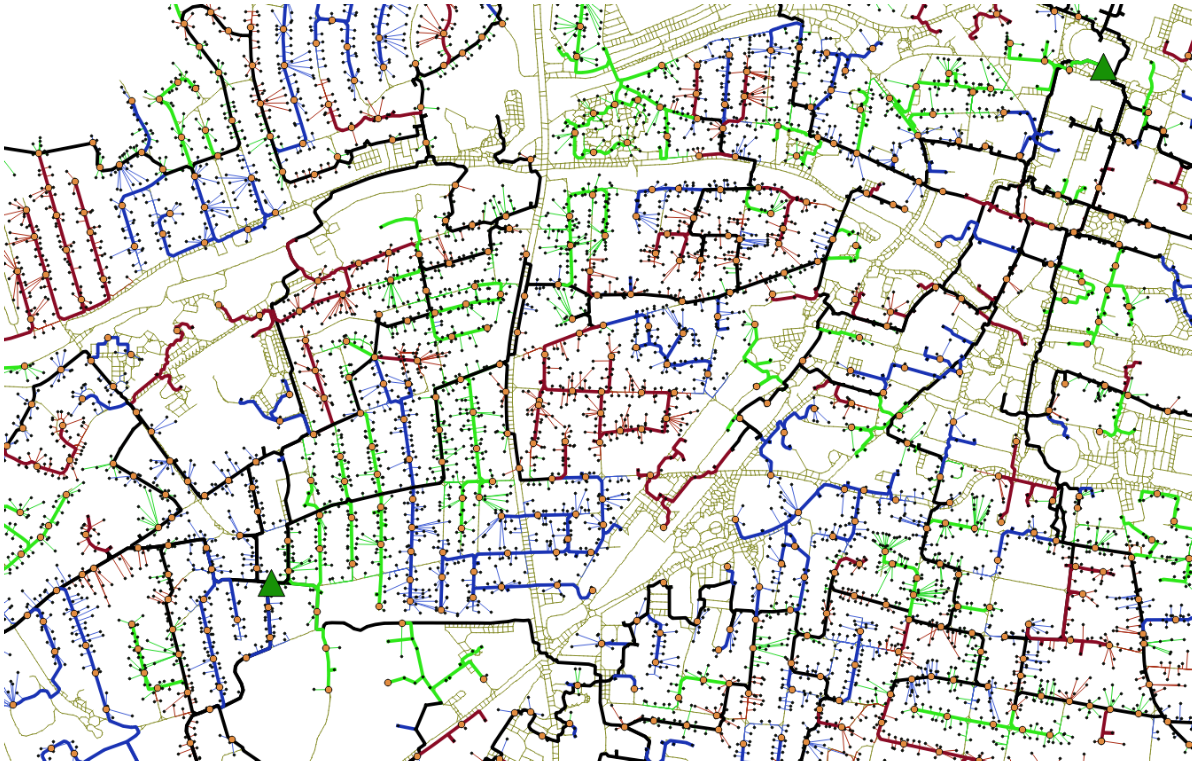
HV/MV Substation

Distribution transformer

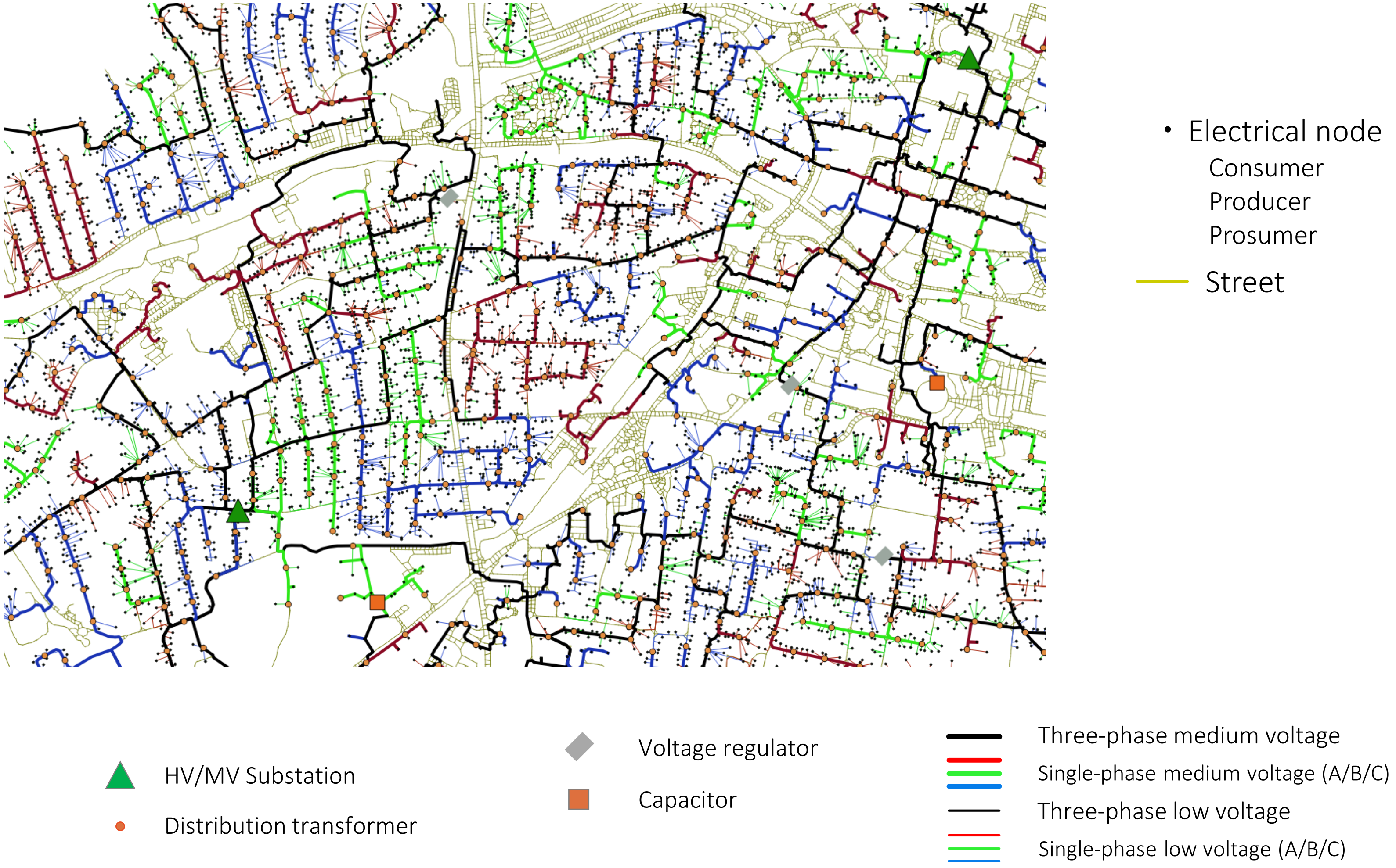
Three-phase medium voltage

Three-phase low voltage

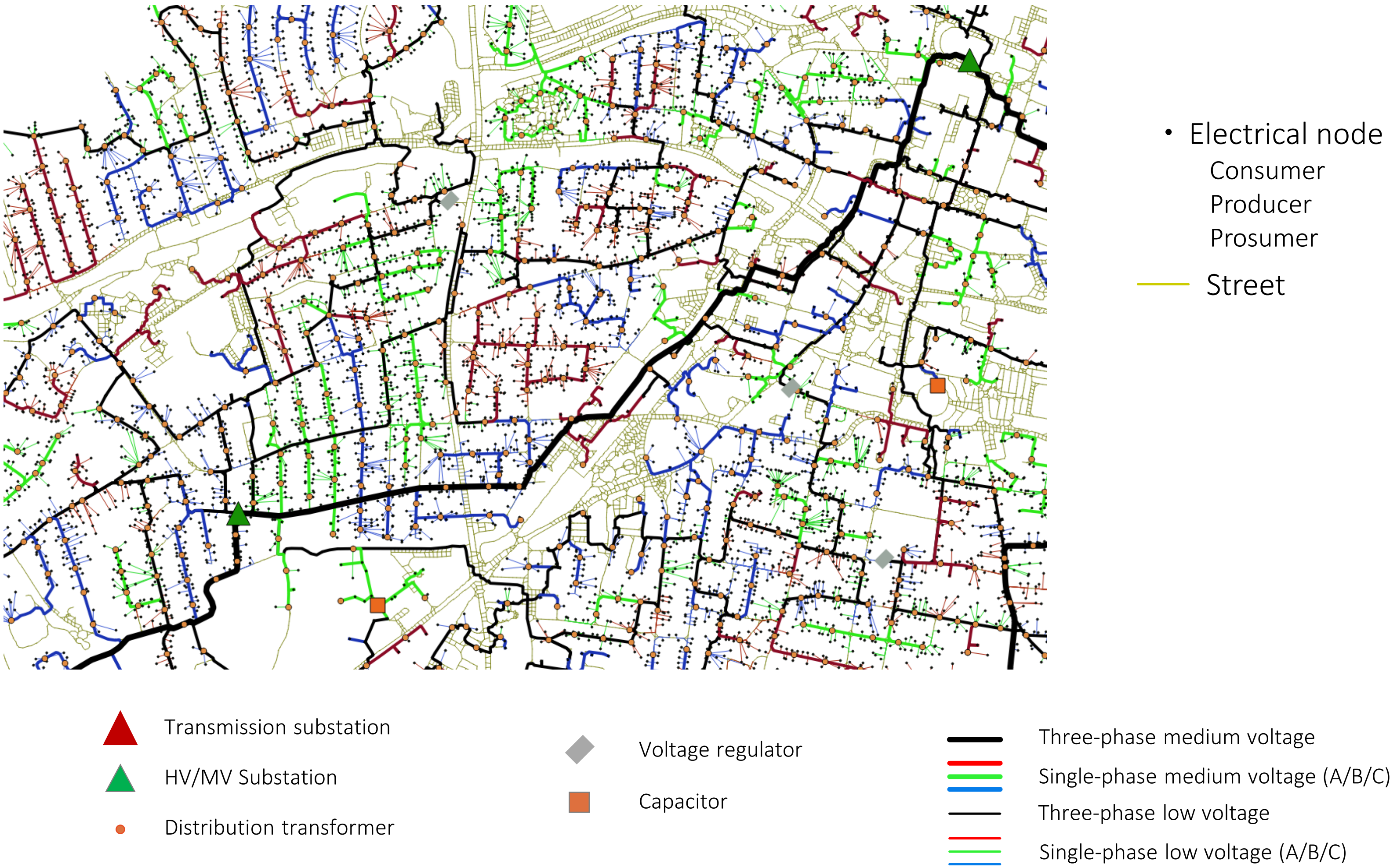
RNM decides on the phase, or number of phases, that feeds each consumer



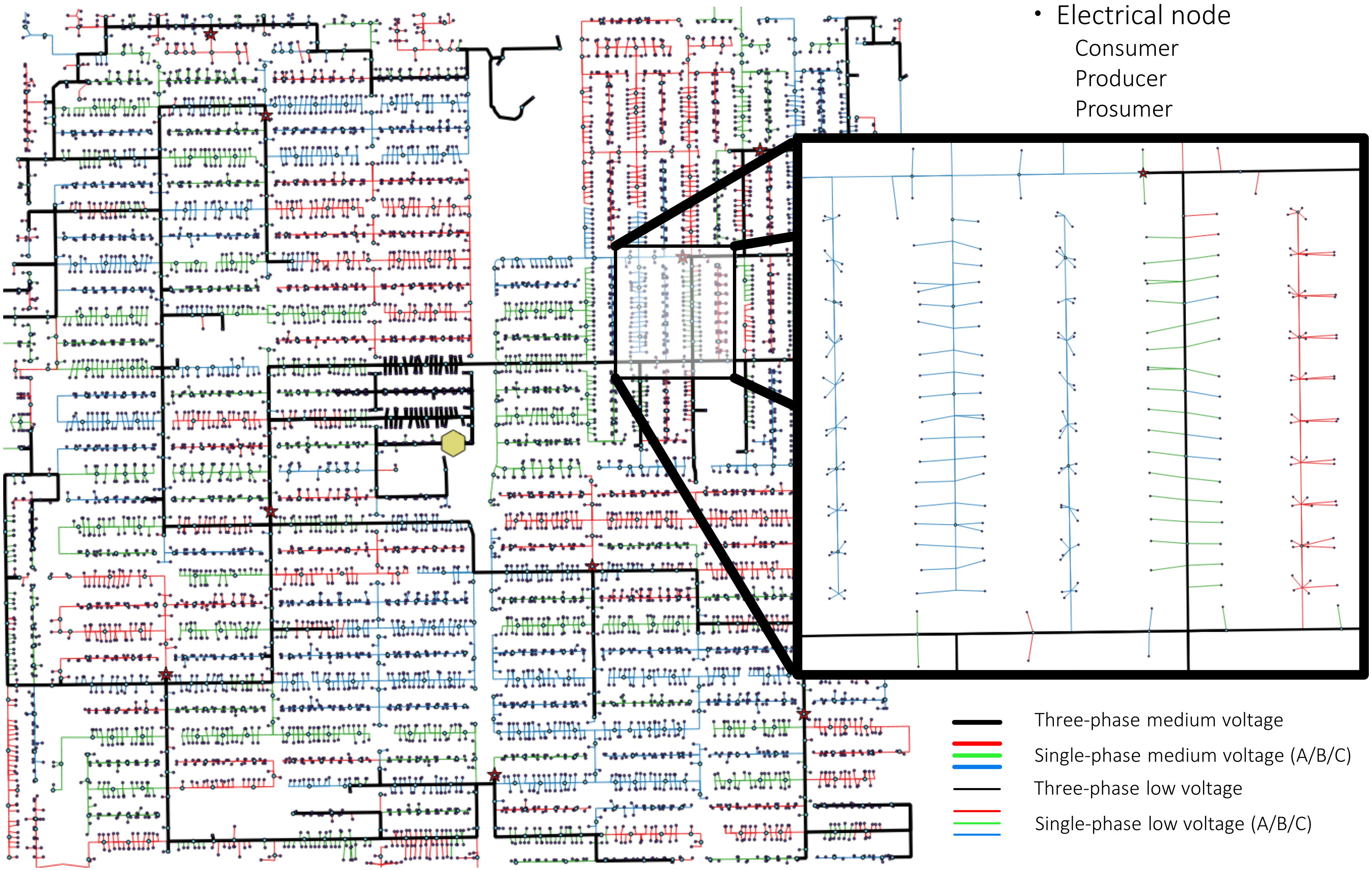
RNM installs capacitors and voltage regulators to alleviate voltage constraints



RNM places sub-transmission lines and adds transmission substations if needed



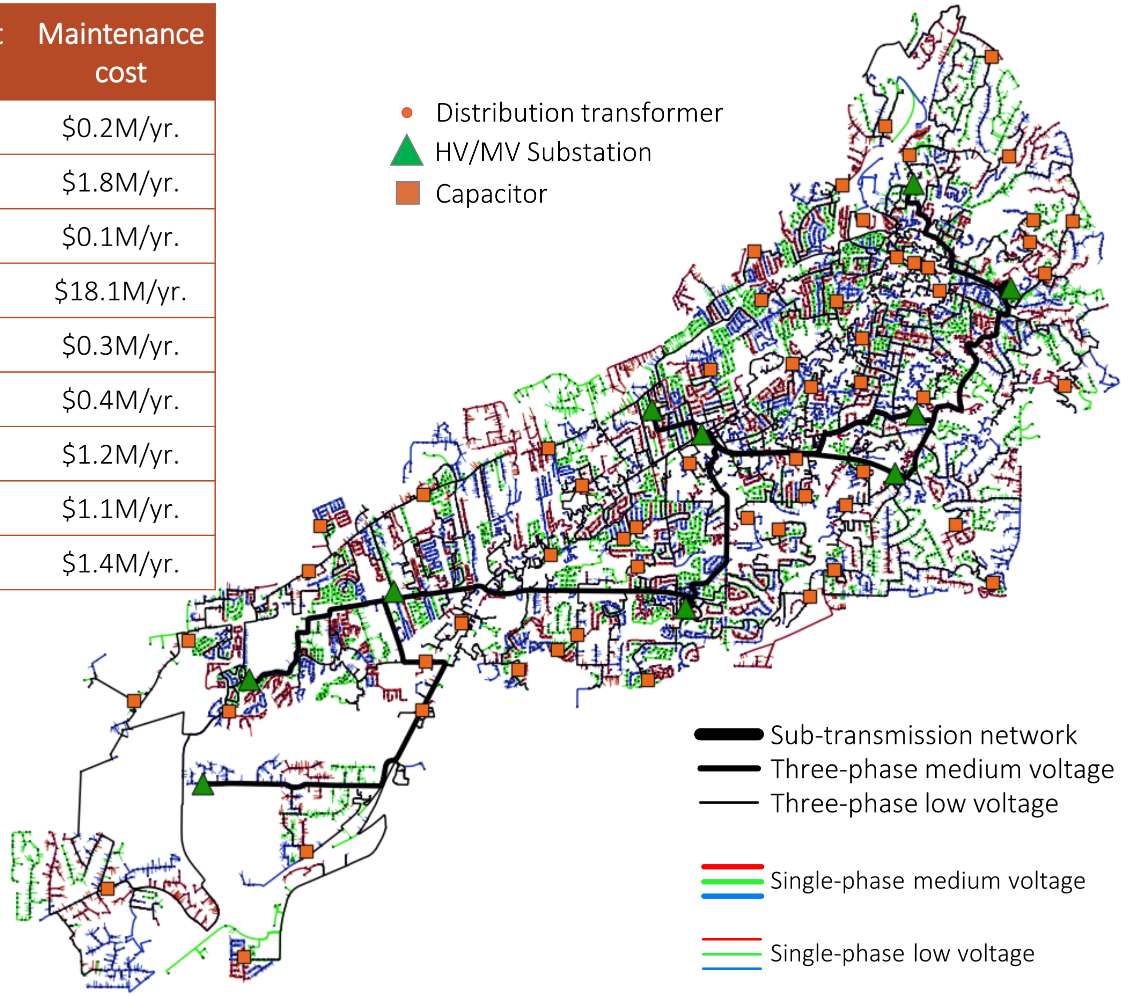
Another example of a neighborhood in Chicago (IL)



Identifying and decomposing distribution costs is key for techno-economic analysis

Equipment	Number	Investment cost	Maintenance cost
HV lines	43 km	$21.3M	$0.2M/yr.
MV lines	945 km	$175.4M	$1.8M/yr.
LV lines	982 km	$9.3M	$0.1M/yr.
Switches	6,054	$181.6M	$18.1M/yr.
Re-closers	58	$3.5M	$0.3M/yr.
Breakers	68	$4.1M	$0.4M/yr.
Fuses	1,263	$12.6M	$1.2M/yr.
HV/MV substations	10	$40.2M	$1.1M/yr.
Distr. transformers	10,548	$52.3M	$1.4M/yr.

Greatly useful as benchmark for distribution remuneration

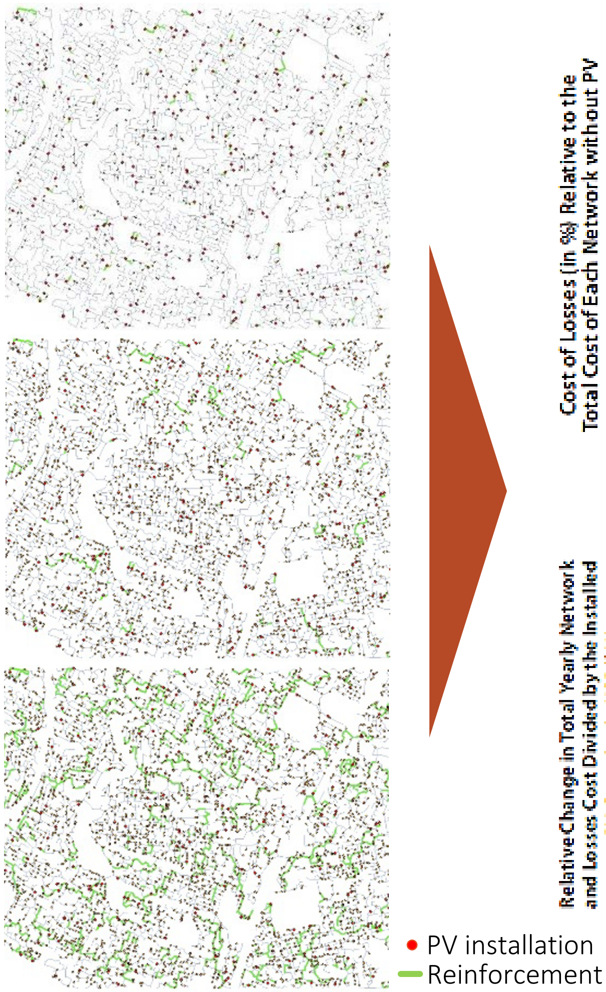


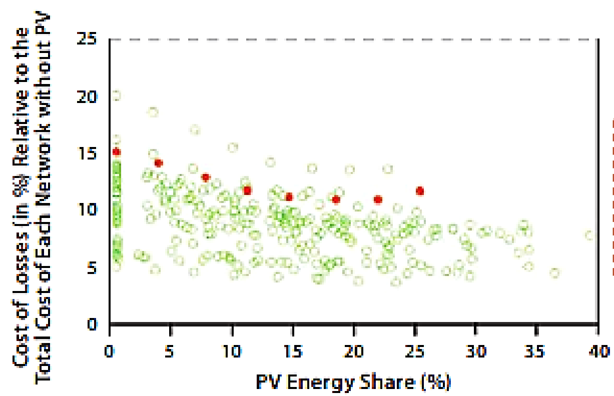
Examining potential impact of intermittent generation in network costs

5% PV energy

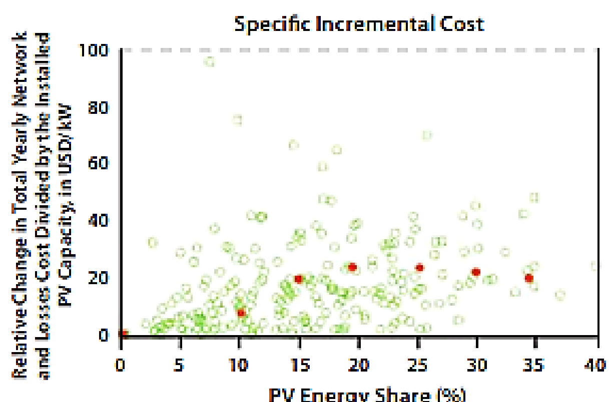
15% PV energy

25% PV energy





PV may generate additional costs due to network losses

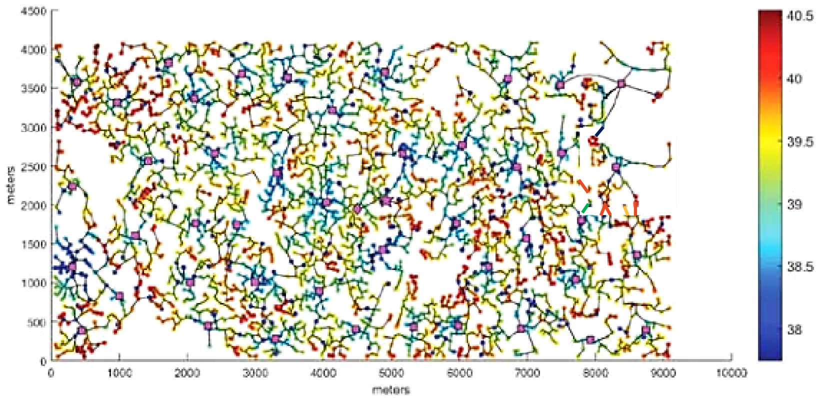


PV may cause additional costs due to reinforcements

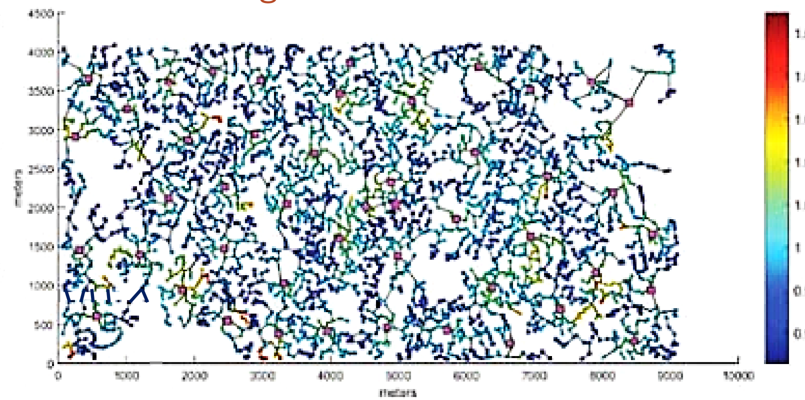
The Future of Solar Energy, MIT Energy Initiative

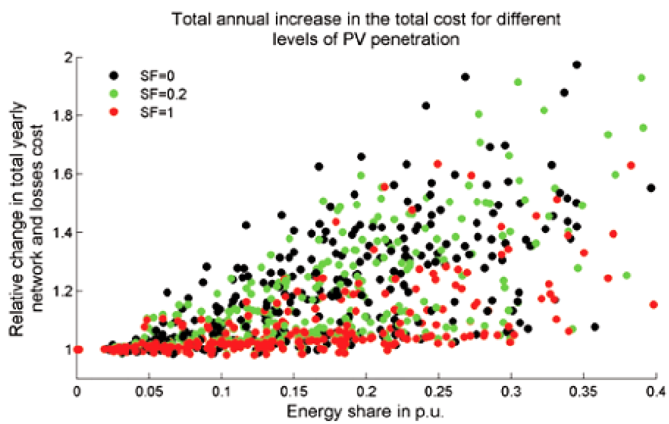
Smartly placing batteries to support renewable integration

Power congested locations



Voltage constrained locations





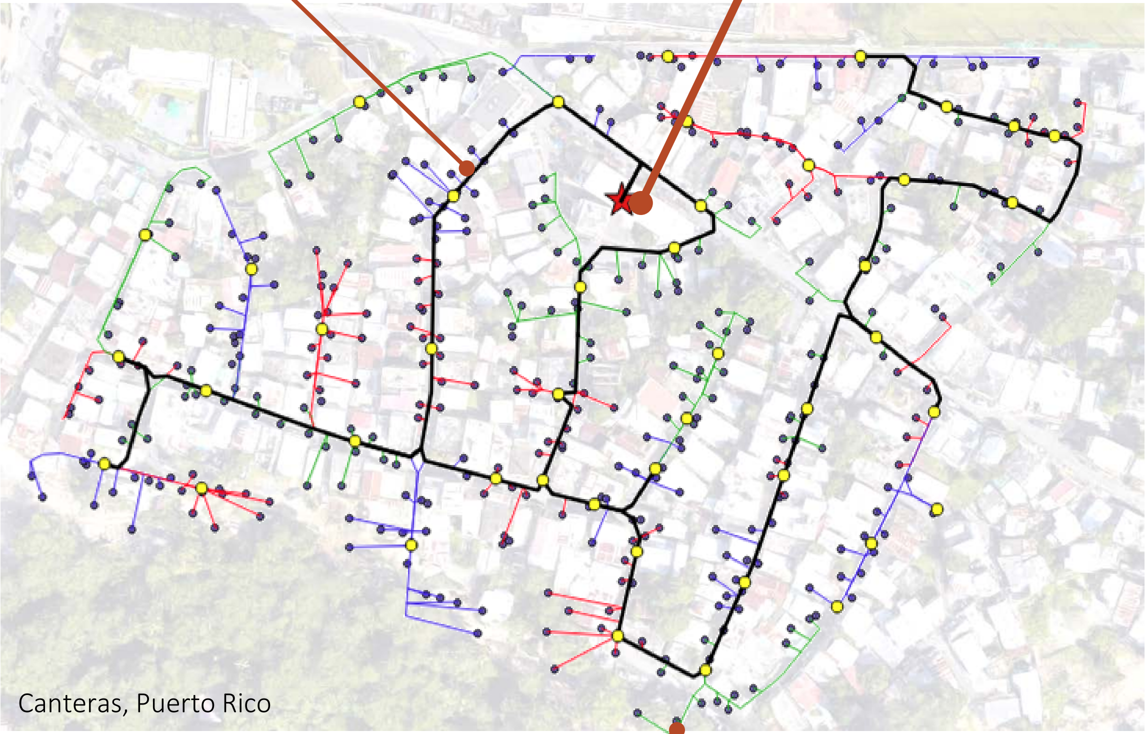
Network costs decrease as long as storage capacity is progressively installed in a network with presence of PV installation. The highest network costs show up when no storage capacity is installed (SF=0). Even when storage capacity is equal to PV capacity (SF=1), locating batteries incorrectly diminishes their cost-mitigation effect.

Utility of the Future, MIT Energy Initiative

Designing microgrids with distributed generation for a resilient distribution grid

Power lines and transformers are underground to avoid being affected by future hurricanes

Distributed generation is placed in critical demand centers, such as hospitals, schools or shelters.

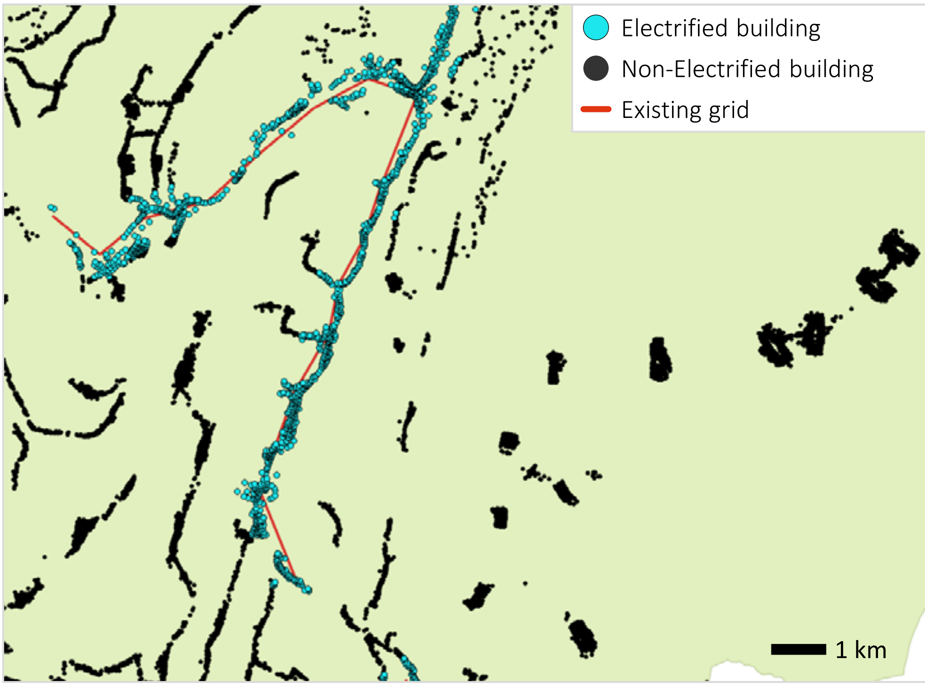


After hurricane Maria, Puerto Rico has experienced continuous blackouts. Hardened microgrids with distributed generation can help to mitigate the effects of hurricanes by maintaining a minimum service

Every individual household receives energy enough for the refrigerator, few hours of AC during the afternoon and some additional loads (lighting, leisure)

Distribution networks and technologies may look different in developing countries

Is a comprehensive method for universal energy access possible?



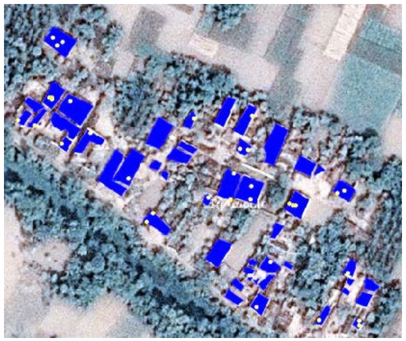
- Electrification mode?
- Technologies?
- Service “tier”?
- Rate/Tariff structure?
- Subsidy allocation?
- Level of aggregation?
- Time horizon?

An electrification plan is a mix of on- and off-grid solutions to provide reliable and reasonable access to all at minimum cost subject to techno-economic aspects and social, political and regulatory implications

The economics that defines the adequate electrification mode

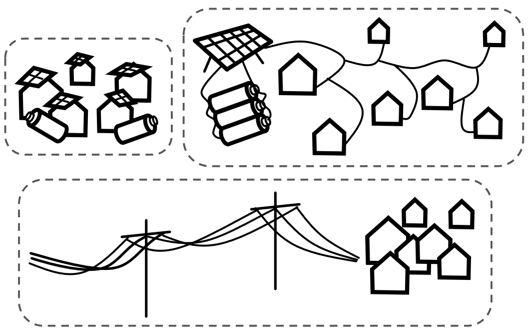
- On-grid solution
  - Investment & operation costs of new grid
  - Reinforcements of existing grid
  - “Upstream” cost of grid-supplied electricity
  - Cost of non served energy
- Off-grid solution
  - Microgrids
    - Investment & operation costs of generation and storage
    - Investment cost of network
    - Cost of non served energy
  - Stand-alone systems
    - Investment & operation costs of generation and storage
    - Cost of non served energy

The Reference Electrification Model (REM) enables powering non-electrified areas



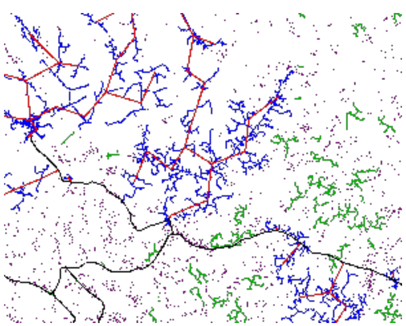
Data preparation

Machine vision and Artificial Intelligence to identify customers and the associated characteristics (type, demand, electrification status) in unmapped areas



Optimization

Large-scale optimization to design the appropriate access infrastructure for each consumer through standalone systems, microgrids or grid extension



Processing and implementation

Governments, utilities, and private firms use detailed system designs to implement solutions in the field

What does REM need to build an implementable electrification plan?

Local data

- **Buildings** location, status, type
- **Network** LV/MV layout, reliability, cost
- **Demand** growth, hourly annual pattern
- **Weather** solar potential
- **Topography** elevation, protected zones

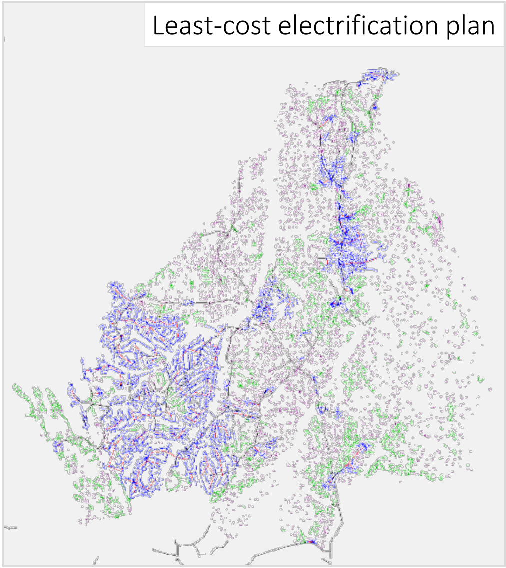
Equipment data

- **Electricity generation** diesel, PV
- **Batteries**
- **Power electronics** inverter, controller
- **Network equipment** lines, transformers

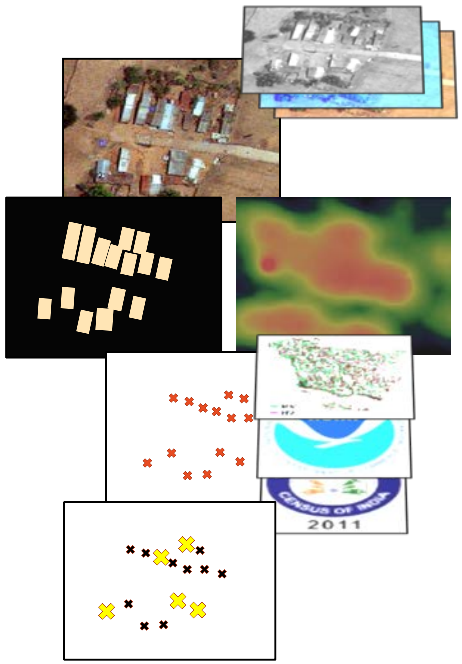
User preferences

- **Finance** discount rate, years, NSE cost, economies of scale
- **Operational strategy** cost-based, load following, cycle charging

REM


Least-cost electrification plan

Input preprocessing for REM - Building location and electrification status



Building Extraction

↓

Load Localization and Characterization

↓

Electrification Status Estimation

↓

Reference Electrification Model

1. Microgrid generation design
2. Clustering process
3. Final design

REM first designs microgrids for different combinations of consumer archetypes

Starting point(s)
0% | 100% diesel

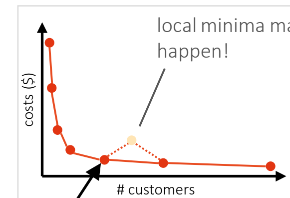
The algorithm starts on a corner of the search space with a given combination of demand patterns.

Master problem
Diesel capacity

Analyzes cost levels with current and previous diesel capacity.
Determines initial point for the slave problem.

Optimum reached?

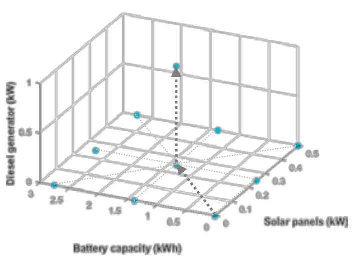
Yes → **Solution**

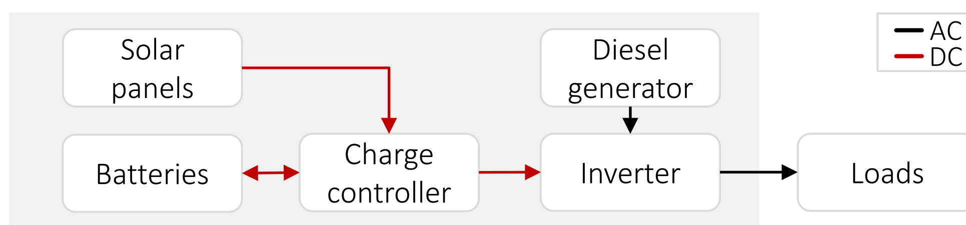


No → **Slave problem**
Battery & PV capacity

Compares cost levels for both previous and current solutions of the master problem.

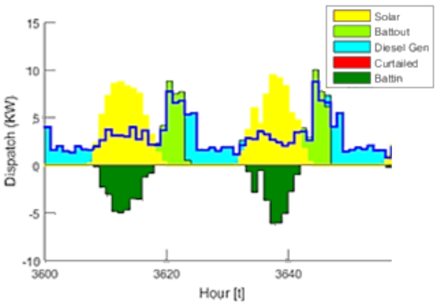
Decides optimum battery and PV generation capacity for current diesel level.



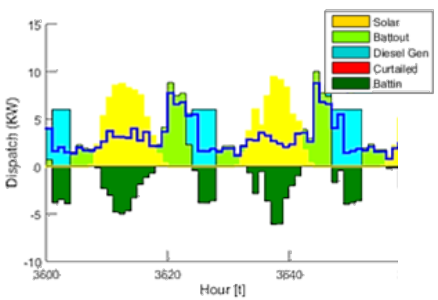


REM considers real control strategies when designing the microgrids

Load following



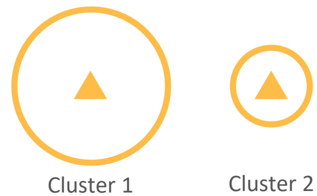
Cycle charging



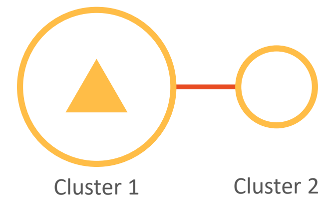
- Real controllers embed some simple priority rules instead of optimization-based rules
  - When charging/discharging the battery?
- Optimization based on this heuristic dispatch strategies
  - Opportunity cost. The priority depends on the battery SOC, which equals the cost of PV/diesel/NSE.
  - Load following. PV → battery → diesel. Charging the battery only with PV surplus.
  - Cycle charging. PV → battery → diesel. When battery SOC is below a threshold, if the diesel generator is on, it operates at maximum to charge battery.

REM then joins consumers into off-grid clusters to exploit economies of scale

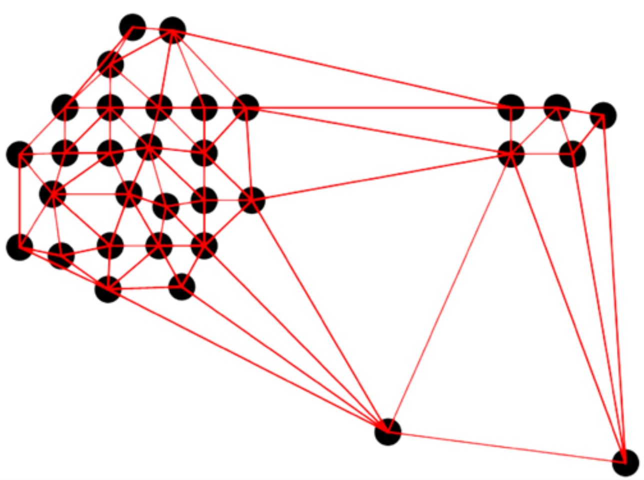
- The Delaunay triangulation connects all consumers in a region
  - Off-grid clustering loop
    1. Select closest neighbor
    2. Join neighbors through real line
    3. Loop until no new connection
  - From shorter to longer arcs
    - Savings from being together

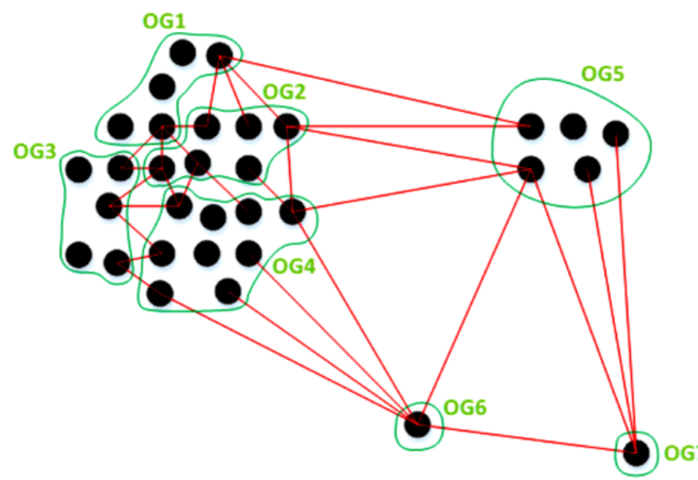


Generation cost of cluster 1
Generation cost of cluster 2
O&M cost of cluster 1
O&M cost of cluster 2



Generation cost of joined cluster
Cost of line that joins clusters
O&M cost of joined cluster

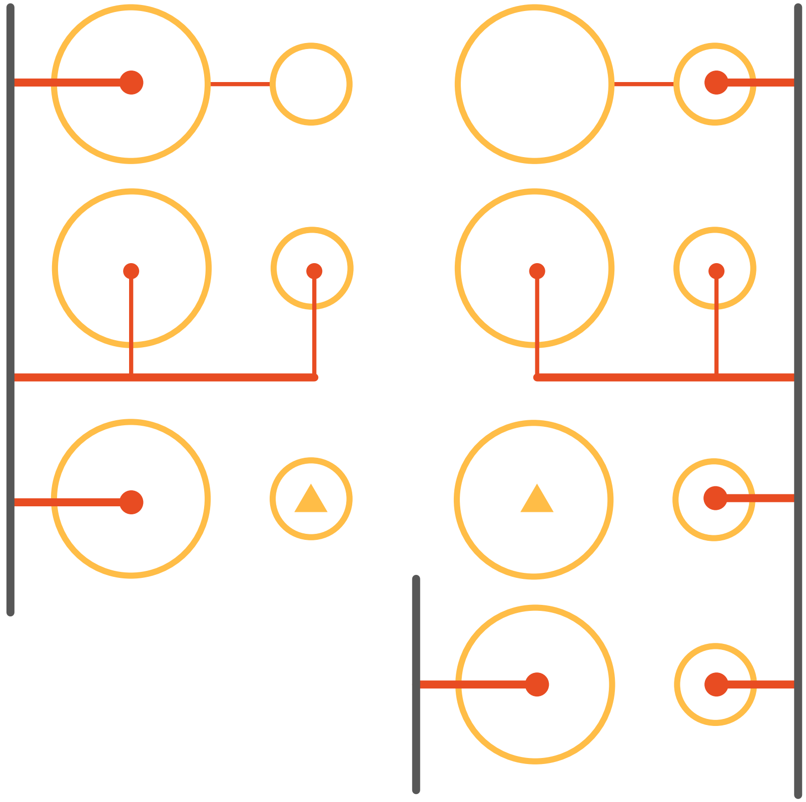




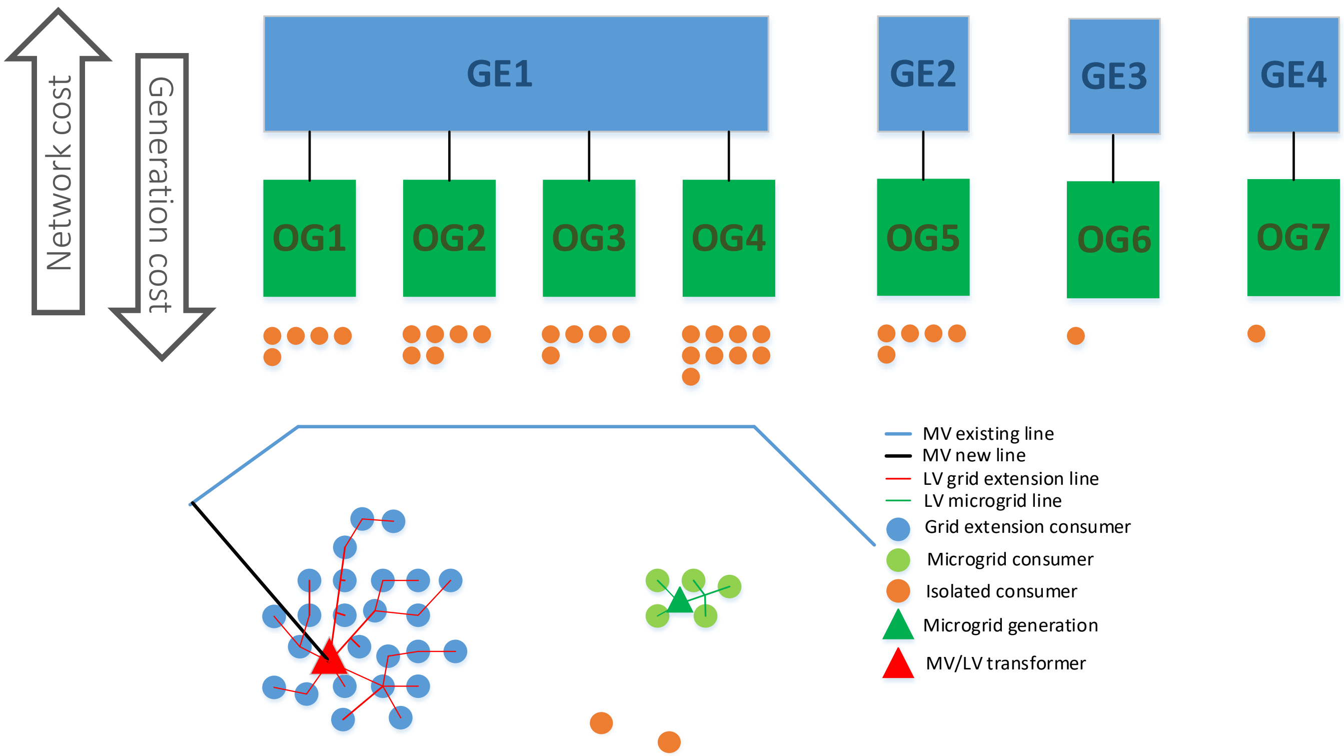
REM later connects, or not, off-grid clusters to the existing grid

- On-grid clustering
  - Clusters of all consumers assuming grid connection is possible
  - From shorter to longer arcs
    - Assuming one is a grid extension
    - Costs of being together

Generation cost of cluster 1
Generation cost of cluster 2
MV/LV transformers
LV (or MV) line from cluster 1 to cluster 2
LV (or MV) line from network to cluster 1
LV (or MV) line from network to cluster 2
Grid energy cost and NSE cost
O&M costs of clusters

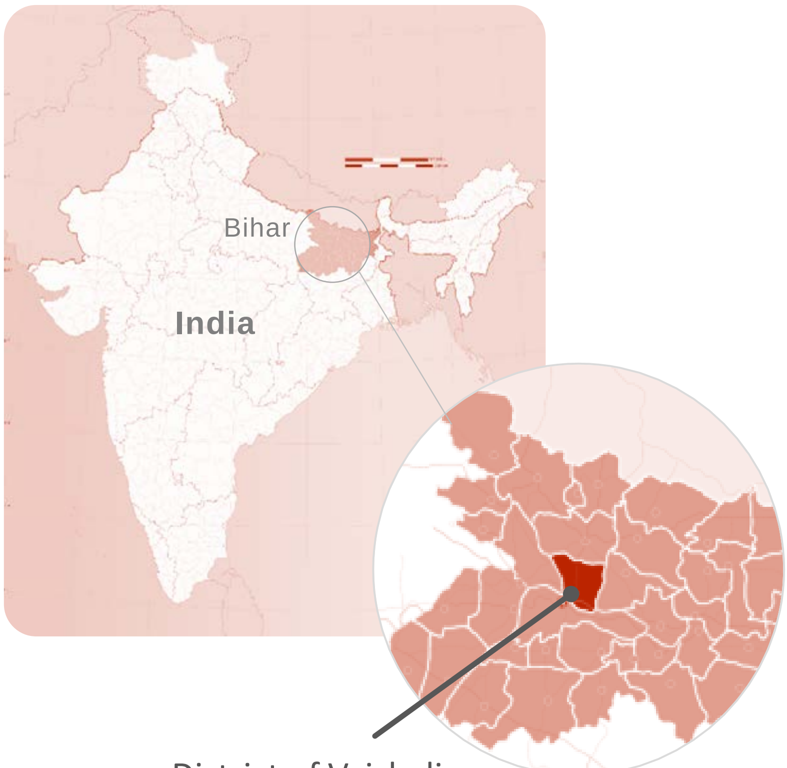


REM finally creates a hierarchical structure of solutions and chooses the best one

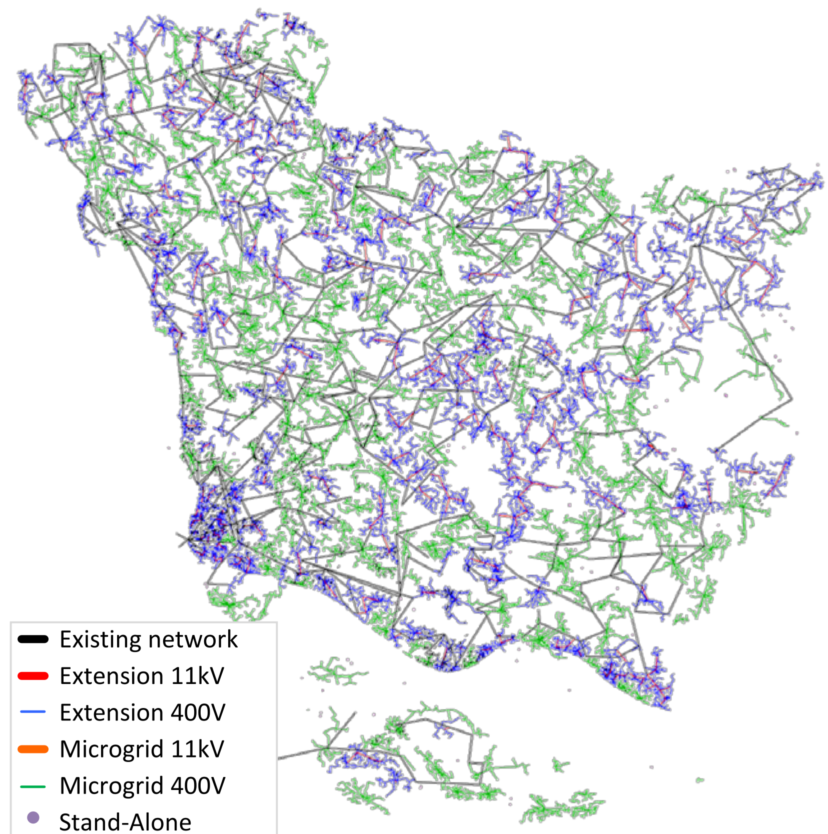


REM evaluates standalone systems, and off- and on-grid clusters to determine the best solution for each consumer which corresponds to the least-cost solution while providing required reliability levels

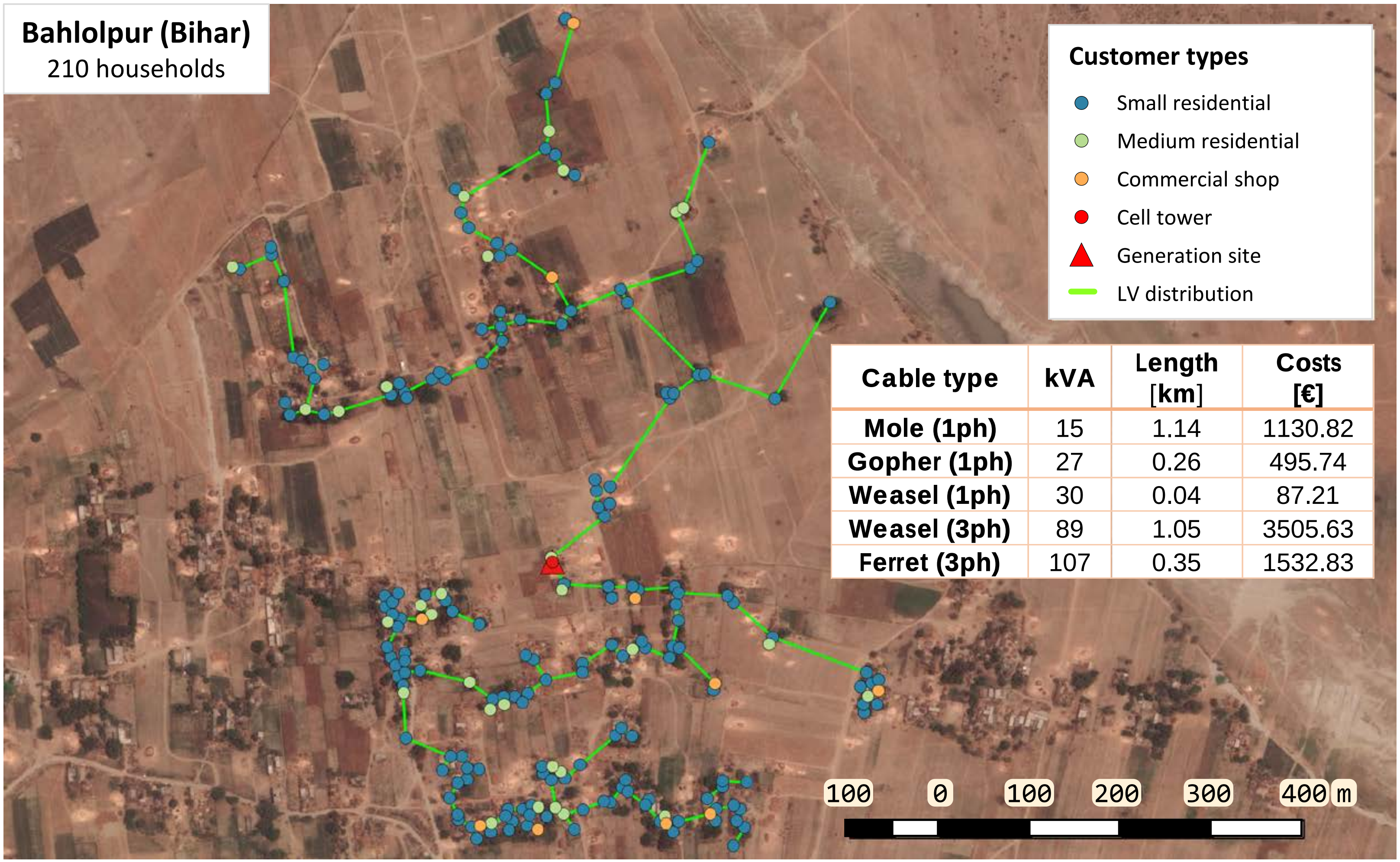
REM provides comprehensive large-scale regional electrification planning



District of Vaishali
~600,000 households

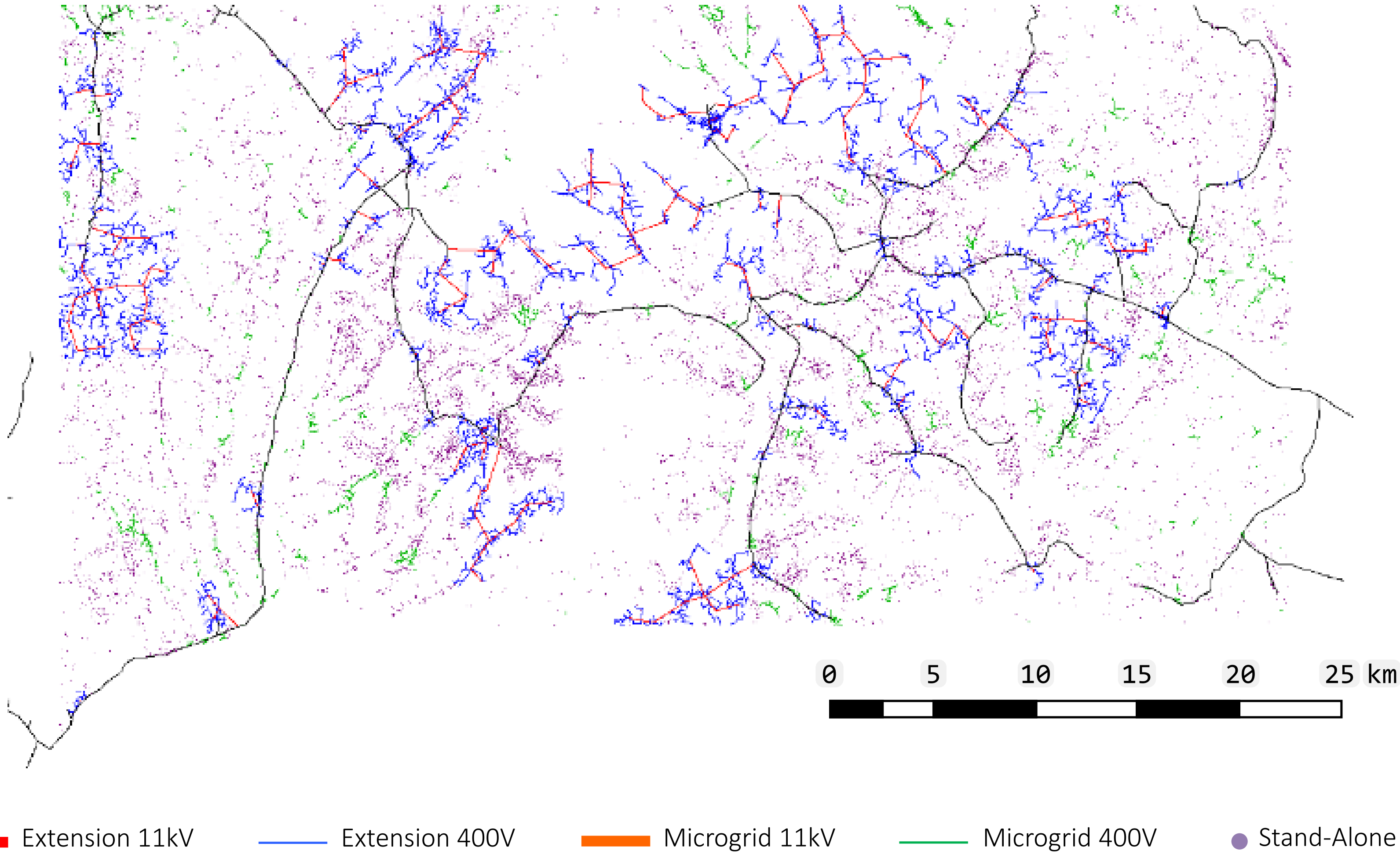


REM provides granular detail about local electrification designs

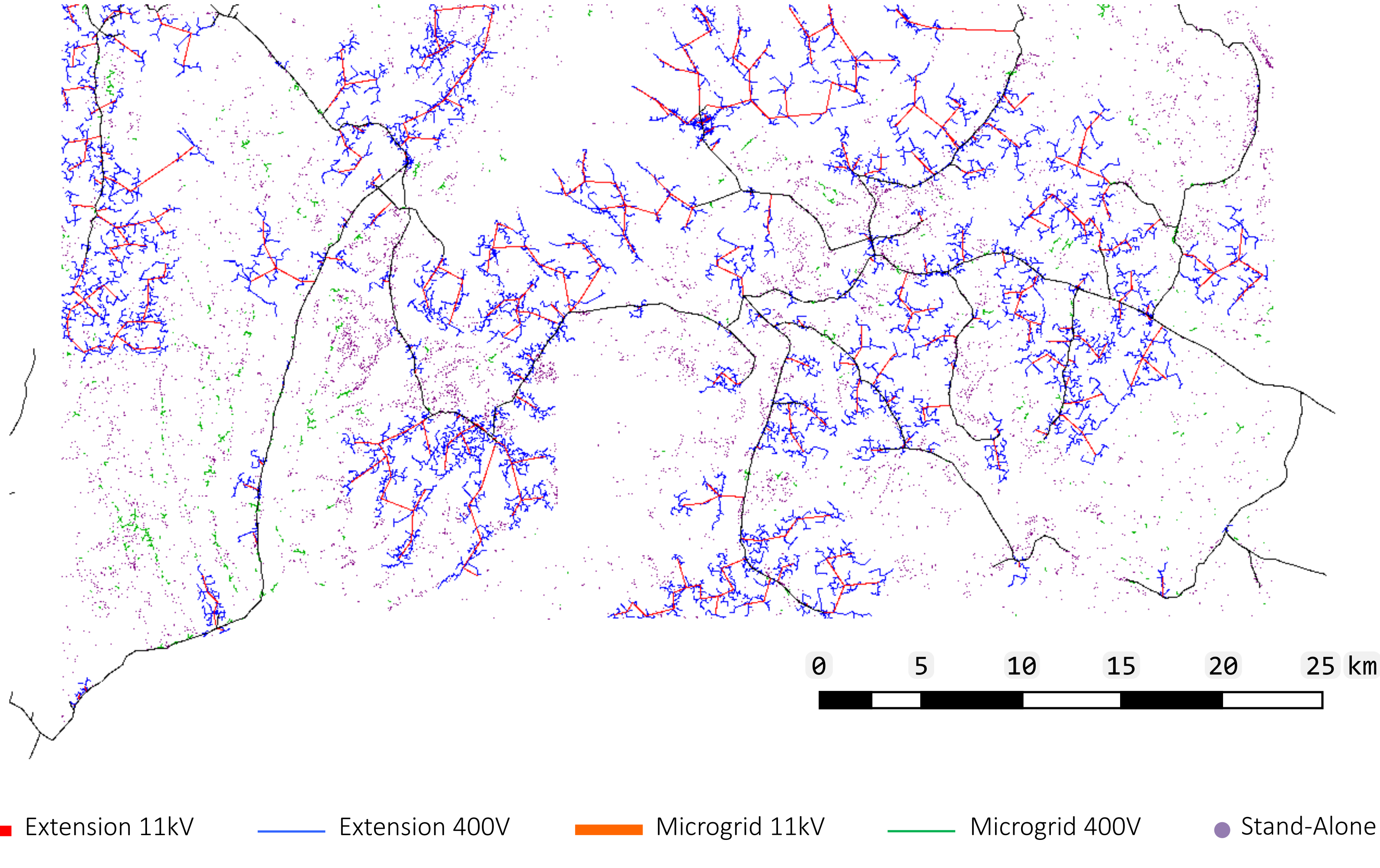


Cable type	kVA	Length [km]	Costs [€]
Mole (1ph)	15	1.14	1130.82
Gopher (1ph)	27	0.26	495.74
Weasel (1ph)	30	0.04	87.21
Weasel (3ph)	89	1.05	3505.63
Ferret (3ph)	107	0.35	1532.83

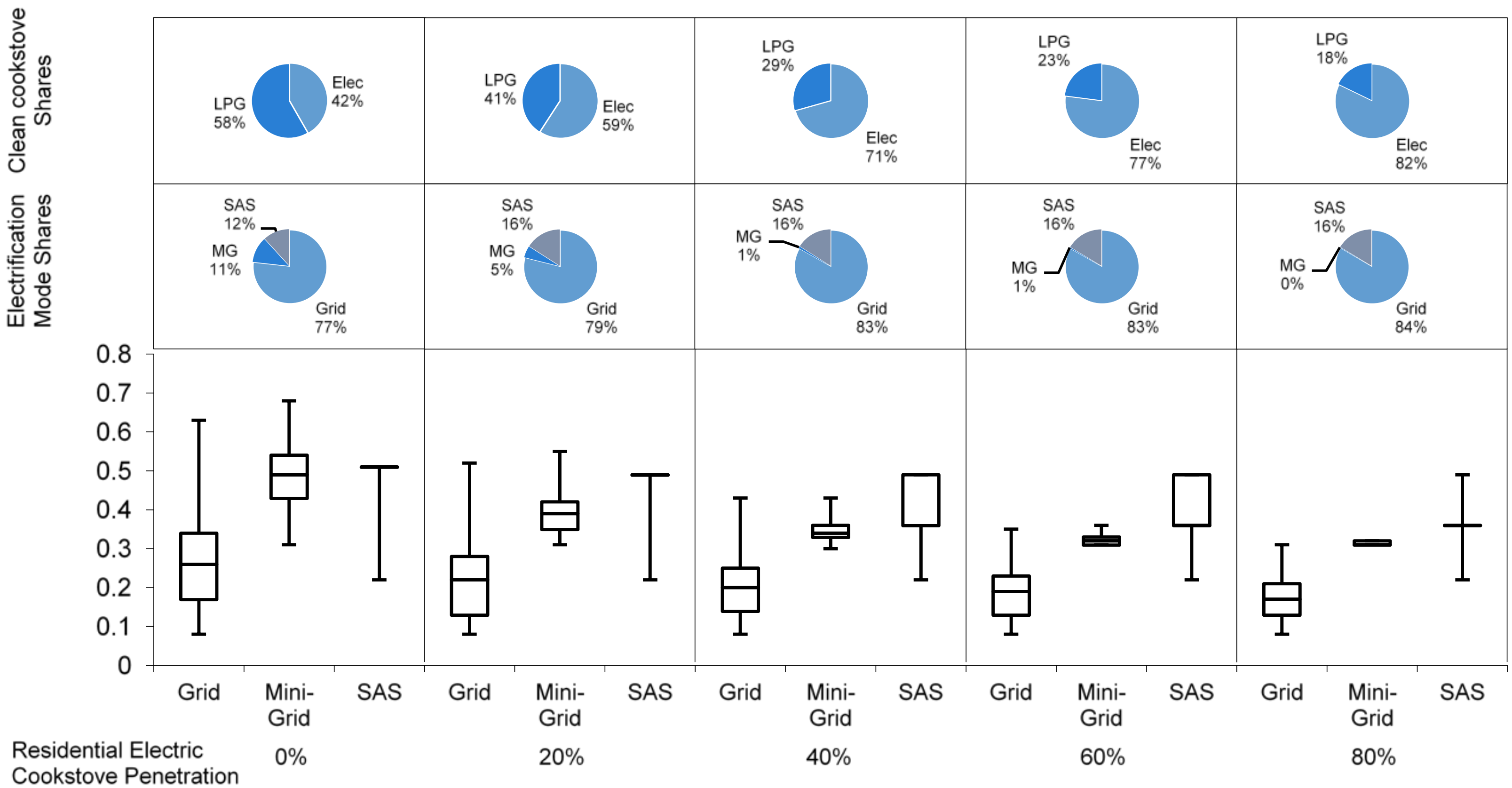
Let's electrify a rectangle in the Southern Territories of Uganda



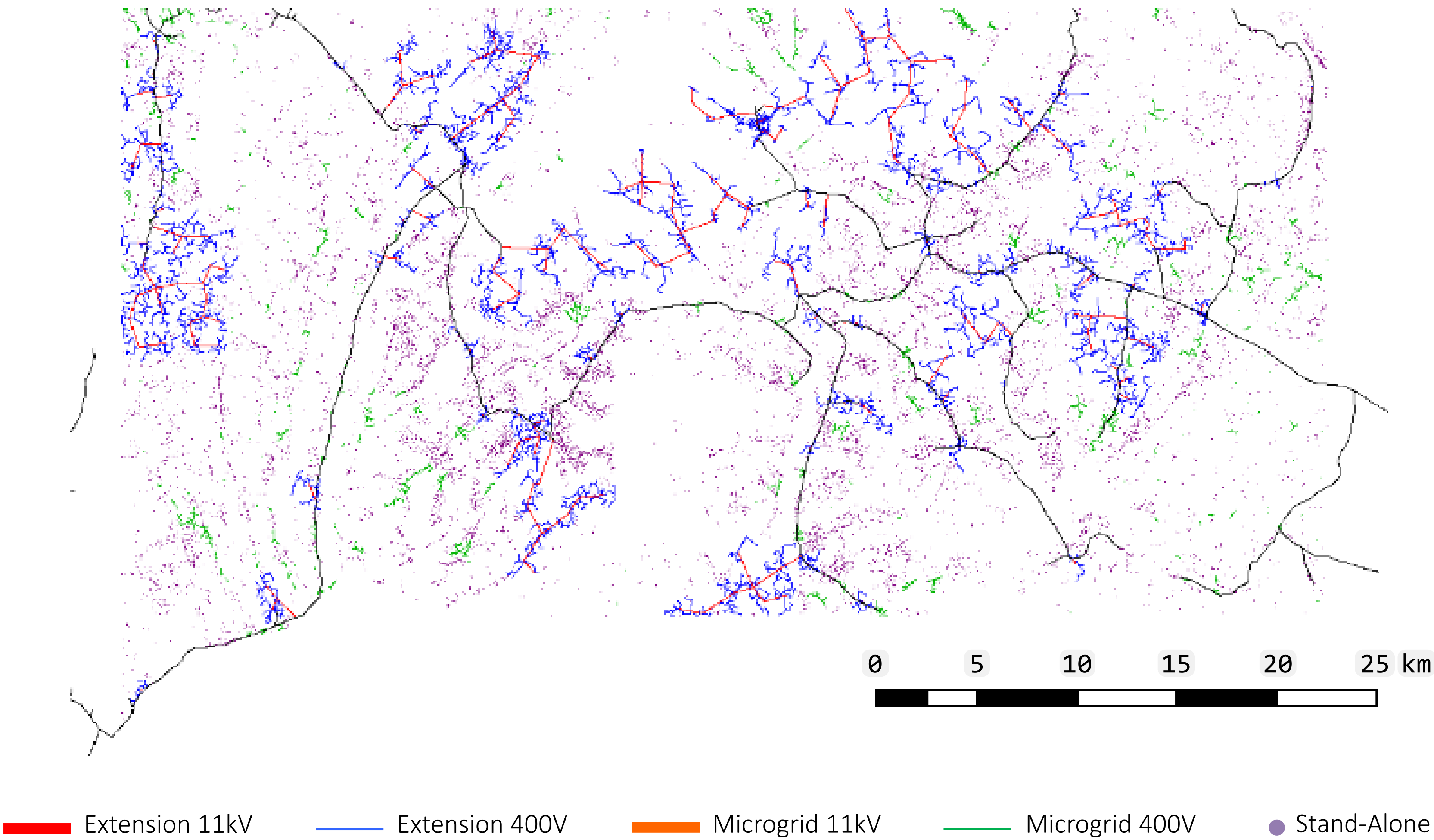
How would the electrification plan change if the demand doubles?



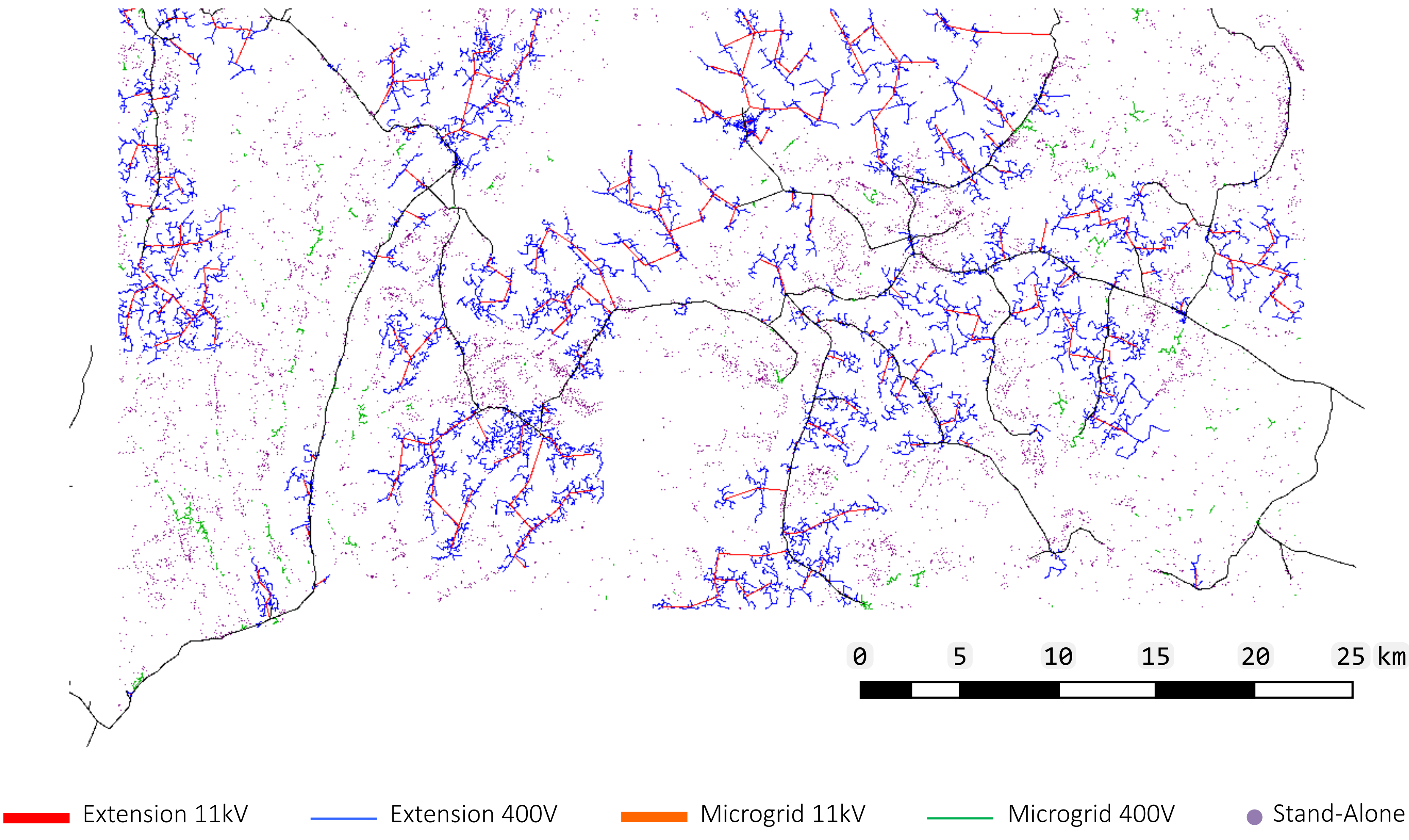
Electrifying the energy needs in the communities is advantageous



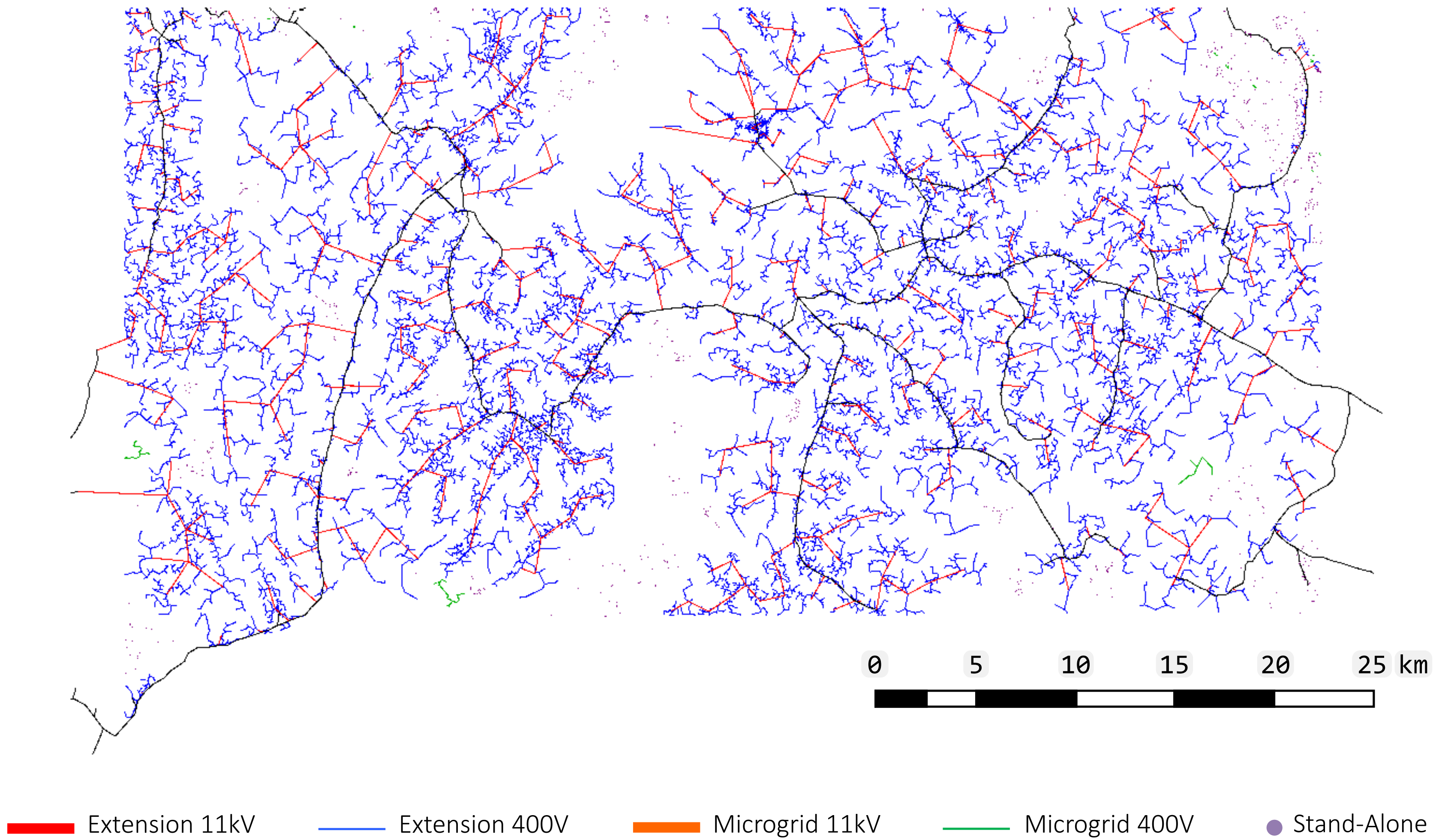
Let’s electrify a rectangle in the Southern Territories of Uganda



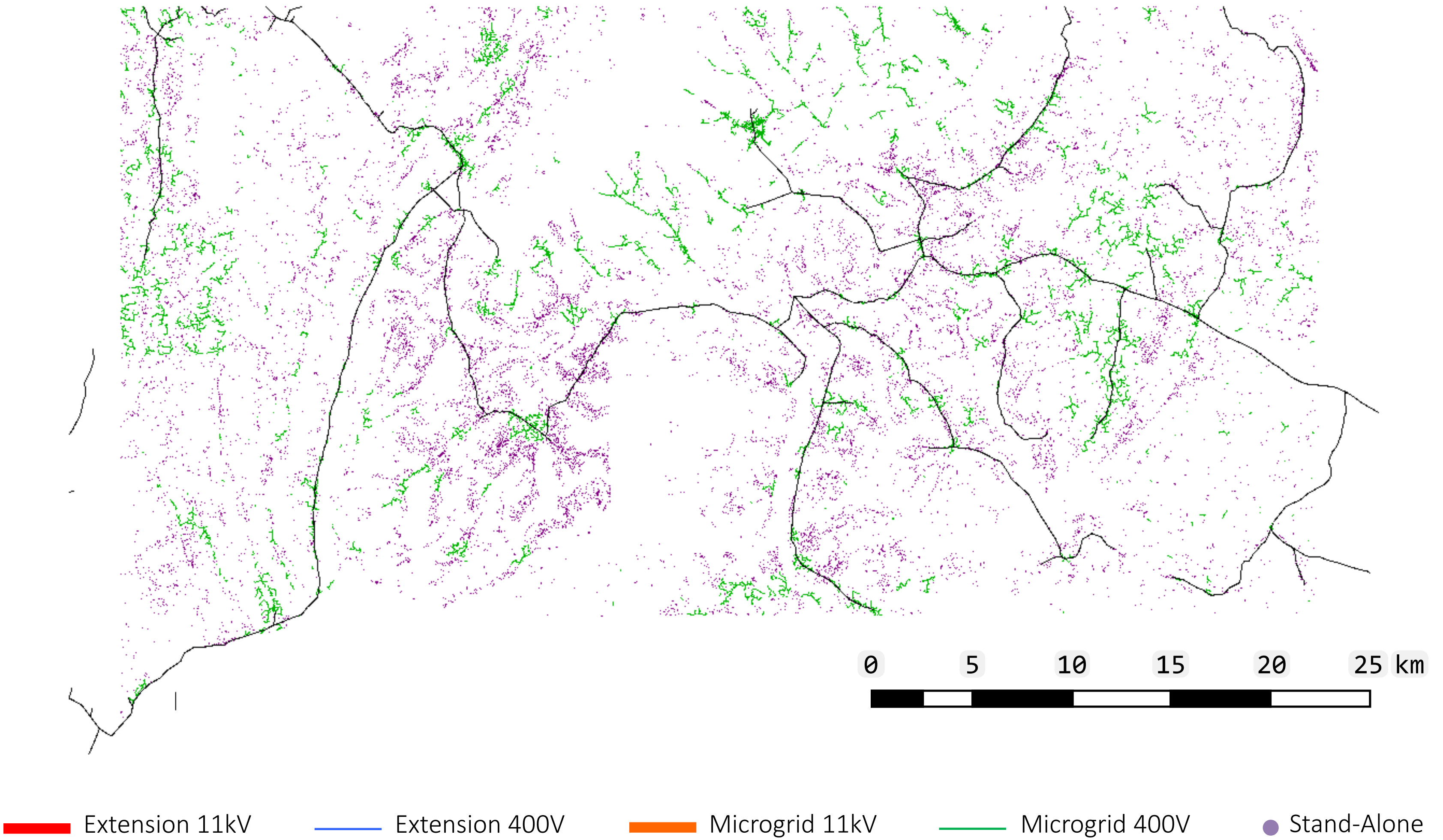
How would the electrification plan change with high grid reliability?



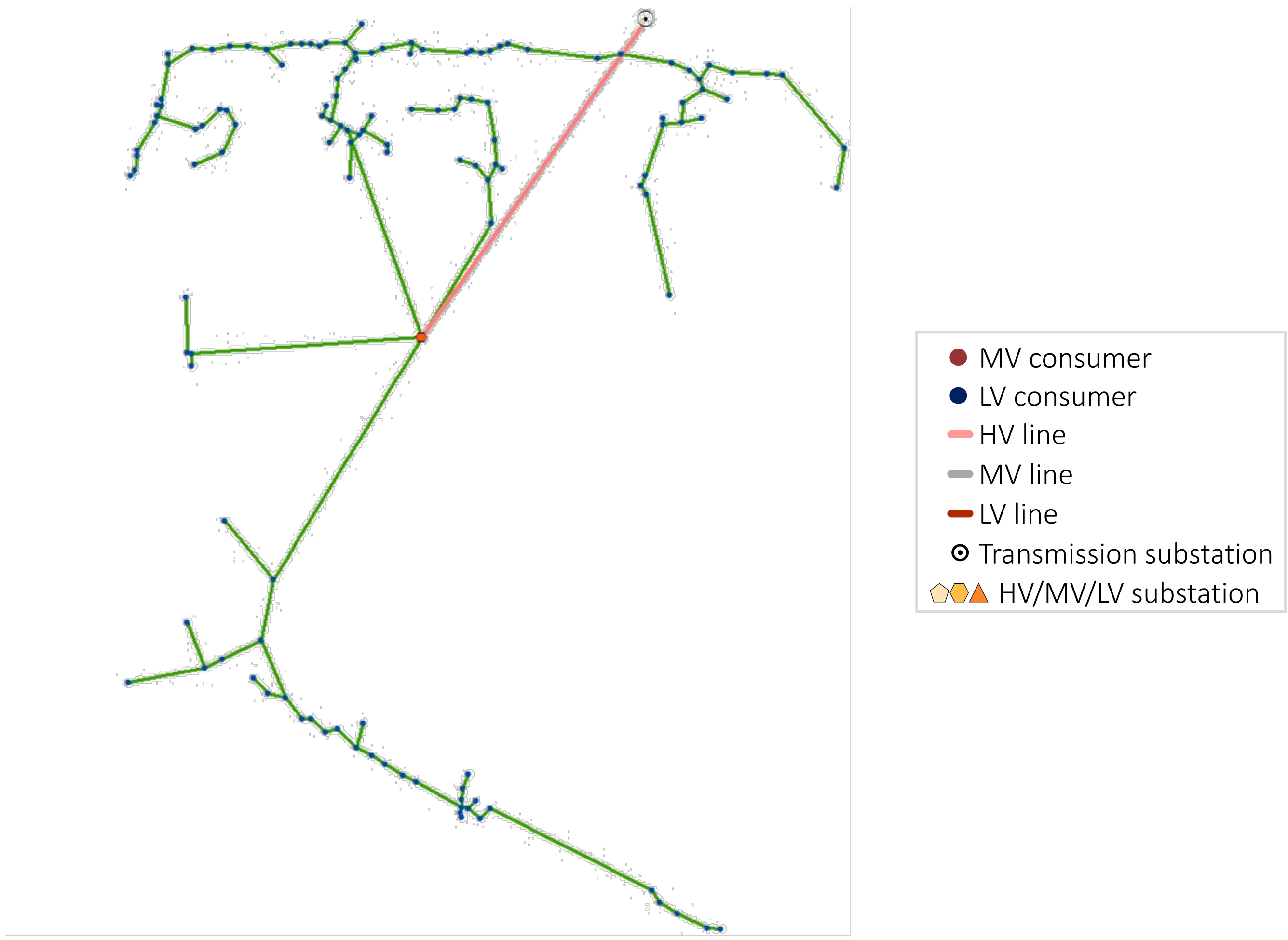
REM can do full grid extension as desired by local governments



REM can also be forced to do full off-grid electrification

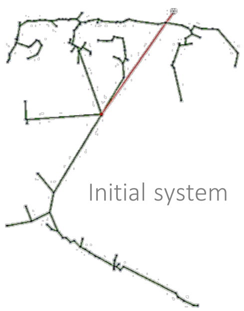


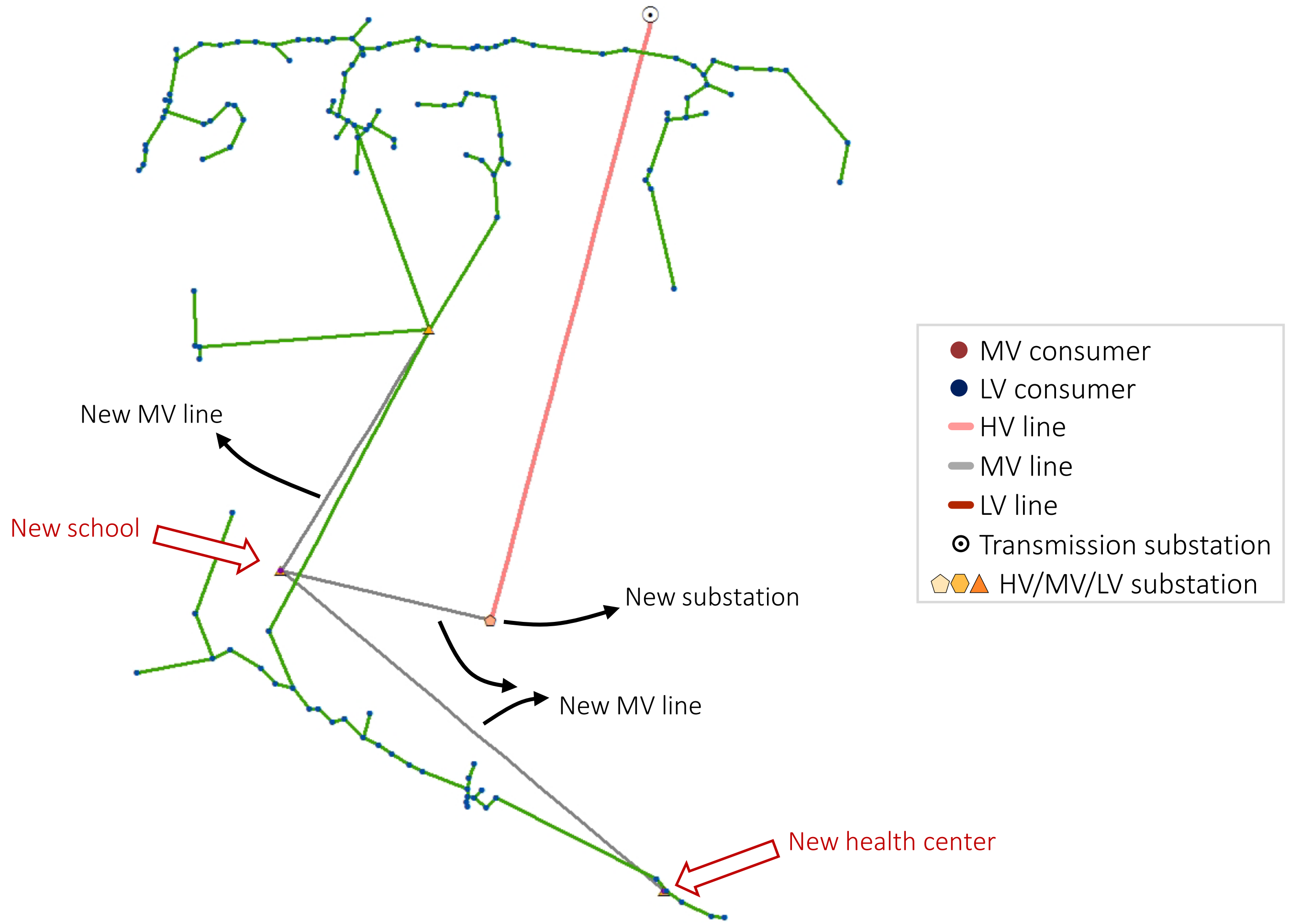
Let's electrify Tayabpur in India through grid extension



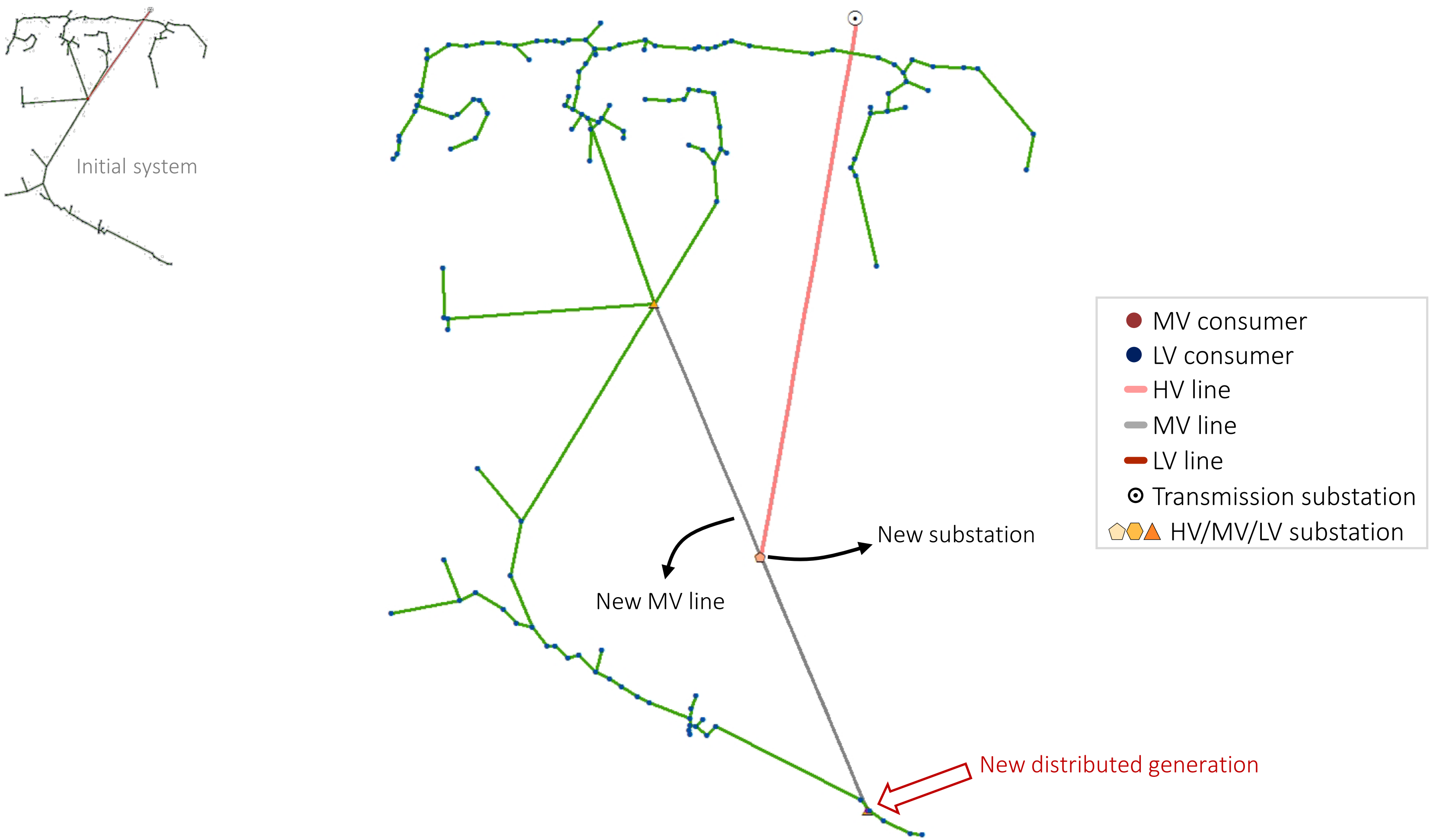
Let’s observe the effect of building a new school in the community

Let's observe the consequences of a new health center in the community

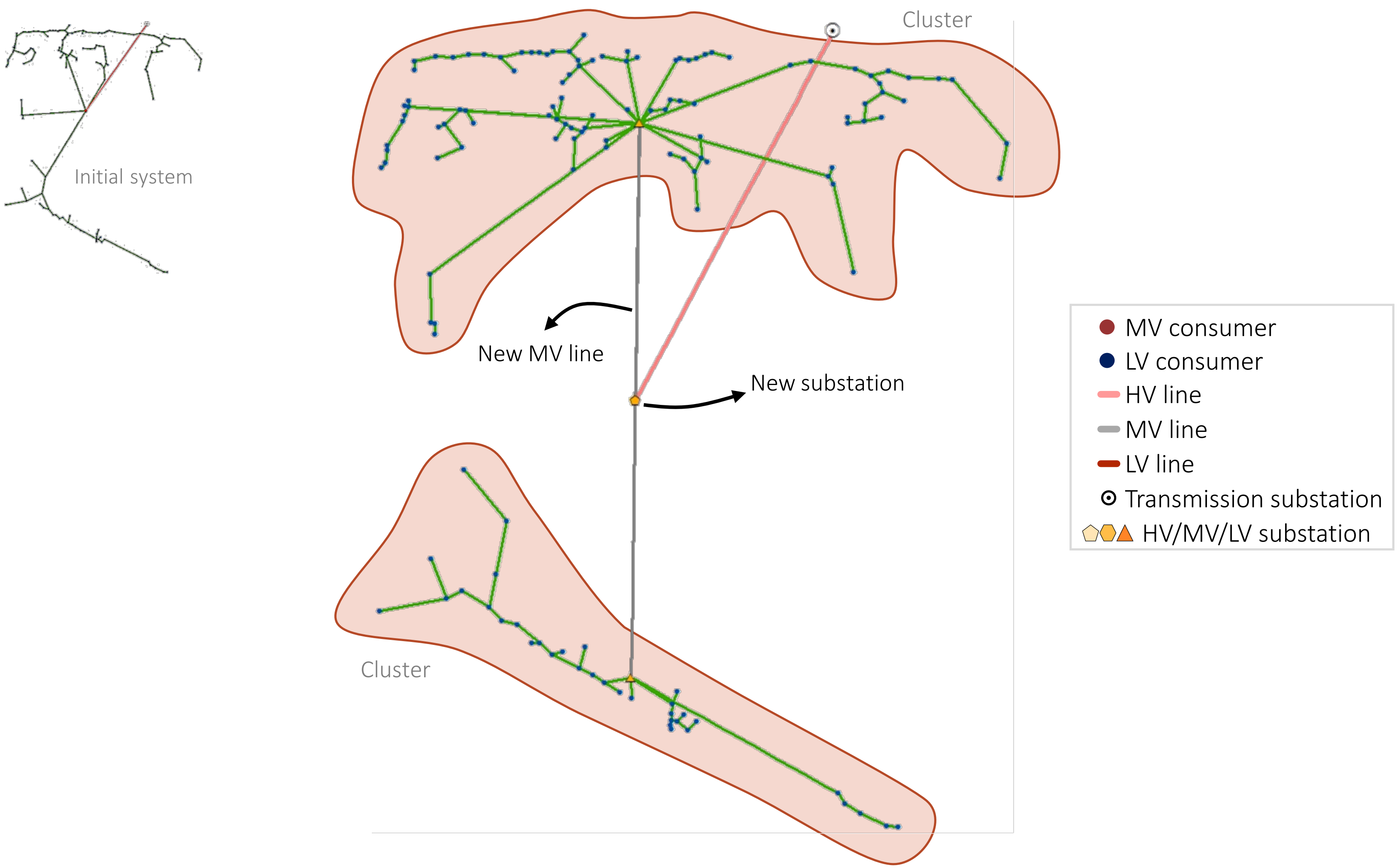




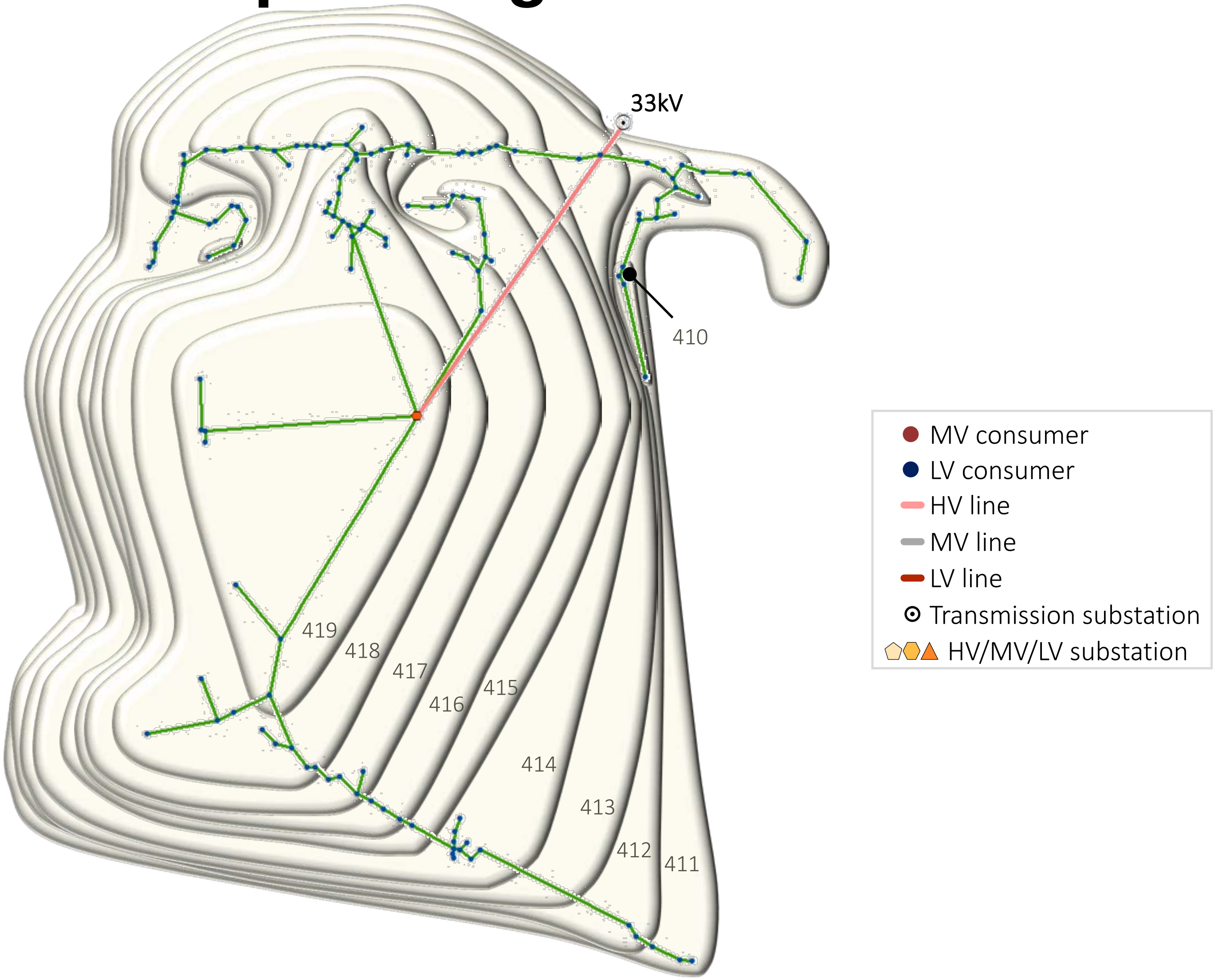
What if we add distributed generation to improve the quality of service?



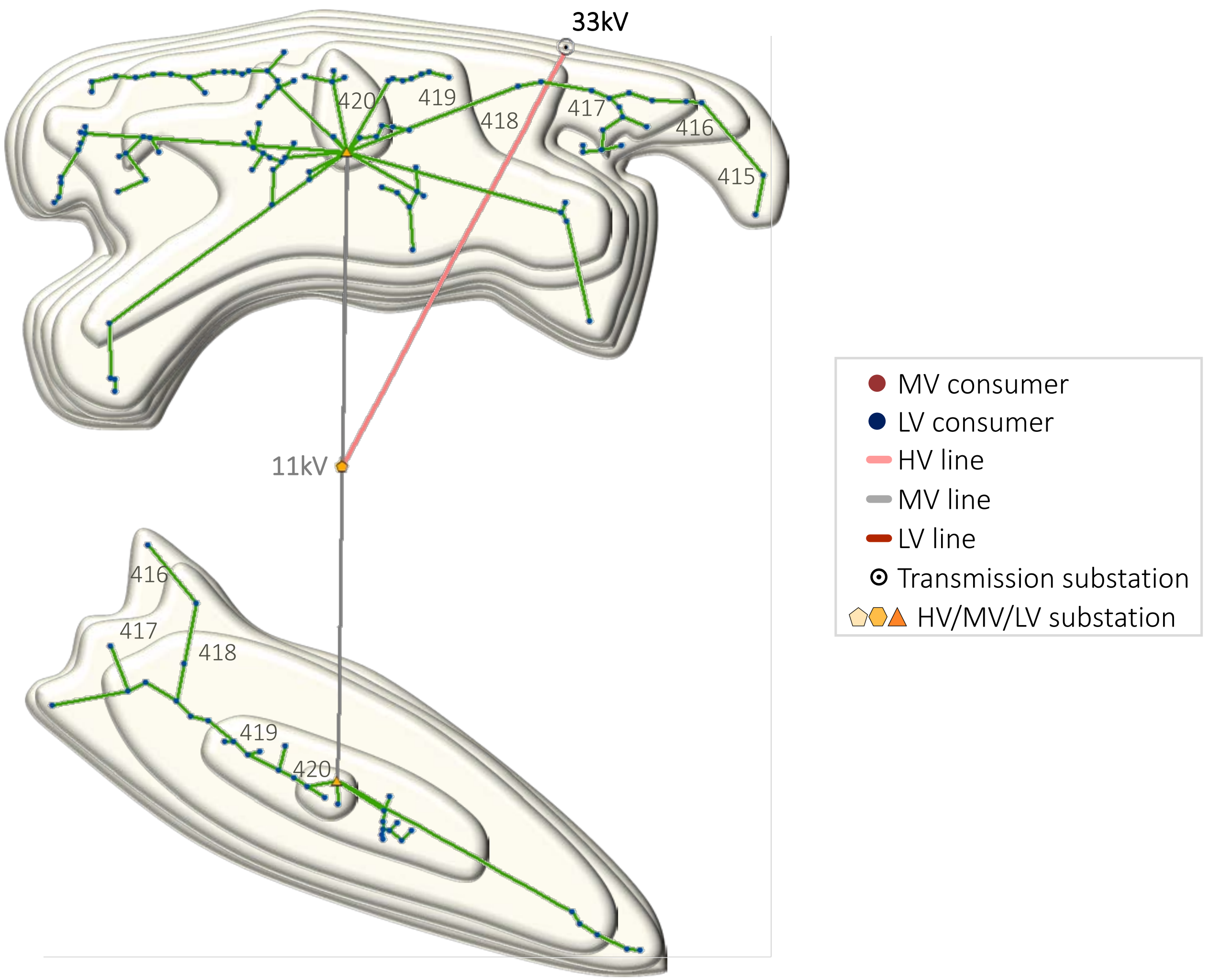
Increasing the demand entails installing additional transformers



Voltages are the most important variable in distribution planning



Voltages are the most important variable in distribution planning



Thank you!