Geospatial Electrification Planning: The REM Model

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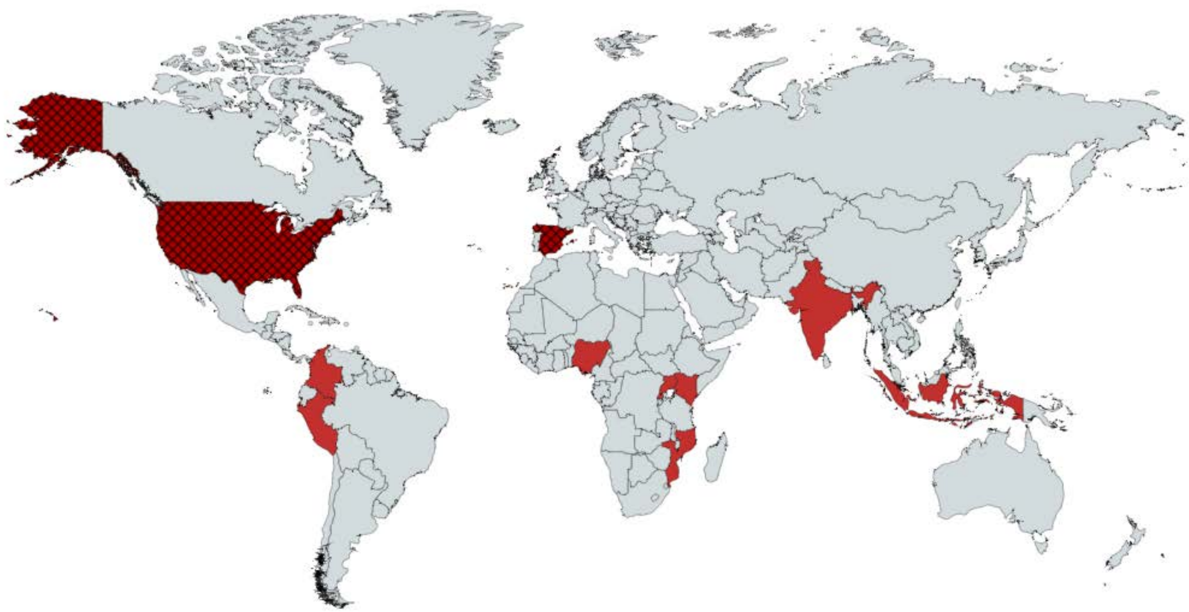
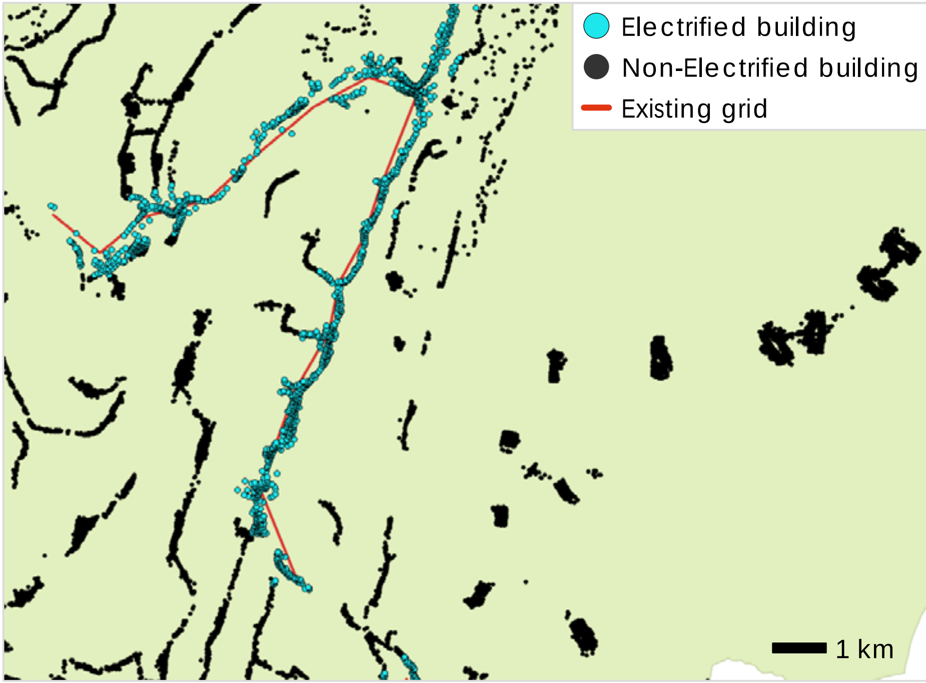
Universal Energy Access Lab: MIT & IIT-Comillas



All started 5+ years ago

- 5 senior faculty and researchers
- 4 junior researchers and post-docs
- 22 past and present students

Is a comprehensive planning method possible?



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

Can we create a method in which both **technoeconomic** considerations and **social, political, and regulatory** factors can be combined to create a comprehensive regional planning tool?

What is an electrification plan?

Mix of **on- & off-grid expansions** providing electricity **access to all** at **minimum cost**

- Some prescribed demand for each consumer
- Minimum reliability requirements
- Additional constraints, e.g., limit on diesel utilization

The economics behind the plan

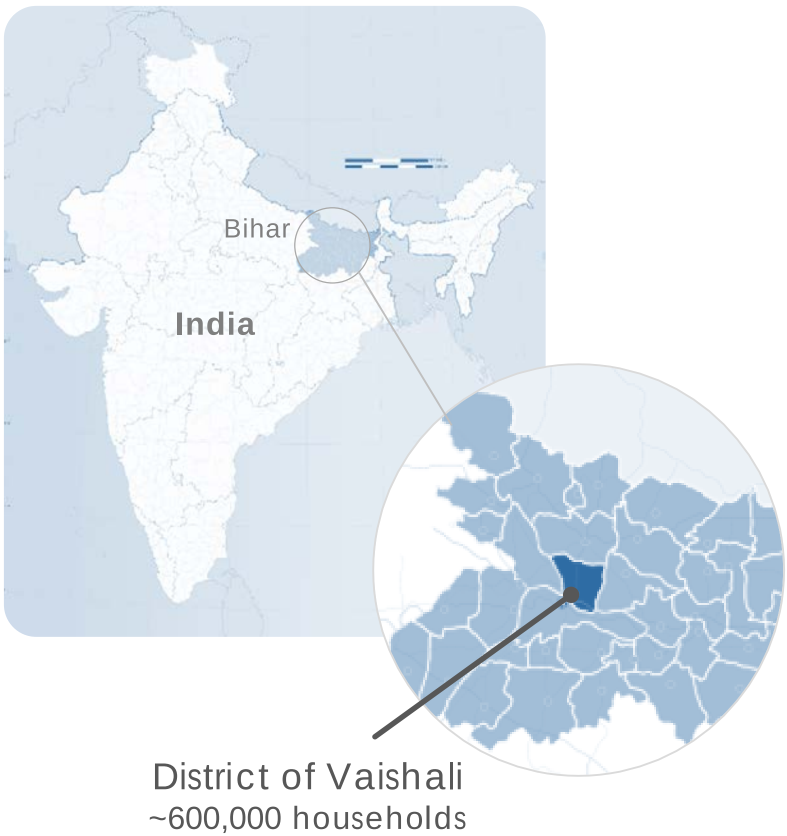
On-grid solution (grid extension)

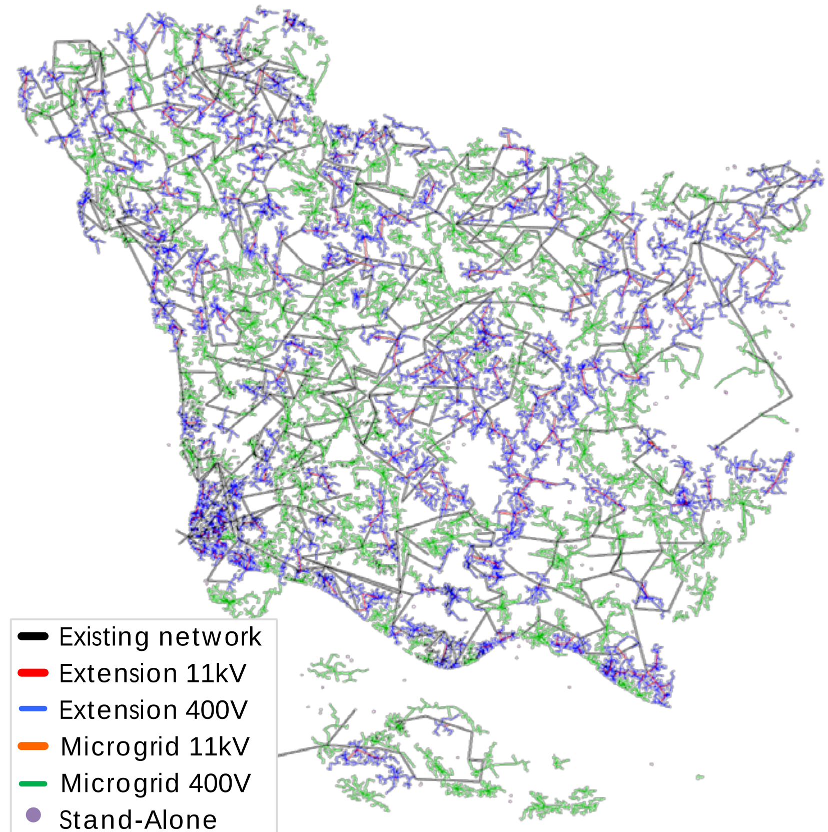
- Investment & operation costs of new grid
- Reinforcements of existing grid
- “Upstream” cost of grid-supplied electricity
- Cost of non served energy

Off-grid solution

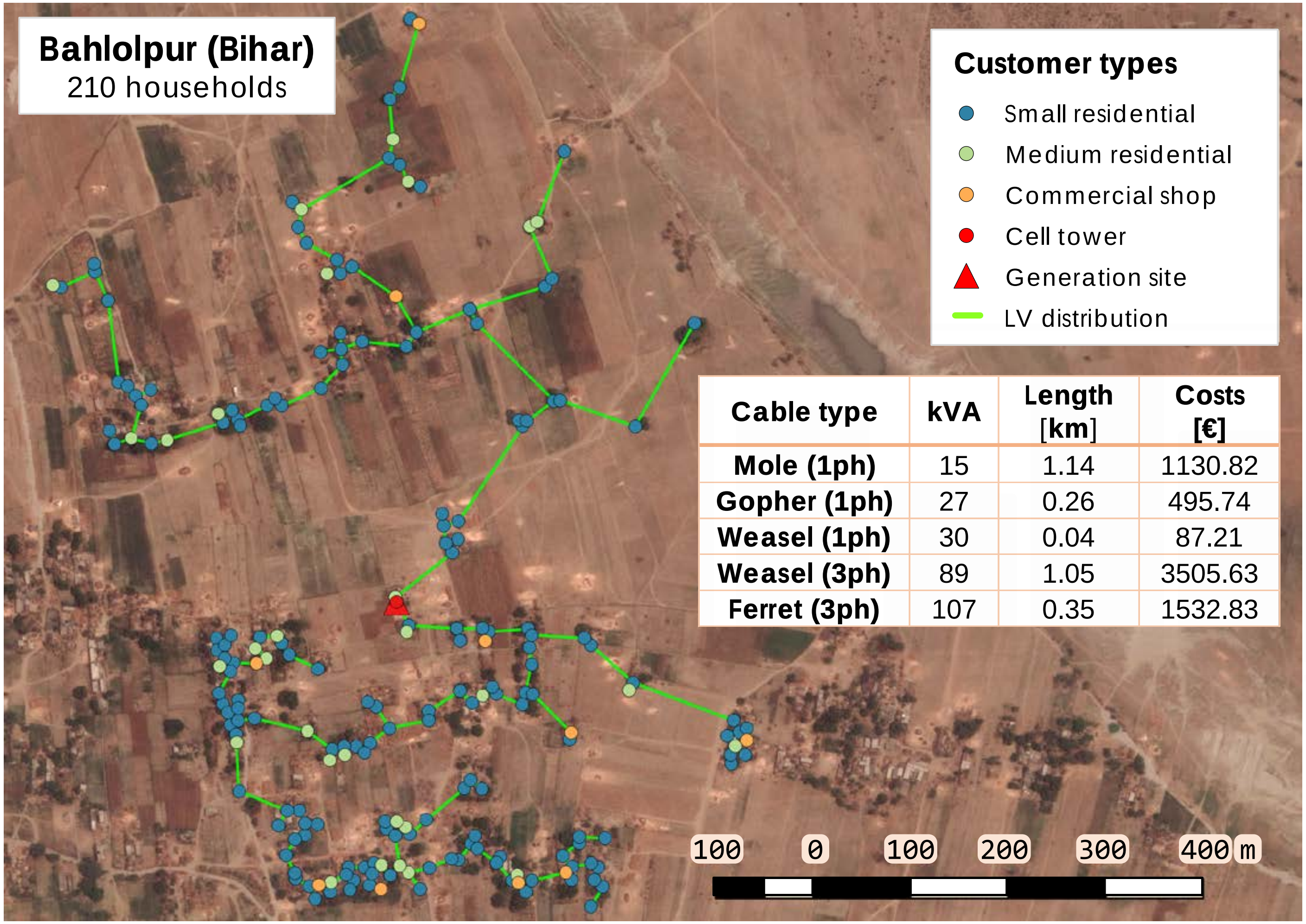
- Microgrids
  - Investment & operation costs of generation and storage
  - Investment cost of network
  - Cost of non served energy
- Stand-alone systems
  - Investment & operation costs of generation and storage
  - Cost of non served energy

Large-scale electrification planning



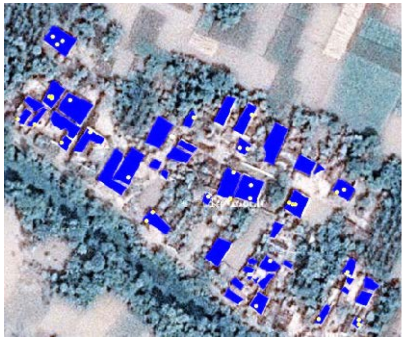


Local electrification design



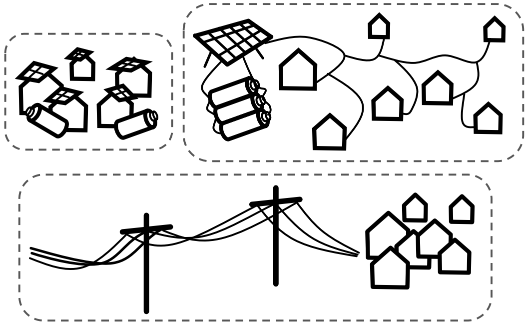
Cable type	kVA	Length [km]	Costs [€]
Mole (1ph)	15	1.14	1130.82
Gopher (1ph)	27	0.26	495.74
Weasel (1ph)	30	0.04	87.21
Weasel (3ph)	89	1.05	3505.63
Ferret (3ph)	107	0.35	1532.83

The technology inside REM



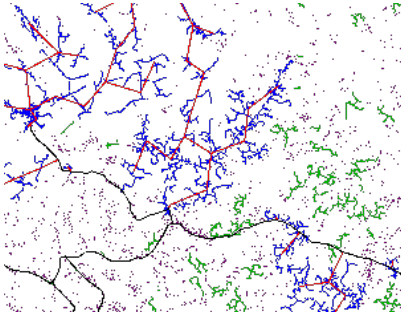
Data preparation

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



Optimization

Large-scale optimization to design the appropriate access infrastructure for each consumer through solar home systems, microgrids or network extension



Processing and implementation

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

REM inputs overview

Local data

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

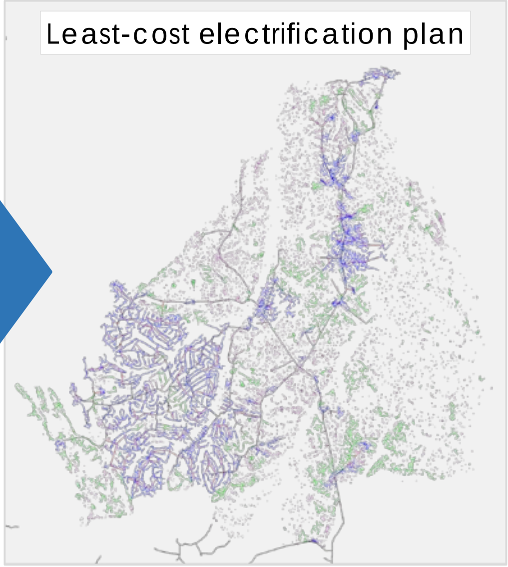
Equipment data

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

User preferences

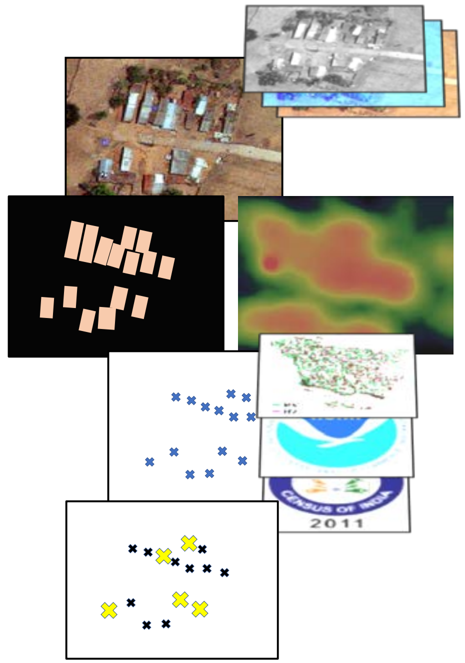
- **Finance** discount rate, years, NSE cost, economies of scale
- **Operational strategy** cost-based, load following, cycle charging

REM



Least-cost electrification plan

Building extraction and electrification status estimation



Building Extraction

↓

Load Localization and Characterization

↓

Electrification Status Estimation

↓

Reference Electrification Model

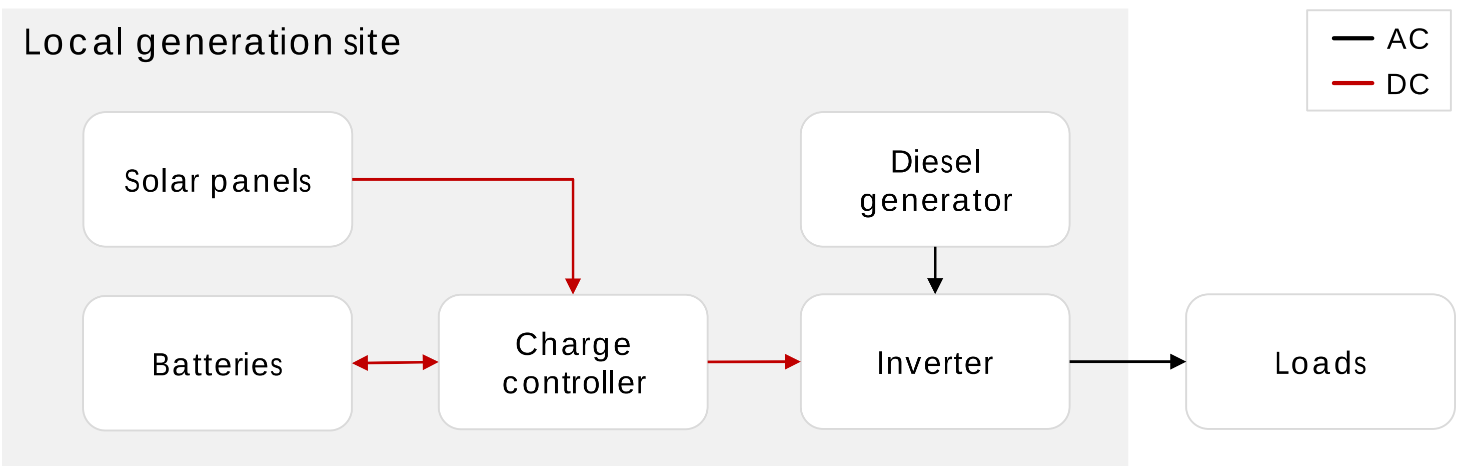
1. Microgrid generation design
2. Clustering process
3. Final design

Microgrid generation designs (1)

Each off-grid system has a **single centralized** generation system. The chosen architecture:

- Can be supported with an available **catalogue of components**.
- Provides **AC service**, allowing a direct comparison with grid extension designs.

REM builds a **lookup table**, or hypercube, which contains sample accurate designs for combinations of customers types, to speed up calculations.



Microgrid generation designs (2)

Starting point(s)
0% | 100% diesel

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

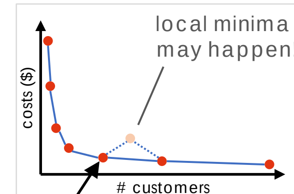
Master problem
Diesel capacity

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

Optimum reached?

Yes

Solution

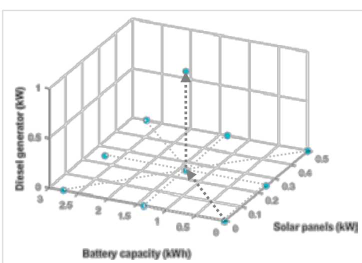


No

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

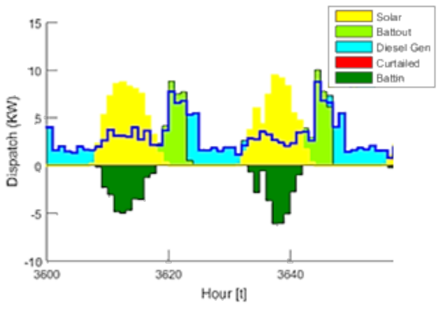
Slave problem
Battery & PV capacity

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

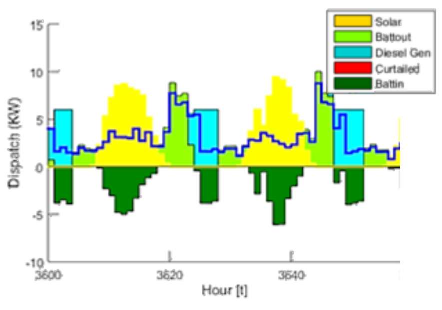


Microgrid generation designs (3)

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.

Clustering process (1)

The Delaunay triangulation connects all consumers in a region

– Off-grid clustering loop

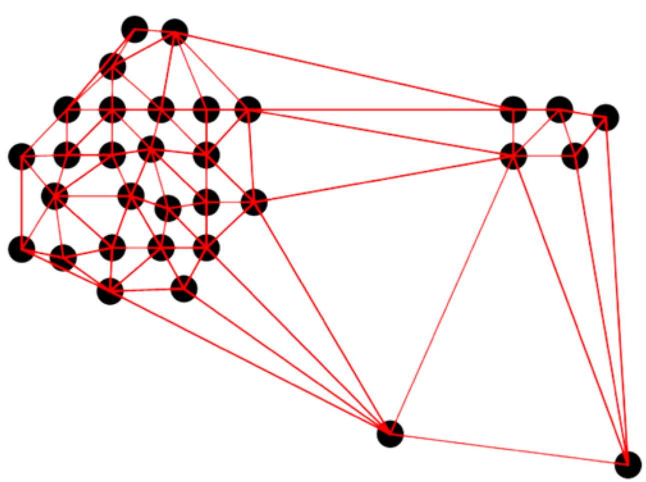
1. Select closest neighbor
2. Join neighbors through real line
3. Loop until no new connection

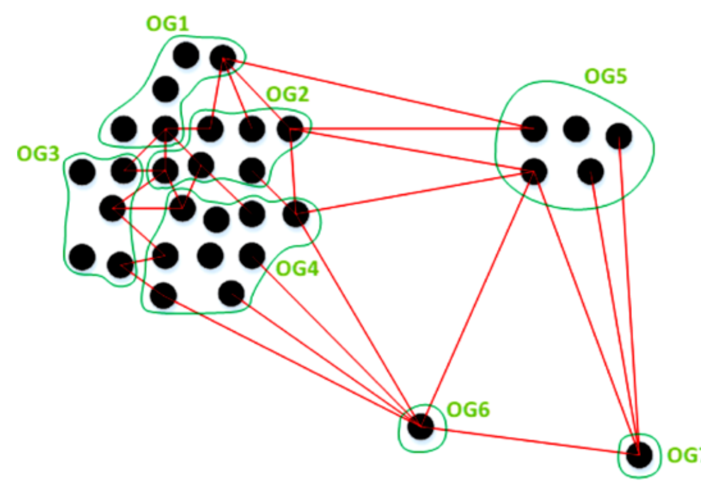
– From shorter to longer arcs

- 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

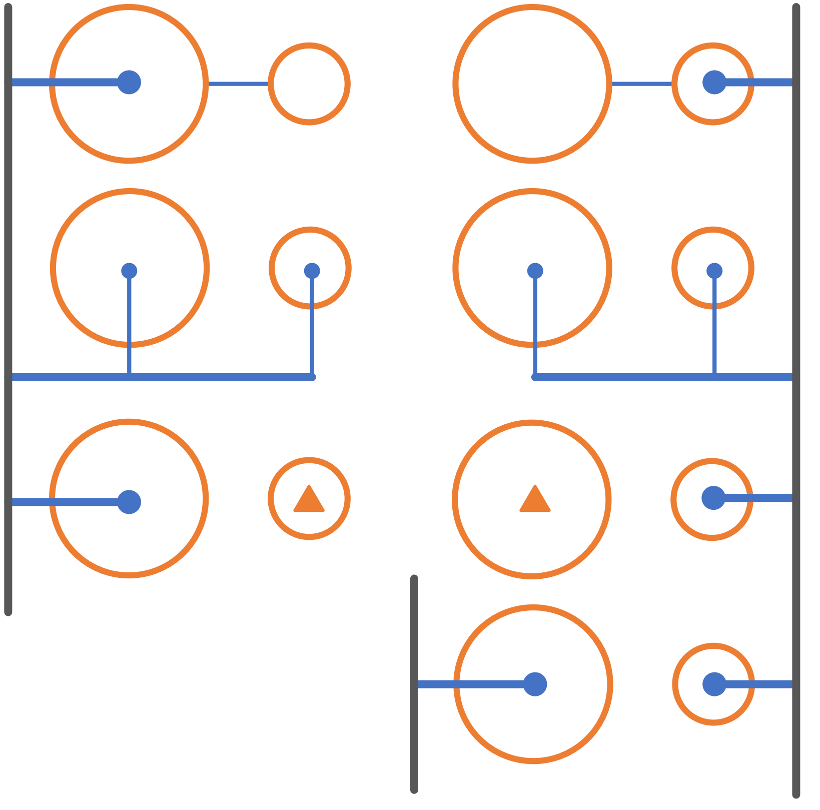




Clustering process (2)

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



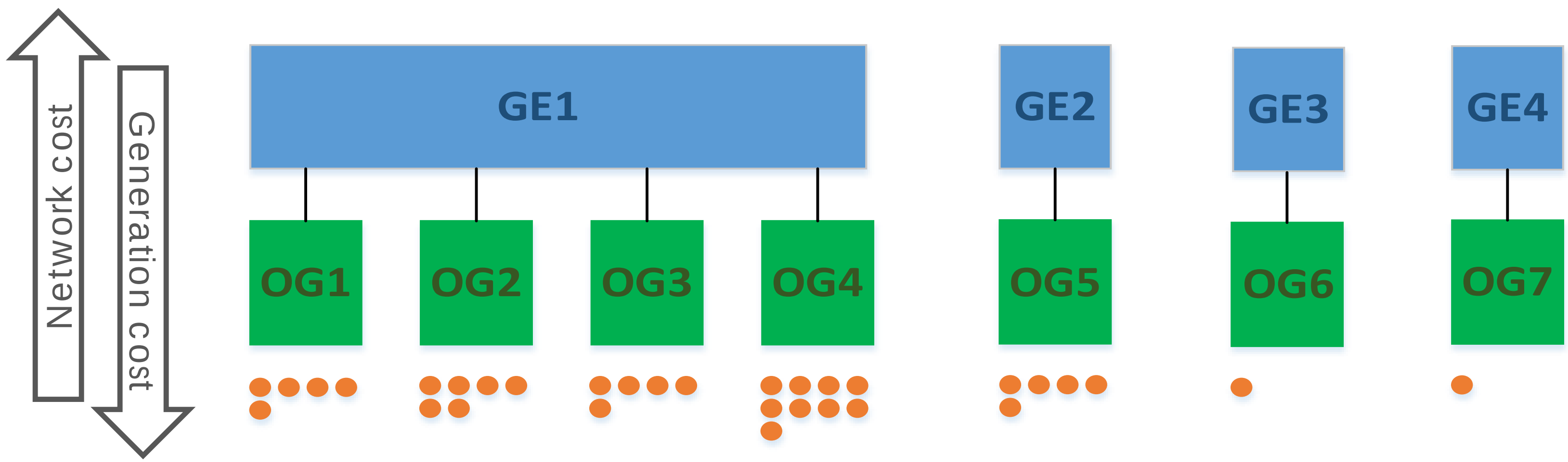
Generation cost of cluster 1
Generation cost of cluster 2
MV/LV transformers
LV (or MV) line from cluster 1 to cluster 2
LV (or MV) line from network to cluster 1
LV (or MV) line from network to cluster 2
Grid energy cost and NSE cost
O&M costs of clusters

Final design (1)

The clustering process creates a hierarchical structure of problems

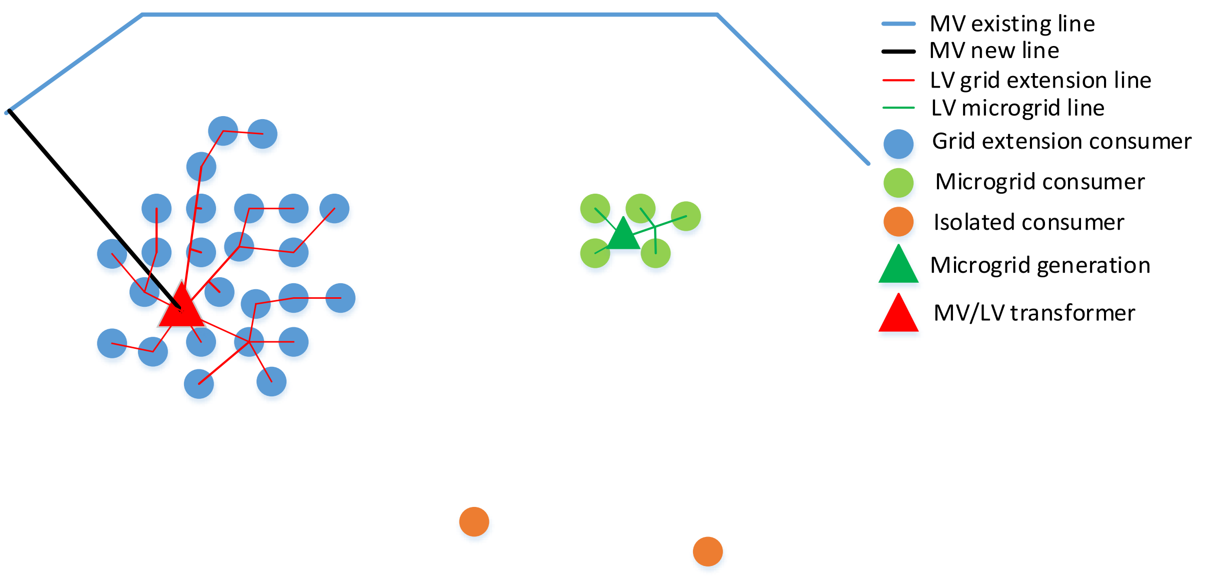
– REM Evaluates Isolated Systems, Off-grid Clusters, and On-grid Clusters to determine the best solution for each consumer

– The "best solution" corresponds to the least-cost solution while providing required reliability levels

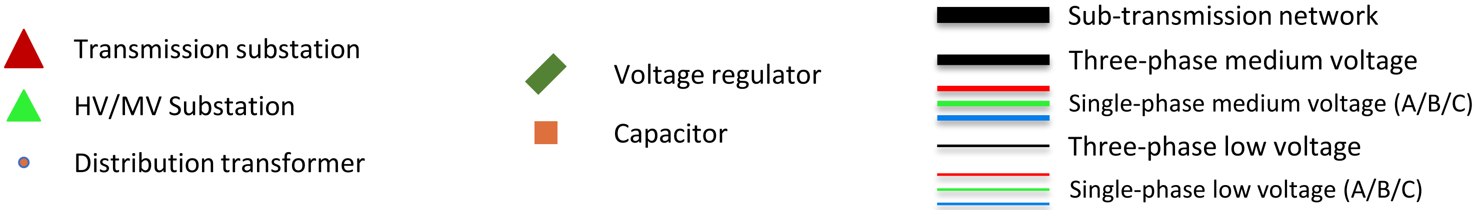


Final design (2)

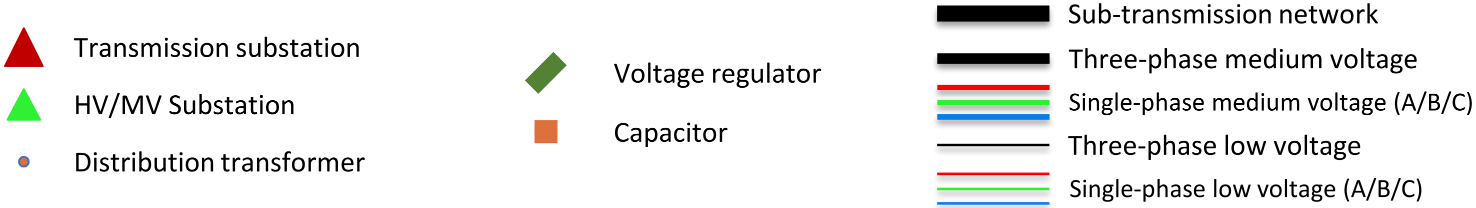
The final solution is a combination of choices from the isolated systems, off-grid clusters, and on-grid clusters



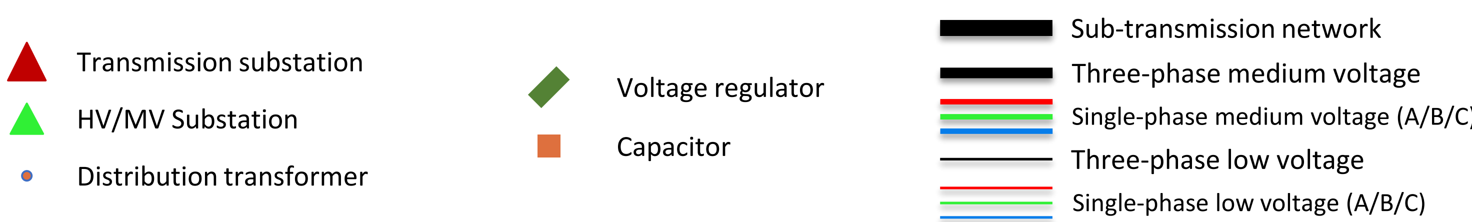
Reference Network Model: consumers and paths



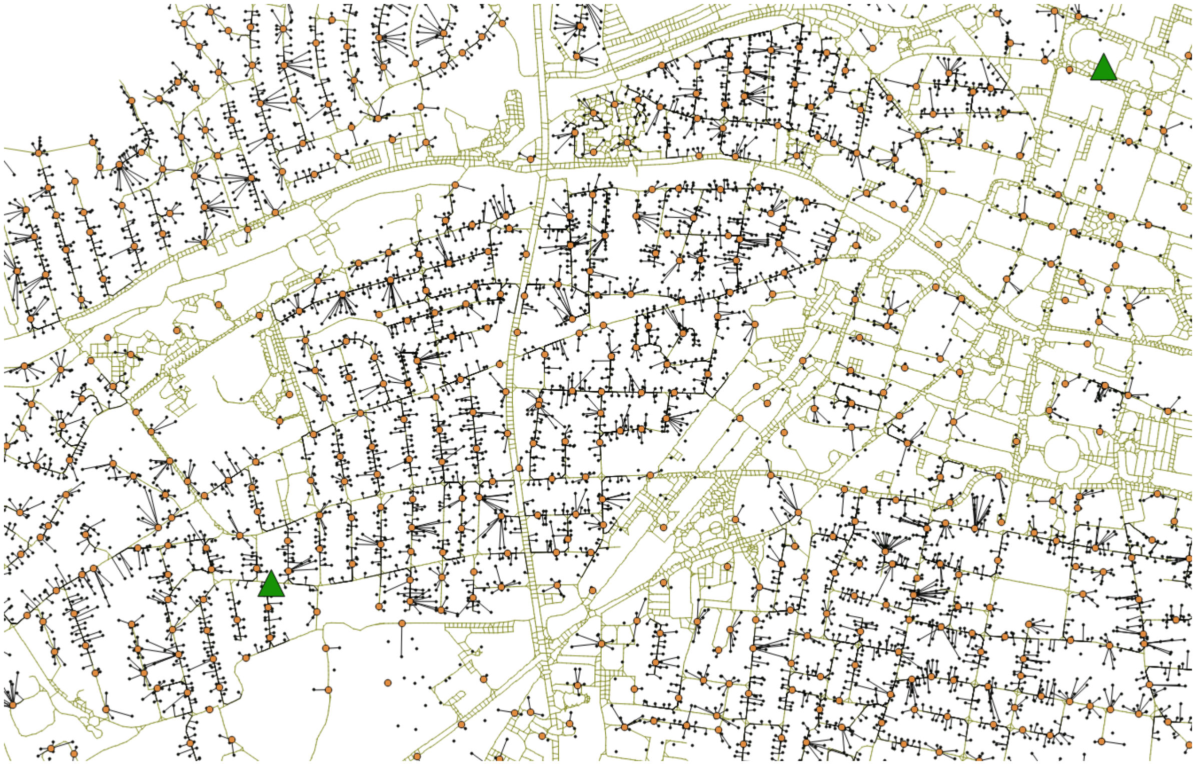
Reference Network Model: distribution transformers

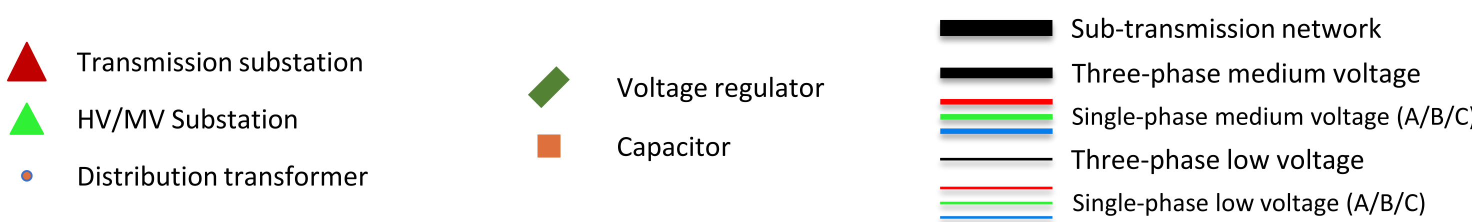


Reference Network Model: LV network

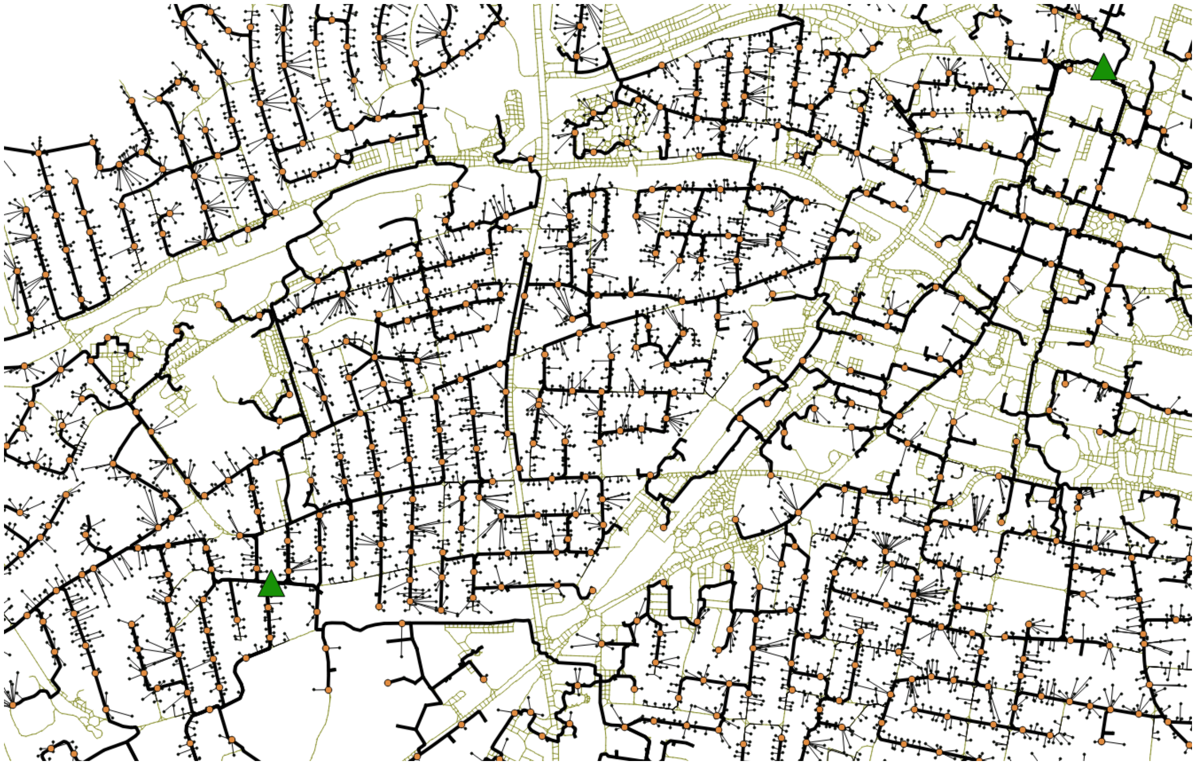


Reference Network Model: HV/MV substations





Reference Network Model: MV network



Transmission substation

HV/MV Substation

Distribution transformer

Voltage regulator

Capacitor

Sub-transmission network

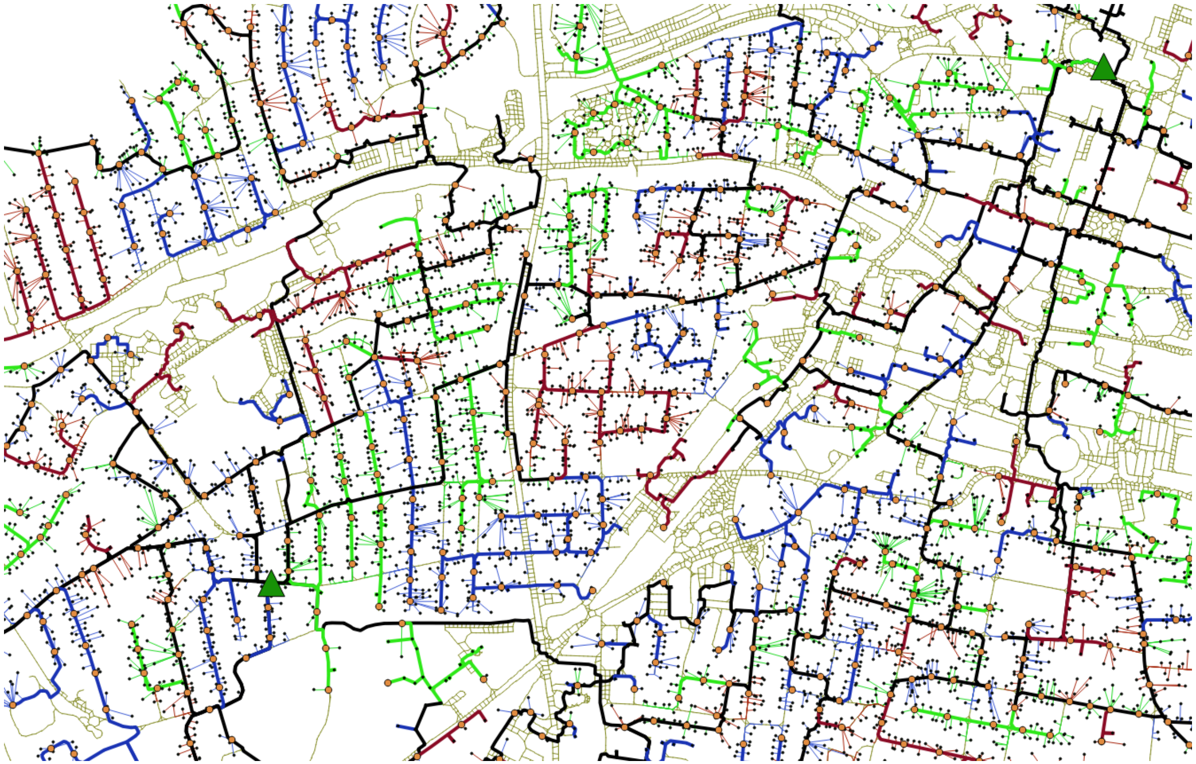
Three-phase medium voltage

Single-phase medium voltage (A/B/C)

Three-phase low voltage

Single-phase low voltage (A/B/C)

Reference Network Model: Phases



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Three-phase medium voltage

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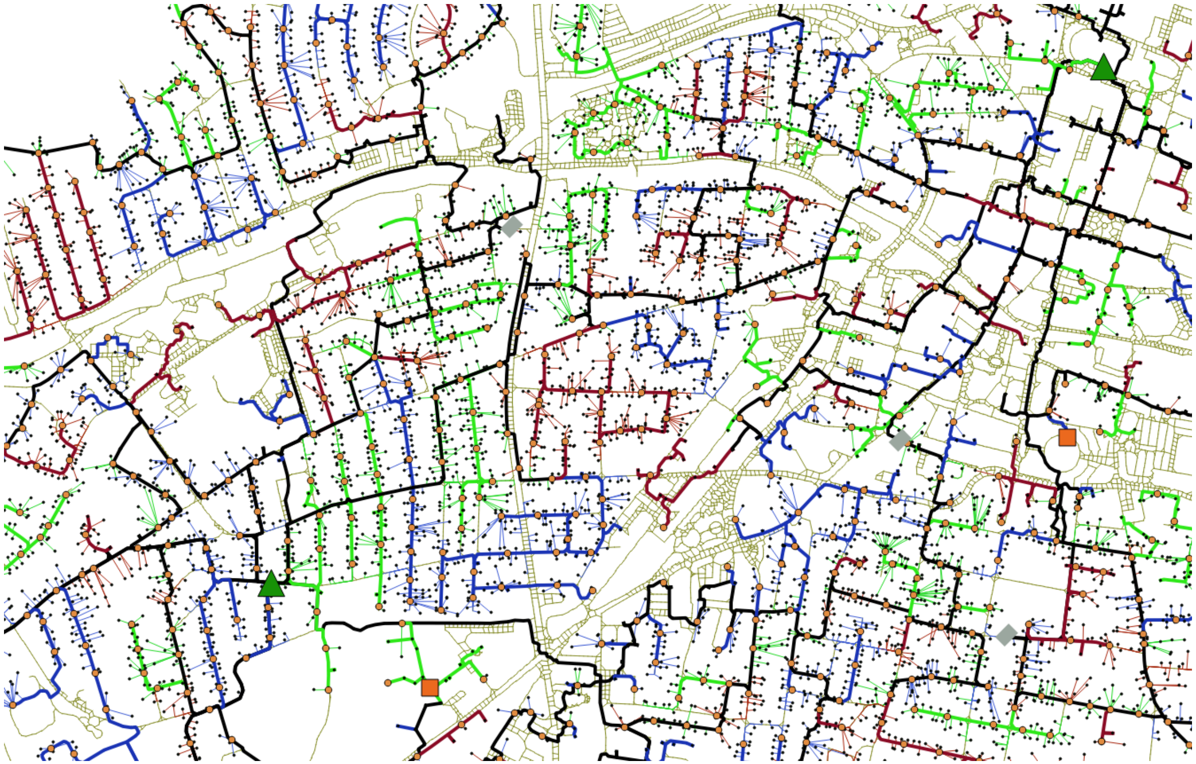
Reference Network Model: capacitors and voltage regulators



Transmission substation

HV/MV Substation

Distribution transformer

Voltage regulator

Capacitor

Sub-transmission network

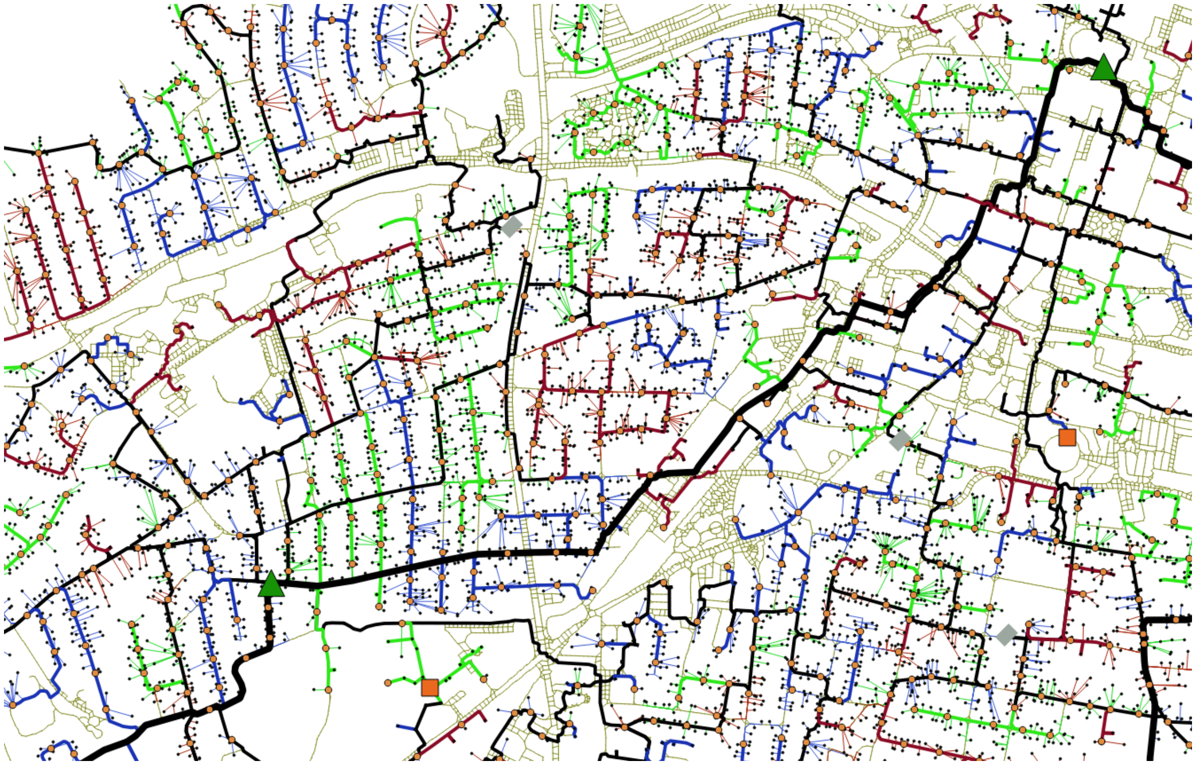
Three-phase medium voltage

Single-phase medium voltage (A/B/C)

Three-phase low voltage

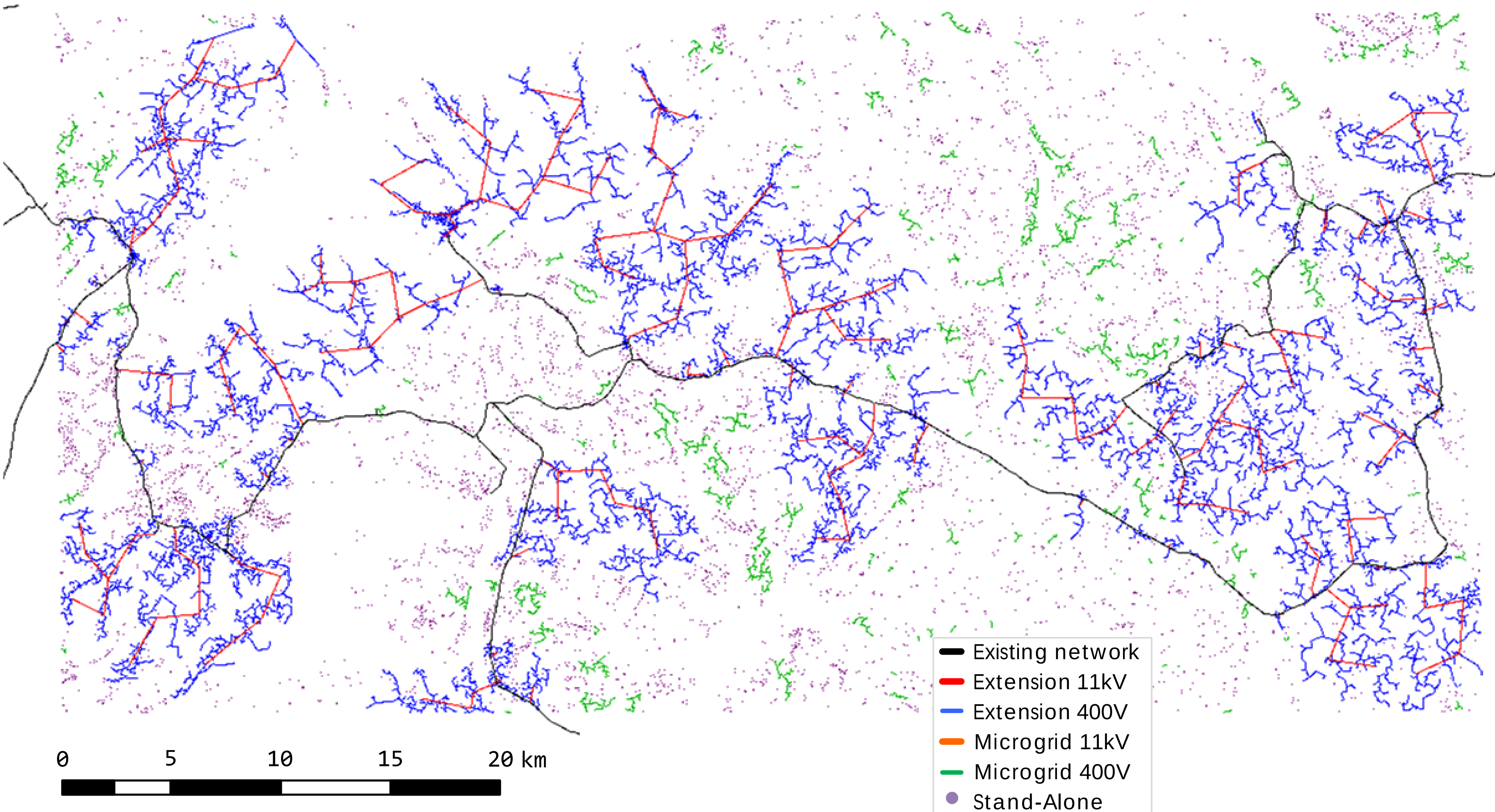
Single-phase low voltage (A/B/C)

Reference Network Model: HV network

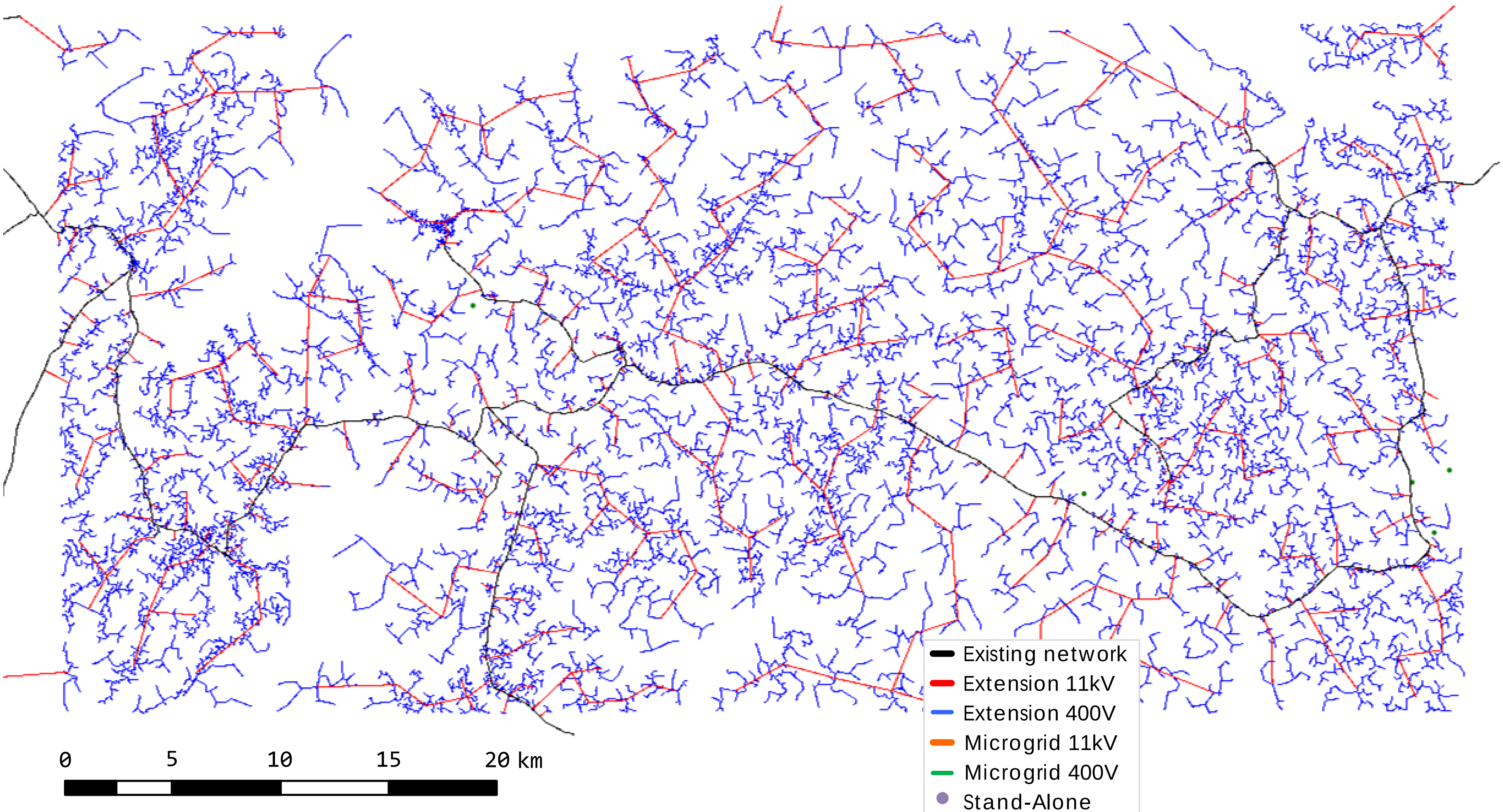


- Transmission substation
- HV/MV Substation
- Distribution transformer
- Voltage regulator
- Capacitor
- Sub-transmission network
- Three-phase medium voltage
- Single-phase medium voltage (A/B/C)
- Three-phase low voltage
- Single-phase low voltage (A/B/C)

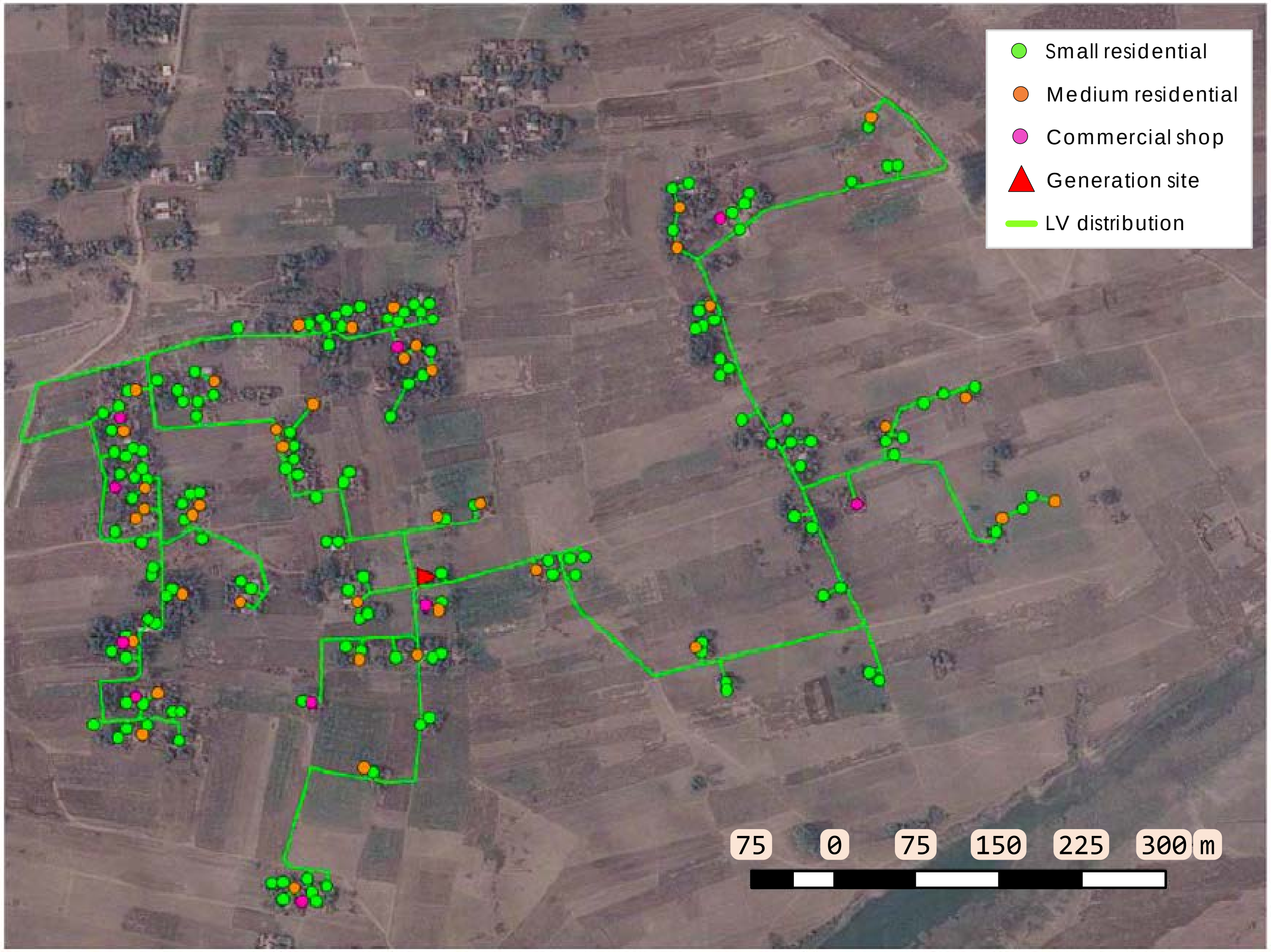
Example of large scale REM output



Sensitivity: Forced 100% grid extension



Detail of design of a microgrid



Thank you!