Planning tools for Rural Electrification

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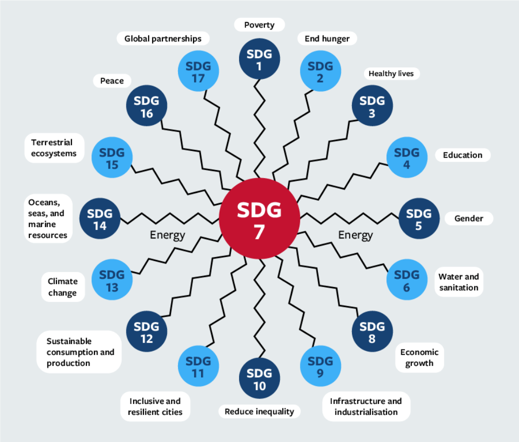
Motivation

How important is electricity in modern societies?

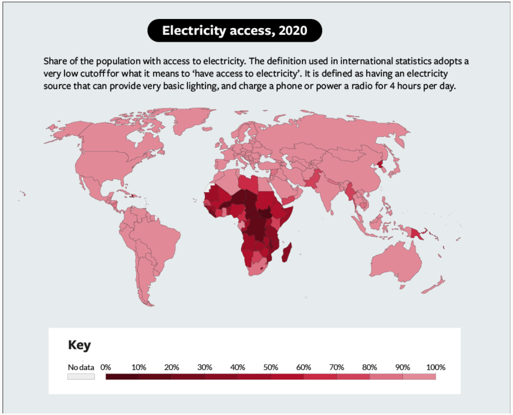
- People use electricity for lighting, heating, cooling, and refrigeration and for operating appliances, computers, electronics, machinery, and public transportation systems.
- Access to electricity impacts explicitly or implicitly poverty, health, education, gender equality, water and sanitation, economic growth, etc.
- **UN Sustainable Development Goal 7**: Ensure access to affordable, reliable, sustainable and modern energy for all



What is the current global access to electricity?

Current status

- 13% of the world's population, or about **940 million people**, do not have access to electricity
- Majority of these people are in **sub-Saharan Africa**, which is home to about two-thirds of those without electricity
- South Asia also has a significant number of people without electricity



Electricity access, 2020

Share of the population with access to electricity. The definition used in international statistics adopts a very low cutoff for what it means to 'have access to electricity'. It is defined as having an electricity source that can provide very basic lighting, and charge a phone or power a radio for 4 hours per day.

Hannah Ritchie, Max Roser and Pablo Rosado (2020) - "Access to Energy". Published online at `OurWorldInData.org`

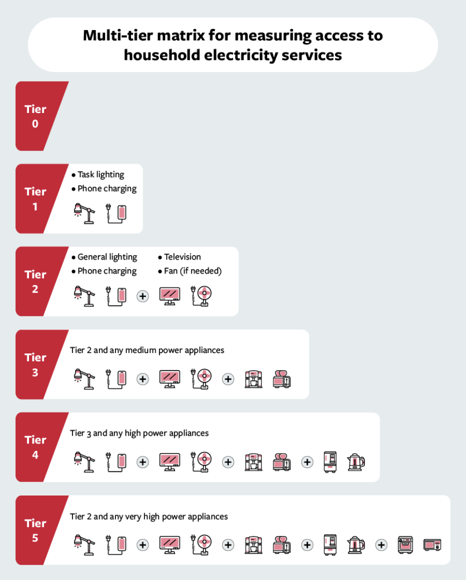
Is all electricity the same?

World Bank Multi-tier matrix

- **Hundreds of millions** of households have varying degrees of access due to poor and unreliable electricity supplies
- Six levels, or tiers, that describe different attributes of energy supply

Tier 0	**Tier 1**	**Tier 2**
None	> 3 W	> 50 W

Tier 3	**Tier 4**	**Tier 5**
> 200 W	> 800 W	> 2 kW



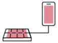
Bhatia, Mikul; Angelou, Niki. 2015. Beyond Connections: Energy Access Redefined. ESMAP Technical Report; 008/15. World Bank,

How can we electrify rural areas?

Types of rural electrification

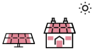
Pico **0-10W**

- Small individual devices
- Poor / low income



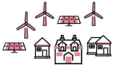
Solar home systems (SHS) **10-100W**

- Stand alone system for residence
- Micro-commercial, poor / middle class households



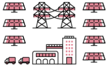
Microgrids **< 10 MW**

- Distribution system for localised group of customers isolated from grid supply
- Unserved / underserved areas



Grids **> 10 MW**

- Interconnected network: electricity to multiple customers, large distance
- Industry / commercial, urban, reachable rural areas



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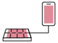

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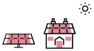

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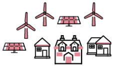

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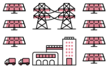
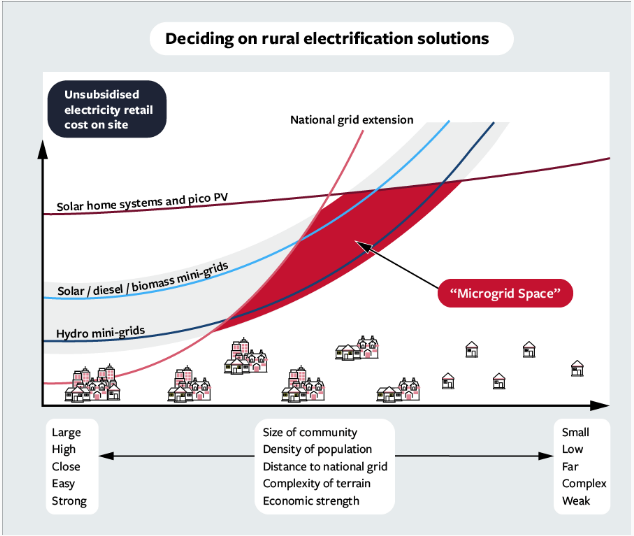


	Commercial policy, consumer financing		Energy policy, structured infrastructure financing	
Types of electrical systems (capacity)	**Pico** 1–10W	**Solar home systems (SHS)** 10–100W	**Mini-grids** typically <10MW	**Grids** always ≥10MW
Energy access tier and type of system	**Tier 1** Small individual devices	**Tier 2–3** Stand alone system for residences	**Tier 3–5** Distribution system for local group of customers, isolated from grid supply	**Tier 2–5** Interconnected network, electricity to multiple customers, large distance
Primary market	Poor, low income	Micro-commercial, poor/middle class households	Rural business, community, households	Urban households, industry/commercial, reachable rural areas
Cost (per connection)	5–200 USD	200–1300 USD	400–1500 USD	Urban: 750 USD Rural: 2300 USD
Market barriers	• Commercial policies to support business and markets e.g. high import tariffs, tax policy, foreign currency restrictions, lack of mobile money and no access to local debt capital • Affordability for the poor	• Commercial policies to support business and markets e.g. high import tariffs, tax policy, foreign currency restrictions, lack of mobile money and no access to local debt capital • Affordability for the poor	• High investment cost • Energy rules weak: non-existent or not enforced • Policy and public finance bias, favouring grid	• Utility companies operating at a loss; chronically poor governance • High investment costs

Rural electrification

How do we decide?

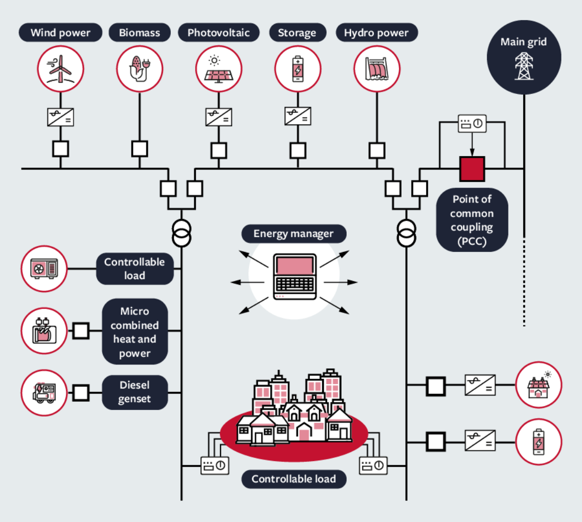
- The distance from the Main Grid.
- The size of the community and density of population.
- The complexity of terrain.
- The customer incomes and electricity uses.



GOGLA, Providing Energy Access through Off-Grid Solar: Guidance for Governments, technical report, 2019

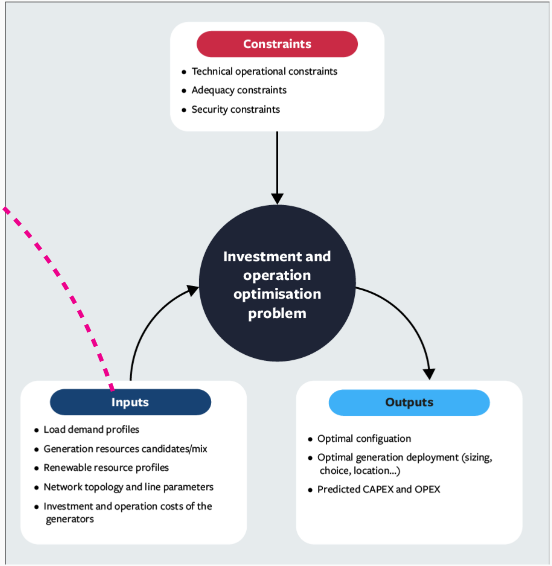
What are Microgrids?

- Low-voltage distribution network composed of various distributed **local load demand** and **local energy resources**
- Can operate in **islanded** (usual case in rural electrification) OR **grid-interconnected** modes (if connected to the Main grid)
- Includes structures to control and coordinate the different resources.



How can we design a new Microgrid?

- We need to collect a lot of data! (Load? Generation? Topology?)



Constraints

- Technical operational constraints
- Adequacy constraints
- Security constraints

Investment and operation optimisation problem

Inputs

- Load demand profiles
- Generation resources candidates/mix
- Renewable resource profiles
- Network topology and line parameters
- Investment and operation costs of the generators

Outputs

- Optimal configuation
- Optimal generation deployment (sizing, choice, location...)
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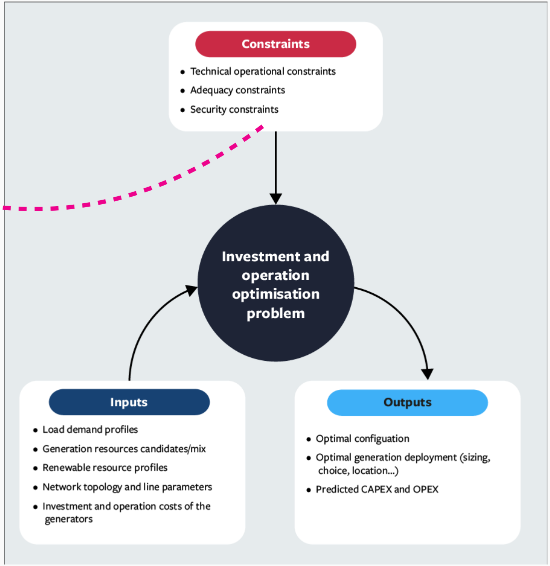

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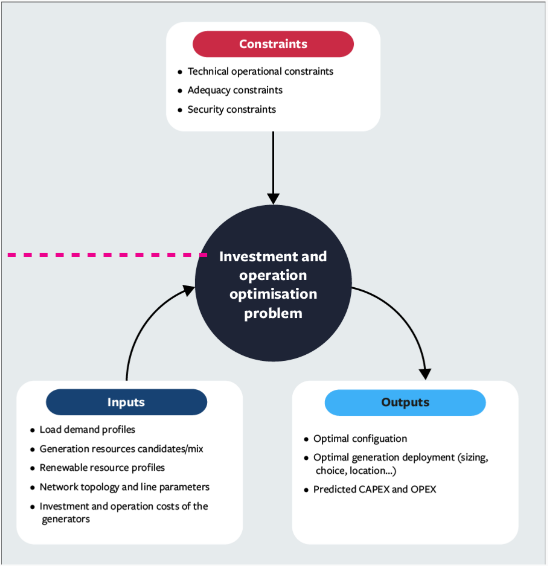

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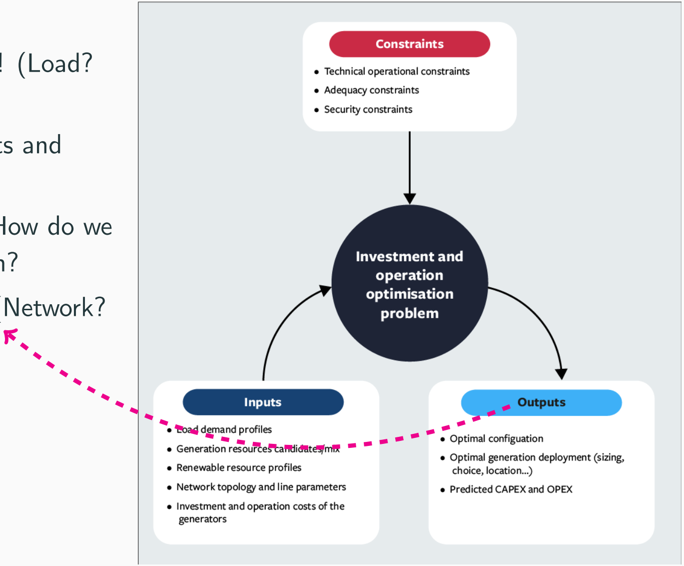
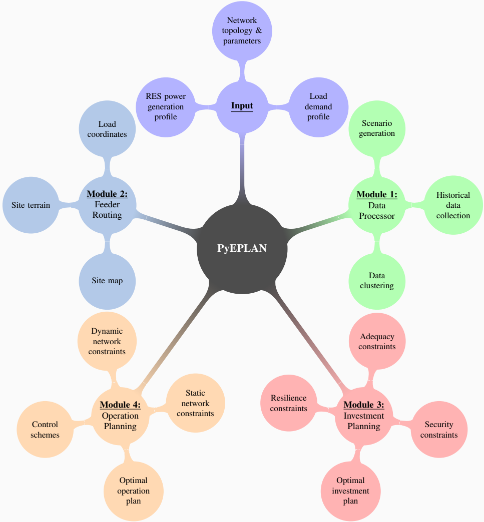
- We need to collect a lot of data! (Load? Generation? Topology?)
- Define the technical requirements and constraints (Tier? Grid Code?)
- **Mathematical optimization**! How do we make the optimal (best) decision?
- Get the best Microgrid design! (Network? Generation? Cost?)



PyEPLAN: A Python-based Energy Planning tool

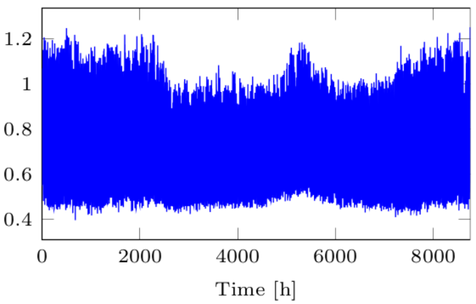
- Python-based, open-source tool for design and operation of optimised Microgrids
- Output of the CRESUM-HYRES research project
- Similar commercial programs cost $>$ \$3000 (training and support charged extra)
- Based on well-known and robust mathematical optimization modelling and solving tools (e.g., Pyomo, CBC, GLPK)
- Able to execute online, using platforms like Google COLAB or Binder without the need for computational resources



Data Requirements

Load demand requirments

- Load characteristics (residential, commercial, productive and flexible load).



"Microgrid load and LCOE modelling results", National Renewable Energy Laboratory, 2018

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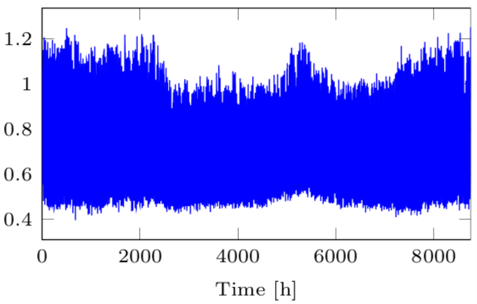

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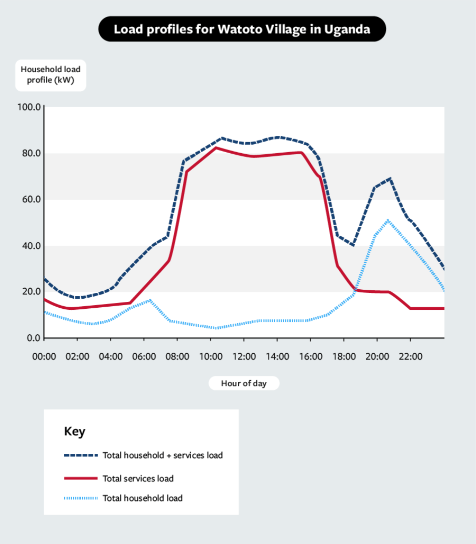
Load demand requirments

- Load characteristics (residential, commercial, productive and flexible load). **Hard to estimate! High uncertainty!**
- Total expected hourly electricity consumption profile of **each load** and the **community profile**
- Location of potential customers (key to line mapping and distribution network design)
- Ability and willingness-to-pay (WTP) of potential consumers which is then applied during tariff design and return on investment



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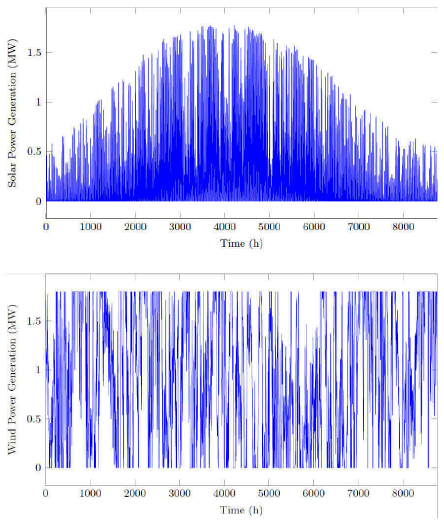
Generation profiles

- Detailed analysis of the resource availability based on historical solar irradiation, temperature and wind speed
- Data showing hourly, seasonal and annual variations
- Can be constructed based on satellite or public data sets



Area mapping & Line routing

1. Create map of the area with load locations. Usually, using a Geographic Information System (GIS) mapping tool.

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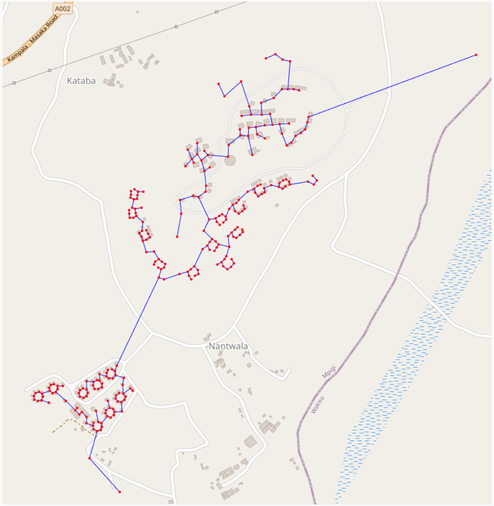
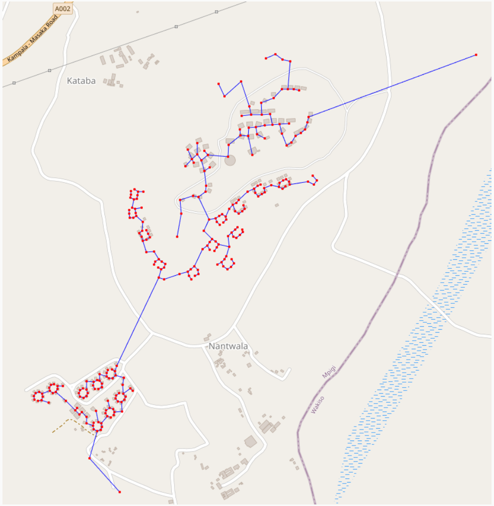
1. Create map of the area with load locations. Usually, using a Geographic Information System (GIS) mapping tool.
2. Perform feeder routing (e.g., Random Search Algorithms, Mixed Integer Non-Linear/Linear Optimisation to Graph Theoretic)



Routing of Watoto Village case study using PyEPLAN.

Area mapping & Line routing

1. Create map of the area with load locations. Usually, using a Geographic Information System (GIS) mapping tool.
2. Perform feeder routing (e.g., Random Search Algorithms, Mixed Integer Non-Linear/Linear Optimisation to Graph Theoretic)
3. Determine the line configuration (e.g., single-phase, split-phase, or three-phase) and conductor size to meet the expected **load demand requirements** across the network given the system constraints
4. Extract investment costs, line losses, reliability, thermal limits and voltage drop.



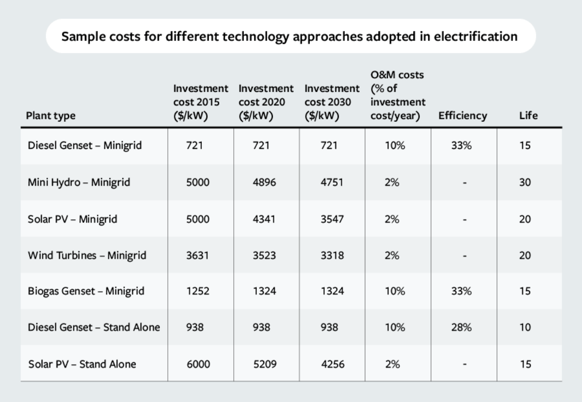
Financial information

Required costs

- Annualized cost of investment expenditures (I)
- Annual maintenance and operations expenditures (OM)
- Annual fuel expenditures (if applicable) (F)

Energy required

- Sum of all electricity generated (E)



Sample costs for different technology approaches adopted in electrification

Plant type	Investment cost 2015 ($/kW)	Investment cost 2020 ($/kW)	Investment cost 2030 ($/kW)	O&M costs (% of investment cost/year)	Efficiency	Life
Diesel Genset – Minigrid	721	721	721	10%	33%	15
Mini Hydro – Minigrid	5000	4896	4751	2%	-	30
Solar PV – Minigrid	5000	4341	3547	2%	-	20
Wind Turbines – Minigrid	3631	3523	3318	2%	-	20
Biogas Genset – Minigrid	1252	1324	1324	10%	33%	15
Diesel Genset – Stand Alone	938	938	938	10%	28%	10
Solar PV – Stand Alone	6000	5209	4256	2%	-	15

Mini Grids for Half a Billion People: Market Outlook and Handbook for Decision Makers. Energy Sector Management Assistance Program (ESMAP), 2019

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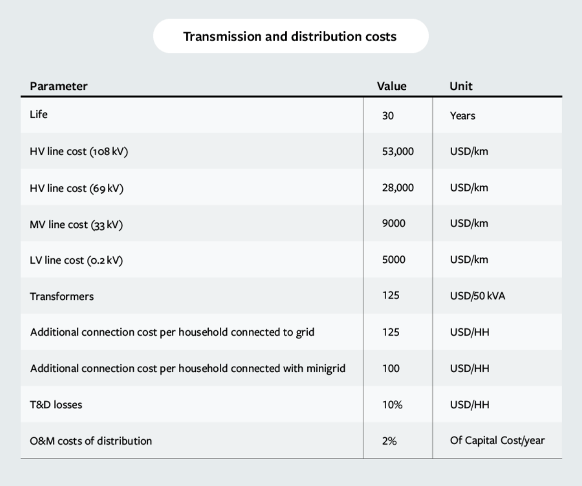

Transmission and distribution costs

Parameter	Value	Unit
Life	30	Years
HV line cost (108 kV)	53,000	USD/km
HV line cost (69 kV)	28,000	USD/km
MV line cost (33 kV)	9000	USD/km
LV line cost (0.2 kV)	5000	USD/km
Transformers	125	USD/50 kVA
Additional connection cost per household connected to grid	125	USD/HH
Additional connection cost per household connected with minigrid	100	USD/HH
T&D losses	10%	USD/HH
O&M costs of distribution	2%	Of Capital Cost/year

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Levelised Cost of Electricity (LCOE)

$$LCOE \approx \frac{I + OM + F}{E}$$

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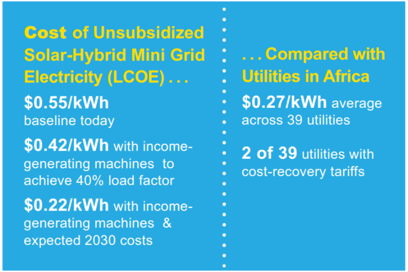
Target LCOE



Cost of Unsubsidized Solar-Hybrid Mini Grid Electricity (LCOE) . . .

$0.55/kWh baseline today

$0.42/kWh with income-generating machines to achieve 40% load factor

$0.22/kWh with income-generating machines & expected 2030 costs

. . . Compared with Utilities in Africa

$0.27/kWh average across 39 utilities

2 of 39 utilities with cost-recovery tariffs

Mini Grids for Half a Billion People: Market Outlook and Handbook for Decision Makers. Energy Sector Management Assistance Program (ESMAP), 2019

Microgrid planning methods

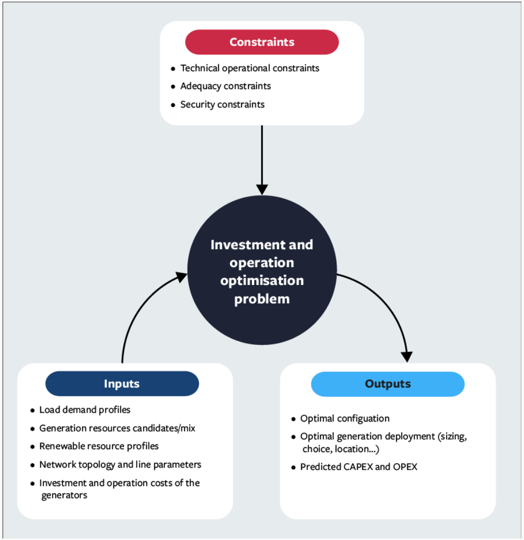
Microgrid planning problem

Objective:

Minimize: Investment + Operation costs

Subject to:

- Technical operational, adequacy, and security constraints
- Input data (load demand, system topology, generation profiles, costs)
- Output constraints (e.g., LCOE limits, etc.)
- Environmental constraints (e.g., CO_2 limits, limit in using fossil fuel, etc.)



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LCOE

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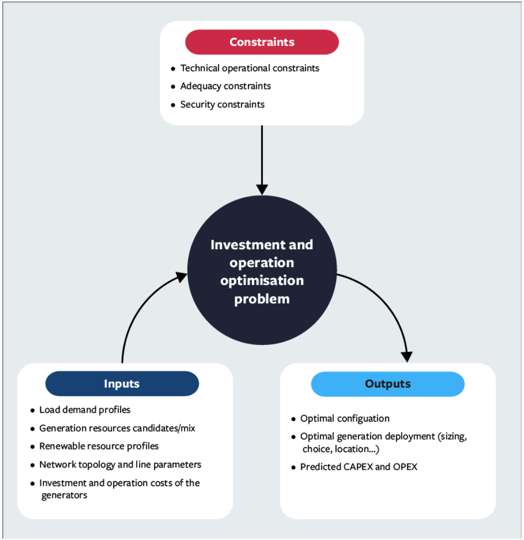

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$$\min_{\chi \in \Omega^{\mathrm{MG}}} \Theta^{\mathrm{inv}}(\chi^{\mathrm{inv}}) + \Theta^{\mathrm{opr}}(\chi^{\mathrm{inv}}, \chi^{\mathrm{opr}}) \tag{1a}$$

$$\text{s.t.} \quad \Phi(\chi^{\mathrm{inv}}, \chi^{\mathrm{opr}}) = 0, \tag{1b}$$

$$\Lambda(\chi^{\mathrm{inv}}, \chi^{\mathrm{opr}}) \leq 0 \tag{1c}$$

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- Investment (χ^{inv}) and Operation decision (χ^{opr}) variables
- Equality constraints (1b)
- Inequality constraints (1c)

Microgrid planning problem: Technical constraints

Dispatchable Generation Constraints → Describe the behaviour of the generating units

$$0 \leq p_{sto} \leq \overline{p}_s \cdot z_s, \quad -\overline{q}_s \cdot z_s \leq q_{sto} \leq \overline{q}_s \cdot z_s, \quad -\mathrm{rp}_s^{\mathrm{dn}} \leq p_{sto} - p_{s(t-1)o} \leq \mathrm{rp}_s^{\mathrm{up}}, \qquad \forall s, t, o$$

$$0 \leq p_{rto} \leq \tilde{p}_{rto} \cdot z_r, \quad -\tan \overline{\phi}_r \cdot \tilde{p}_{rto} \cdot z_r \leq q_{rto} \leq \tan \overline{\phi}_r \cdot \tilde{p}_{rto} \cdot z_r, \qquad \forall r, t, o$$

Battery Behaviour and Constraints → Describe the behaviour of the batteries

$$0 \leq p_{bto}^{\mathrm{dch}} \leq \overline{p}_b^{\mathrm{dch}} \cdot z_{bto}^{\mathrm{dch}}, \quad 0 \leq p_{bto}^{\mathrm{ch}} \leq \overline{p}_b^{\mathrm{ch}} \cdot z_{bto}^{\mathrm{ch}}, \quad z_{bto}^{\mathrm{dch}} + z_{bto}^{\mathrm{ch}} = z_b, \qquad \forall b, t, o$$

$$\underline{e}_b \cdot z_b \leq e_{bo}^{\mathrm{ini}} + \sum_{\tau=1}^{t} \left(\xi_b^{\mathrm{ch}} \cdot p_{b\tau o}^{\mathrm{ch}} - \frac{1}{\xi_b^{\mathrm{dch}}} \cdot p_{b\tau o}^{\mathrm{dch}} \right) \leq \overline{e}_b \cdot z_b, \qquad \forall b, t, o$$

$$\sum_{t \in \mathscr{T}} \left(\xi_b^{\mathrm{ch}} \cdot p_{bto}^{\mathrm{ch}} - \frac{1}{\xi_b^{\mathrm{dch}}} \cdot p_{bto}^{\mathrm{dch}} \right) = 0, \qquad \forall b, o$$

Microgrid planning problem: Technical constraints

AC Power Flow Equations → Dictate the loading of the lines, the currents, and voltages

$$s_{it}^{\mathrm{d}} - s_{t|i=1}^{\mathrm{imp}} + s_{t|i=1}^{\mathrm{exp}} - \sum_{g \in \mathscr{G}^i} s_{gt} = \sum_{\eta(l^+)=i} S_{l^+} + \sum_{\eta(l^-)=i} S_{l^-} \qquad \forall i, t$$

$$S_{l^+} = V_{\eta(l^+)t}(I_{l^+})^*, \qquad S_{l^-} = V_{\eta(l^-)t}(I_{l^-})^*, \qquad \forall l, t$$

$$I_{l^+} = y_l^s(V_{\eta(l^+)} - V_{\eta(l^-)}) + y_l^{sh} V_{\eta(l^+)}, \qquad \forall l, t$$

$$I_{l^-} = y_l^s(V_{\eta(l^-)} - V_{\eta(l^+)}) + y_l^{sh} V_{\eta(l^-)}, \qquad \forall l, t$$

Thermal Loading and Voltage Constraints

$$P_{lto}^2 + Q_{lto}^2 \leq \left(\overline{S}_l^0\right)^2 \cdot z_l^0 + \left(\overline{S}_l\right)^2 \cdot z_l, \qquad \forall l, t, o$$

$$z_l^0 + z_l = 1, \qquad \forall l$$

$$\underline{v} \leq v_{ito} \leq \overline{v}, \qquad v_{to|i=1} = 1, \qquad \forall i, t, o$$

Problem characterization

Large-scale, multi-period, mixed-integer, non-linear, stochastic, optimization problem

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Complex problems, hard to solve, computationally intensive!

Challenge 1: Handling non-linear power-flow equations

Normal AC Power Flow Equations → NLP → Intractable

$$s_{it}^{\mathrm{d}} - s_{t|i=1}^{\mathrm{imp}} + s_{t|i=1}^{\mathrm{exp}} - \sum_{g \in \mathscr{G}^i} s_{gt} = \sum_{\eta(l^+)=i} S_{l^+} + \sum_{\eta(l^-)=i} S_{l^-} \qquad \forall i, t \qquad (2a)$$

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$$I_{l^-} = y_l^s(V_{\eta(l^-)} - V_{\eta(l^+)}) + y_l^{sh} V_{\eta(l^-)}, \qquad \forall l, t \qquad (2d)$$

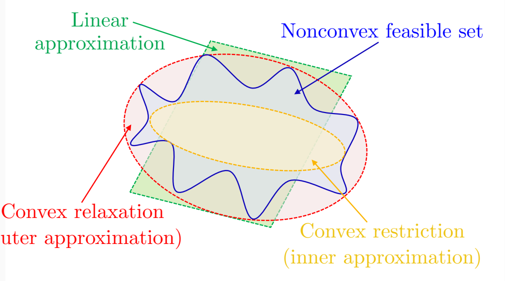
A. Nakiganda, S. Dehghan, P. Aristidou, "Comparison of AC Optimal Power Flow Methods in Low-Voltage Distribution Networks", Proc. of the 2021 ISGT conf., 2021.

Challenge 1: Handling non-linear power-flow equations

Convex formulations/relaxations → Second-Order Cone Programming → Tractable

i. Elimination of the voltage and current angles from (2). This is performed by the separation of the complex real and imaginary parts.

ii. Convexification of the non-convex hyperbolic constraint (2b), this is achieved by relaxing the equality using SOCP to an inequality.



A. Nakiganda, S. Dehghan, P. Aristidou, "Comparison of AC Optimal Power Flow Methods in Low-Voltage Distribution Networks", Proc. of the 2021 ISGT conf., 2021.

Challenge 1: Handling non-linear power-flow equations

Convex formulations/relaxations → Second-Order Cone Programming → Tractable

- Modified Lin-DistFlow Relaxation (LinDF)
- Adapted DistFlow Relaxation (DF)
- Extended DistFlow Relaxation with Line Shunts (ExDF)
- Augmented DistFlow with Line Shunts (ExAgDF)

	NLP	LinDF	DF	ExDF	ExAgDF
Computation Time [s]	727.34	0.18	2.04	2.86	171.52
Total Cost [$]	38133	39088	41155	38122	38080
% $\delta_{V_i}^{\text{relax}}$	-	0.52	0.57	0.005	0.003
% $\delta_{p_i}^{\text{relax}}$	-	7.54	3.19	0.24	0.03
% $\delta_{q_i}^{\text{relax}}$	-	23.60	23.65	0.33	0.31

A. Nakiganda, S. Dehghan, P. Aristidou, "Comparison of AC Optimal Power Flow Methods in Low-Voltage Distribution Networks", Proc. of the 2021 ISGT conf., 2021.

Challenge 2: Handling uncertainty

Challenge: We need to make decisions about the Microgrid design **under uncertainty**

- **Uncertainty sources:** Generation profiles (especially renewables), load demand, market prices, etc.
- **Uncertainty modelling:** Probability distribution(s), expected value(s), representative day(s) (neutral, risk seeker, risk averse), etc.

A. Nakiganda, S. Dehghan, U. Markovic, G. Hug, P. Aristidou, "A Stochastic-Robust Approach for Resilient Microgrid Investment Planning Under Static and Transient Islanding Security Constraints", IEEE Transactions on Smart Grid, 2022

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Solution approaches:

1. **Stochastic Optimisation → Solve for the expected value of known PDF**

$$\min_{\boldsymbol{x} \in \chi} \left(\mathbb{E}_{\mathbb{P}} \left\{ h\left(\boldsymbol{x}, \tilde{\boldsymbol{u}}\right) \right\} \right)$$

where $\boldsymbol{x}$ is a vector of decision variables, χ is the feasible set of the decision variables, $\mathbb{P}$ is the probability distribution of the uncertain parameters $\tilde{\boldsymbol{u}}$ and h is the cost function.

A. Nakiganda, S. Dehghan, U. Markovic, G. Hug, P. Aristidou, "A Stochastic-Robust Approach for Resilient Microgrid Investment Planning Under Static and Transient Islanding Security Constraints", IEEE Transactions on Smart Grid, 2022

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Solution approaches:

2. **Robust Optimisation → Solve for the worst-case cost over an uncertainty set**

$$\min_{\boldsymbol{x}\in\chi}\left(\max_{\tilde{\boldsymbol{u}}\in\mathscr{V}}\left\{h\big(\boldsymbol{x},\tilde{\boldsymbol{u}}\big)\right\}\right)$$

where $\mathscr{V}$ denotes the uncertainty set of the random parameters $\tilde{u}$.

A. Nakiganda, S. Dehghan, U. Markovic, G. Hug, P. Aristidou, "A Stochastic-Robust Approach for Resilient Microgrid Investment Planning Under Static and Transient Islanding Security Constraints", IEEE Transactions on Smart Grid, 2022

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Solution approaches:

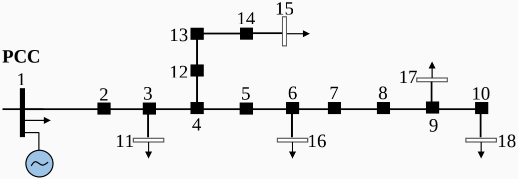
3. **Distributionally Robust Optimisation → Solve for the worst-case expectation with respect to a family of probability distributions of the uncertain parameters**

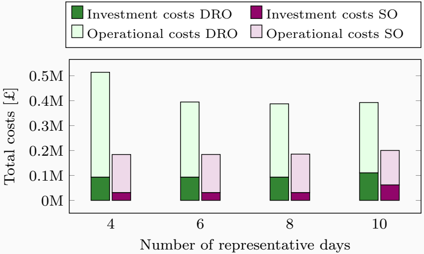
$$\min_{\boldsymbol{x}\in\chi}\left(\max_{\mathbb{P}\in\mathscr{U}}\left(\mathbb{E}_{\mathbb{P}}\left\{h(\boldsymbol{x},\tilde{\boldsymbol{u}})\right\}\right)\right)$$

where $\mathscr{U}$ defines the ambiguity set of PDFs.

A. Nakiganda, S. Dehghan, U. Markovic, G. Hug, P. Aristidou, "A Stochastic-Robust Approach for Resilient Microgrid Investment Planning Under Static and Transient Islanding Security Constraints", IEEE Transactions on Smart Grid, 2022

Challenge 2: Handling uncertainty





	DRO		SO	
Rep. Days	Decision	Comp. Time [s]	Decision	Comp. Time [s]
4	PV_1, PV_2, PV_3	109	PV_1	44
6	PV_1, PV_2, PV_3	333	PV_1	118
8	PV_1, PV_2, PV_3	682	PV_1	217
10	PV_1, PV_2, PV_3, SG_3	1175	PV_1, PV_2	476

A. M. Nakiganda, S Dehghan, P Aristidou, "A Data-Driven Optimization Model for Designing Islanded Microgrids", 2022 International Conference on Probabilistic Methods Applied to Power Systems (PMAPS), 2022

Challenge 3: Handling static and dynamic security

Challenge: How do we ensure that the system is **secure** against faults? E.g., N-1 secure.

- **Static security:** After the loss of a power infeed, the system should be able to feed the loads for a certain amount of time while complying with the security constraints.
- **Dynamic security:** The system should be able to survive the **transient** response immediately after the fault.

A. Nakiganda, P. Aristidou, "Resilient Microgrid Scheduling with Secure Frequency and Voltage Transient Response", IEEE Transactions on Power Systems, 2022.

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Examples:

- Loss of a generator (conventional or renewable).
- Abrupt islanding in case of grid-connected Microgrid.
- Load disconnection.

A. Nakiganda, P. Aristidou, "Resilient Microgrid Scheduling with Secure Frequency and Voltage Transient Response", IEEE Transactions on Power Systems, 2022.

Challenge 3: Handling static and dynamic security

Static security:

- For each fault we want to consider, we add a new set of security constraints with the faulted component missing.
- Investment decision variables are the same for both **pre-fault** and **post-fault** constraints.

$$\min_{\chi \in \Omega^{\mathrm{MG}}} \Theta^{\mathrm{inv}}(\chi^{\mathrm{inv}}) + \Theta^{\mathrm{prf,opr}}(\chi^{\mathrm{inv}}, \chi^{\mathrm{prf,opr}}) + ||\breve{\Theta}^{\mathrm{pof,opr}}(\chi^{\mathrm{inv}}, \chi^{\mathrm{prf,opr}}, \chi^{\mathrm{pof,opr}})||_{\infty} \tag{3a}$$

$$\text{s.t.} \quad \Phi(\chi^{\mathrm{inv}}, \chi^{\mathrm{prf,opr}}, \chi^{\mathrm{pof,opr}}) = 0 \tag{3b}$$

$$\Lambda(\chi^{\mathrm{inv}}, \chi^{\mathrm{prf,opr}}, \chi^{\mathrm{pof,opr}}) \leq 0 \tag{3c}$$

A. Nakiganda, P. Aristidou, "Resilient Microgrid Scheduling with Secure Frequency and Voltage Transient Response", IEEE Transactions on Power Systems, 2022.

Challenge 3: Handling static and dynamic security

Dynamic security: What happens **during** faults?

- Embedding **time-domain dynamics** inside an optimization problem is **extremely challenging**.
- We use linearizations and iterative decomposition methods.

$$\min_{\chi\in\Omega^{\mathrm{MG}}} \Theta^{\mathrm{inv}}(\chi^{\mathrm{inv}})+\Theta^{\mathrm{prf,opr}}(\chi^{\mathrm{inv}},\chi^{\mathrm{prf,opr}})+||\breve{\Theta}^{\mathrm{pof,opr}}(\chi^{\mathrm{inv}},\chi^{\mathrm{prf,opr}},\chi^{\mathrm{pof,opr}})||_\infty \tag{4a}$$

$$\text{s.t.}\quad \Phi(\chi^{\mathrm{inv}},\chi^{\mathrm{prf,opr}},\chi^{\mathrm{pof,opr}})=0 \tag{4b}$$

$$\Lambda(\chi^{\mathrm{inv}},\chi^{\mathrm{prf,opr}},\chi^{\mathrm{pof,opr}})\leq 0 \tag{4c}$$

$$\psi(\chi^{\mathrm{inv}},\chi^{\mathrm{prf,opr}},\dot{\chi}^{\mathrm{opr}})=0 \tag{4d}$$

$$\rho(\chi^{\mathrm{inv}},\chi^{\mathrm{prf,opr}},\dot{\chi}^{\mathrm{opr}})\leq 0 \tag{4e}$$

A. Nakiganda, P. Aristidou, "Resilient Microgrid Scheduling with Secure Frequency and Voltage Transient Response", IEEE Transactions on Power Systems, 2022.

Challenge 3: Handling static and dynamic security

Dynamic security example: Transient frequency security in case of loss of generator or unscheduled islanding.

$$\min_{\chi \in \Omega^{\mathrm{MG}}} \Theta^{\mathrm{inv}}(\chi^{\mathrm{inv}}) + \Theta^{\mathrm{prf,opr}}(\chi^{\mathrm{inv}}, \chi^{\mathrm{prf,opr}}) + ||\breve{\Theta}^{\mathrm{pof,opr}}(\chi^{\mathrm{inv}}, \chi^{\mathrm{prf,opr}}, \chi^{\mathrm{pof,opr}})||_{\infty} \tag{5a}$$

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A. Nakiganda, P. Aristidou, "Resilient Microgrid Scheduling with Secure Frequency and Voltage Transient Response", IEEE Transactions on Power Systems, 2022.

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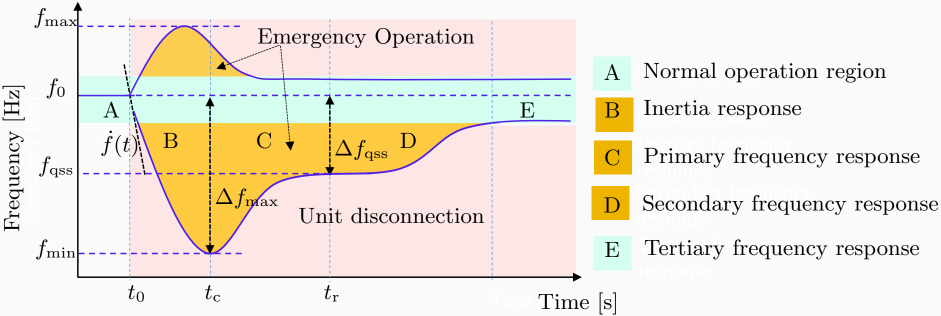

A. Nakiganda, P. Aristidou, "Resilient Microgrid Scheduling with Secure Frequency and Voltage Transient Response", IEEE Transactions on Power Systems, 2022.

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$$
\begin{aligned}
\min_{\chi \in \Omega^{\mathrm{MG}}} \quad & \Theta^{\mathrm{inv}}(\chi^{\mathrm{inv}}) + \Theta^{\mathrm{prf,opr}}(\chi^{\mathrm{inv}}, \chi^{\mathrm{prf,opr}}) + ||\breve{\Theta}^{\mathrm{pof,opr}}(\chi^{\mathrm{inv}}, \chi^{\mathrm{prf,opr}}, \chi^{\mathrm{pof,opr}})||_{\infty} && \text{(6a)} \\
\text{s.t.} \quad & \Phi(\chi^{\mathrm{inv}}, \chi^{\mathrm{prf,opr}}, \chi^{\mathrm{pof,opr}}) = 0 && \text{(6b)} \\
& \Lambda(\chi^{\mathrm{inv}}, \chi^{\mathrm{prf,opr}}, \chi^{\mathrm{pof,opr}}) \leq 0 && \text{(6c)} \\
& \psi(\chi^{\mathrm{inv}}, \chi^{\mathrm{prf,opr}}, \dot{\chi}^{\mathrm{opr}}) = 0 && \text{(6d)} \\
& \dot{f}^{\max} \leq \overline{\dot{f}}^{\max}, && \text{(6e)} \\
& \Delta f^{\max} \leq \overline{\Delta f}^{\max}, && \text{(6f)} \\
& \underline{\Delta f}^{\mathrm{ss}} \leq \Delta f^{\mathrm{ss}} \leq \overline{\Delta f}^{\mathrm{ss}} && \text{(6g)}
\end{aligned}
$$

A. Nakiganda, P. Aristidou, "Resilient Microgrid Scheduling with Secure Frequency and Voltage Transient Response", IEEE Transactions on Power Systems, 2022.

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$$\boxed{\psi(\chi^{\mathrm{inv}},\chi^{\mathrm{prf,opr}},\dot{\chi}^{\mathrm{opr}}) = 0} \tag{6d}$$

$$\dot{f}^{\max} \le \overline{\dot{f}}^{\max}, \tag{6e}$$

$$\Delta f^{\max} \le \overline{\Delta f}^{\max}, \tag{6f}$$

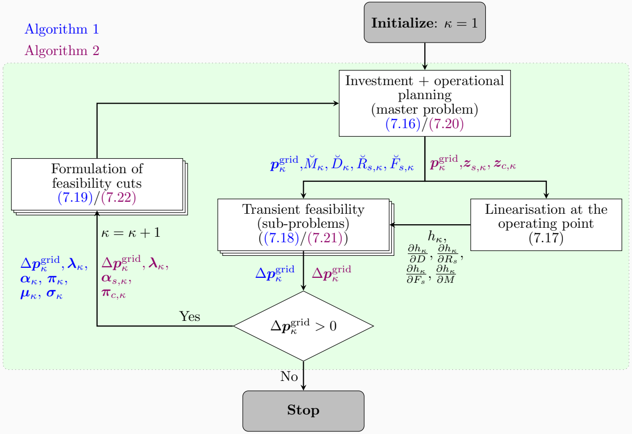
$$\underline{\Delta f}^{\mathrm{ss}} \le \Delta f^{\mathrm{ss}} \le \overline{\Delta f}^{\mathrm{ss}} \tag{6g}$$

Move to sub-problem, replace with linear feasibility cuts, and iterate between master and sub-problem

A. Nakiganda, P. Aristidou, "Resilient Microgrid Scheduling with Secure Frequency and Voltage Transient Response", IEEE Transactions on Power Systems, 2022.

Challenge 3: Handling static and dynamic security

Dynamic security example: Transient frequency security in case of loss of generator or unscheduled islanding.



Algorithm 1

Algorithm 2

Initialize: $\kappa = 1$

Investment + operational planning (master problem) (7.16)/(7.20)

$\boldsymbol{p}_\kappa^{\text{grid}}, \breve{M}_\kappa, \breve{D}_\kappa, \breve{R}_{s,\kappa}, \breve{F}_{s,\kappa}$

$\boldsymbol{p}_\kappa^{\text{grid}}, \boldsymbol{z}_{s,\kappa}, \boldsymbol{z}_{c,\kappa}$

Formulation of feasibility cuts (7.19)/(7.22)

Transient feasibility (sub-problems) ((7.18)/(7.21))

Linearisation at the operating point (7.17)

$h_\kappa, \frac{\partial h_\kappa}{\partial D}, \frac{\partial h_\kappa}{\partial R_s}, \frac{\partial h_\kappa}{\partial F_s}, \frac{\partial h_\kappa}{\partial M}$

$\kappa = \kappa + 1$

$\Delta\boldsymbol{p}_\kappa^{\text{grid}}, \boldsymbol{\lambda}_\kappa, \boldsymbol{\alpha}_\kappa, \boldsymbol{\pi}_\kappa, \boldsymbol{\mu}_\kappa, \boldsymbol{\sigma}_\kappa$

$\Delta\boldsymbol{p}_\kappa^{\text{grid}}, \boldsymbol{\lambda}_\kappa, \boldsymbol{\alpha}_{s,\kappa}, \boldsymbol{\pi}_{c,\kappa}$

$\Delta\boldsymbol{p}_\kappa^{\text{grid}}$

$\Delta\boldsymbol{p}_\kappa^{\text{grid}}$

Yes

$\Delta\boldsymbol{p}_\kappa^{\text{grid}} > 0$

No

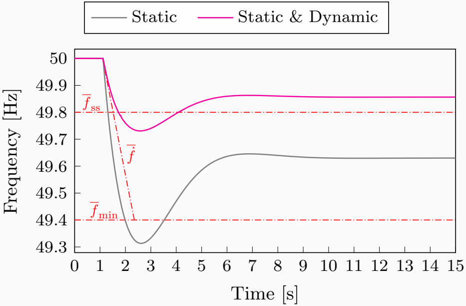
Stop

A. Nakiganda, P. Aristidou, "Resilient Microgrid Scheduling with Secure Frequency and Voltage Transient Response", IEEE Transactions on Power Systems, 2022.

Challenge 3: Handling static and dynamic security

Dynamic security example: Transient frequency security in case of loss of generator or unscheduled islanding.

	Only Static	**Static & Dynamic**
Costs and decisions		
Total cost (\$)	223390	242740
Investment cost (\$)	61000	131000
Investment decisions	PV_3	PV_1, PV_3
Operational cost (\$)	162390	111740
Demand disconnection penalty	14536	5337
Computational performance		
Number of iterations	-	4
Computation time (s)	612	3386
Inertia support		
M (s)	7.84	17.64
D (p.u)	0.50	1.13



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Real Case Study

Watoto Suubi Village (Uganda)

- Christian-founded orphanages set up by Watoto Child Care Ministries in Uganda
- home clusters that house the children and mothers (total 180 homes)
- Kindergarten, primary, secondary and vocation schools, a clinic, a church, fabrication workshops, a baby nursery (Baby Watoto), administrative offices, a goat farm, water pumping systems, staff housing, and multi-functional halls
- Intermittent supply of electric power from the main grid, of poor quality and high cost

Watoto Suubi Village (Uganda)

Homes Cluster

Primary School

Fabrication Workshop

Watoto Clinic

Watoto Suubi Village (Uganda): Input data

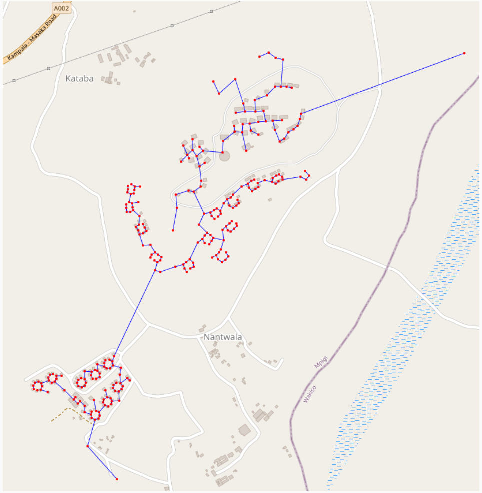
Routing

Watoto Suubi Village (Uganda): Input data

Routing

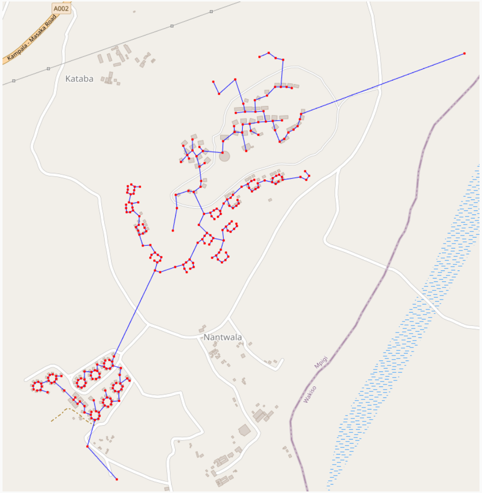
Watoto Suubi Village (Uganda): Input data

Routing

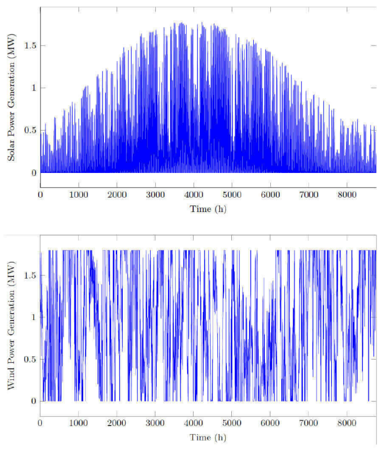


Watoto Suubi Village (Uganda): Input data

Routing

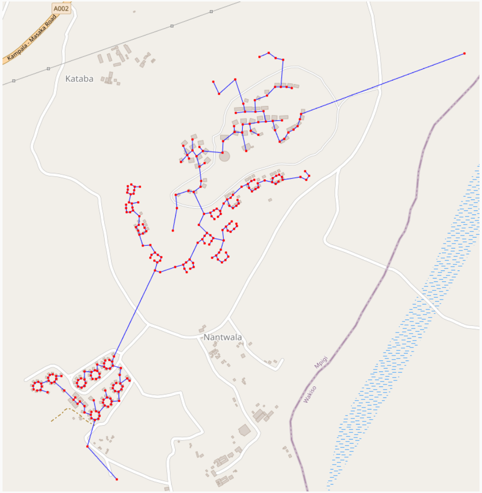


Solar and wind data

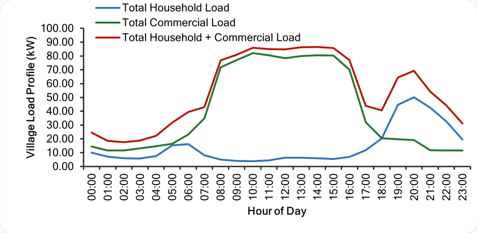


Watoto Suubi Village (Uganda): Input data

Routing



Load data



Watoto Suubi Village (Uganda): Financial input/output

Cost input

Investment Candidate	Capital Cost ($\$/\mathrm{kW}$)	Annualized Capital Cost ($\$/\mathrm{kW-yr}$)	Operation Cost ($\$/\mathrm{kWh}$)	Life Time (years)
Diesel	185	12	0.27	30
Solar	1672	109	0.00	30
Battery	3604	347	0.00	15

Design output

Diesel Unit	Solar Unit	Battery Unit	Investment Cost ($\$-yr$)	Operation Cost ($\$-yr$)	Total Cost ($\$-yr$)	LCOE ($/kWh)
50 kW	250 kW	100 kW	$62,514.98$	692.46	$63,207.45$	0.152

Watoto Suubi Village (Uganda): Google COLAB platform

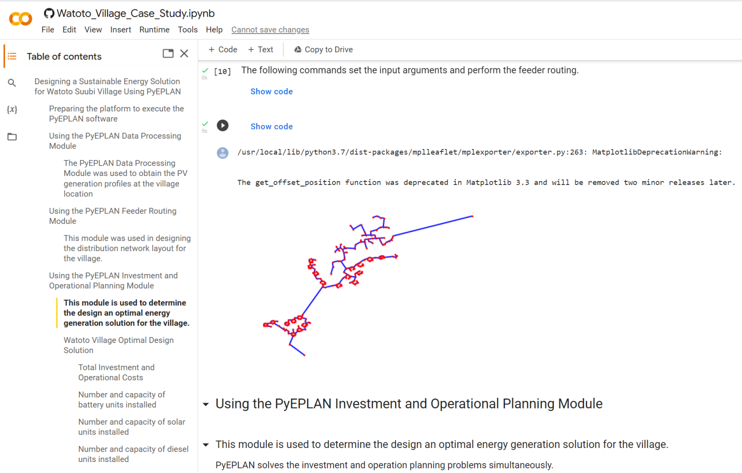


Table of contents

- Designing a Sustainable Energy Solution for Watoto Suubi Village Using PyEPLAN
  - Preparing the platform to execute the PyEPLAN software
  - Using the PyEPLAN Data Processing Module
    - The PyEPLAN Data Processing Module was used to obtain the PV generation profiles at the village location
  - Using the PyEPLAN Feeder Routing Module
    - This module was used in designing the distribution network layout for the village.
  - Using the PyEPLAN Investment and Operational Planning Module
    - **This module is used to determine the design an optimal energy generation solution for the village.**
    - Watoto Village Optimal Design Solution
      - Total Investment and Operational Costs
      - Number and capacity of battery units installed
      - Number and capacity of solar units installed
      - Number and capacity of diesel units installed

[10] The following commands set the input arguments and perform the feeder routing.

```
/usr/local/lib/python3.7/dist-packages/mplleaflet/mplexporter/exporter.py:263: MatplotlibDeprecationWarning:

The get_offset_position function was deprecated in Matplotlib 3.3 and will be removed two minor releases later.
```

Using the PyEPLAN Investment and Operational Planning Module

This module is used to determine the design an optimal energy generation solution for the village.

PyEPLAN solves the investment and operation planning problems simultaneously.

https://pyeplan.sps-lab.org/get_started/examples.html

Concluding remarks

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- Rural electrification is key to achieving the SDG7 set by UN and bringing electricity to almost 1 billion people
- Designing low-cost, secure, and resilient electrification solutions is **data-intensive**, **mathematically complex**, and **computationally challenging**
- There is a need for **easily accessible** and **free** planning tools that will allow for to reduction in the cost of energy and promote electrification efforts.
- There is a need for free and open training and education.

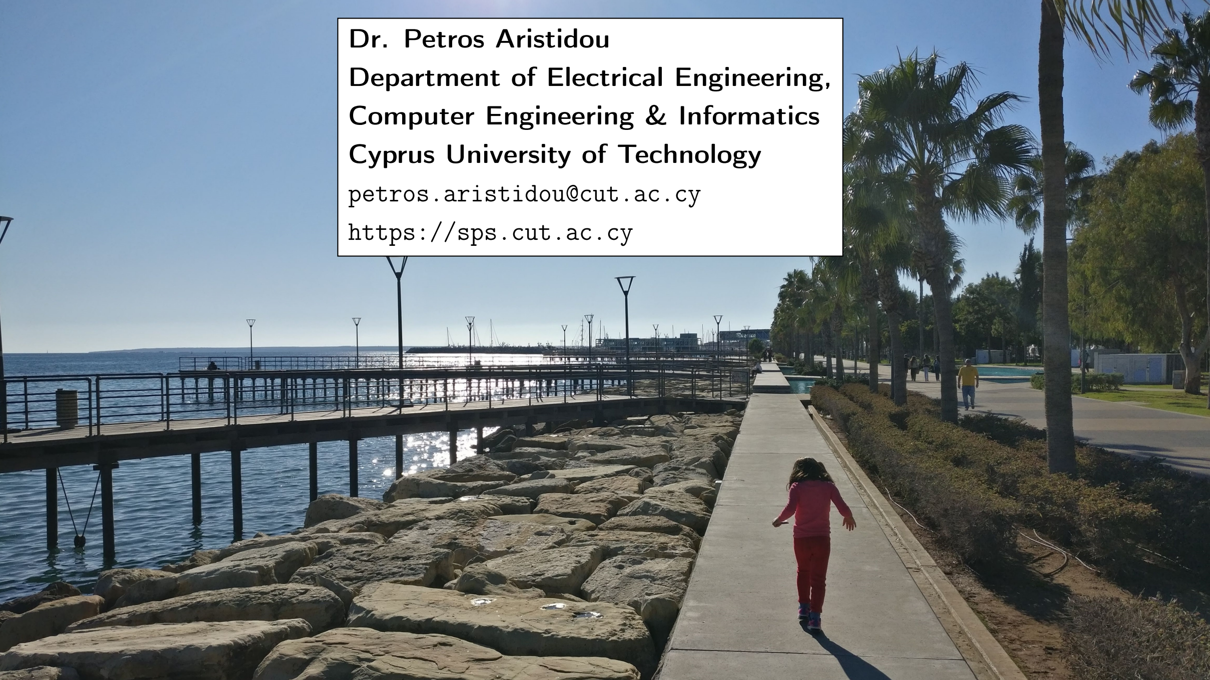
Further reading

Learn more about rural electrification and Microgrid planning

- Renewable Energy: Sustainable Electricity Supply with Microgrids, FutureLearn Online course, `https://www.futurelearn.com/courses/renewable-energy-sustainable-electricity-supply-with-microgrids`
- S. Dehghan, A. Nakiganda, J. Lancaster, P. Aristidou, "Towards a Sustainable Microgrid on Alderney Island Using a Python-based Energy Planning Tool", Proc. of the 2020 MEDPOWER, 2020.

Dive into the techniques and maths behind it

- A. Nakiganda, S. Dehghan, U. Markovic, G. Hug, P. Aristidou, "A Stochastic-Robust Approach for Resilient Microgrid Investment Planning Under Static and Transient Islanding Security Constraints", IEEE Transactions on Smart Grid, 2022.
- A. Nakiganda, P. Aristidou, "Resilient Microgrid Scheduling with Secure Frequency and Voltage Transient Response", IEEE Transactions on Power Systems, 2022.
- A. Nakiganda, S. Dehghan, P. Aristidou, "Comparison of AC Optimal Power Flow Methods in Low-Voltage Distribution Networks", Proc. of the 2021 ISGT conf., 2021.
- S. Dehghan, A. Nakiganda, P. Aristidou, "A Data-Driven Two-Stage Distributionally Robust Planning Tool for Sustainable Microgrids", Proc. of the 2020 IEEE General Meeting, 2020



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