Integrating Stakeholder Preferences into Generation Expansion Planning

– The MEA Model –

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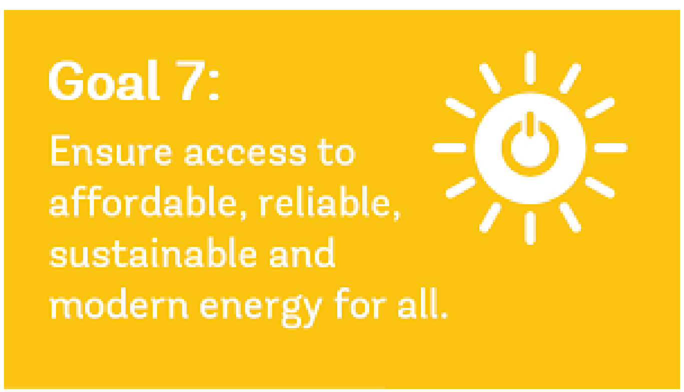

Nock et al 2020 – Applied Energy

Developed World

Situation
- Grid is well developed
- Access is unlimited
- System is reliable (hours of outage per year)

Problem
- Minimize:
  - Cost
- Subject to:
  - Demand, Reliability, and Environmental constraints

Developing World

Situation
- Grid is undeveloped
- Access is limited
- System is unreliable (hours of outage per day)
- Demand may be unknown

Problem
- Maximize:
  - Social Benefit
- Subject to:
  - Cost

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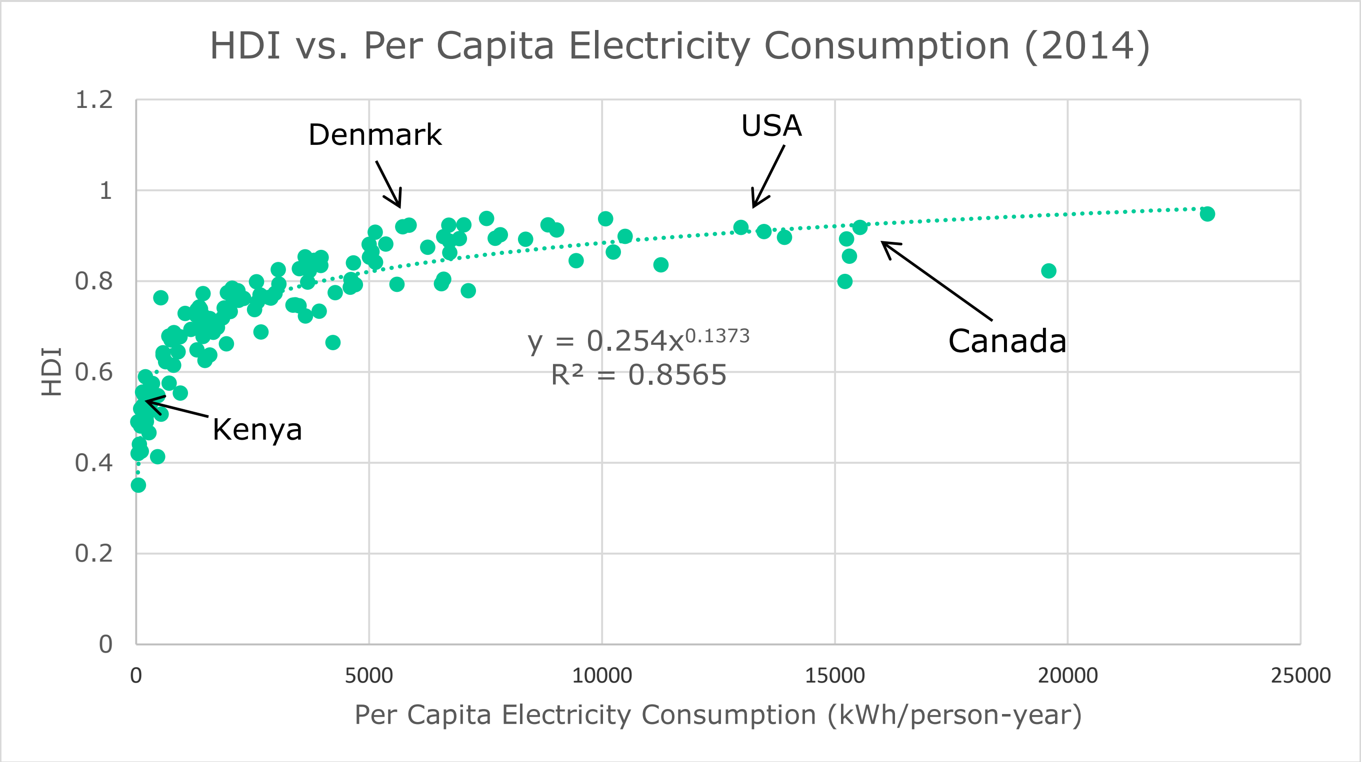
Estimating Social Benefit & Equality Preference Functional Form

- Human Development Index (HDI) is a composite statistic of life expectancy, education, and per capita income indicators created by the United Nations



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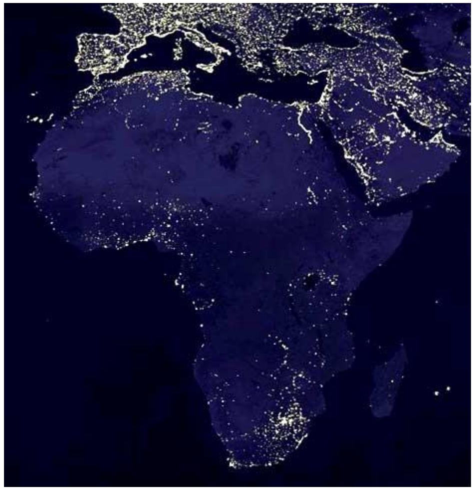
Maximize Energy Access (MEA) Model Objective Function

- Maximize Utility derived from potential electricity access

$$U(\mathbf{x},\mathbf{p}) = \sum_{i \in I} u(x_i, p_i)$$



  - Where utility for the population in node i is defined as:

$$u(x_i, p_i) = p_i \frac{\left(\left(\frac{x_i}{p_i}\right)^{1-\alpha} - 1\right)}{1-\alpha} = p_i \frac{(\rho_i^{1-\alpha} - 1)}{1-\alpha}$$

- x_i = maximum electrical energy that can be delivered to node i
- p_i = number of consumers in node i
- α = equality preference parameter contained in (0,1)
  - 1 = higher preference for distributional equality; 0 = only care about max electricity in nation
  - Mixed Integer Program solved using Gurobi, Python, and a piece-wise linear approximation for the objective function

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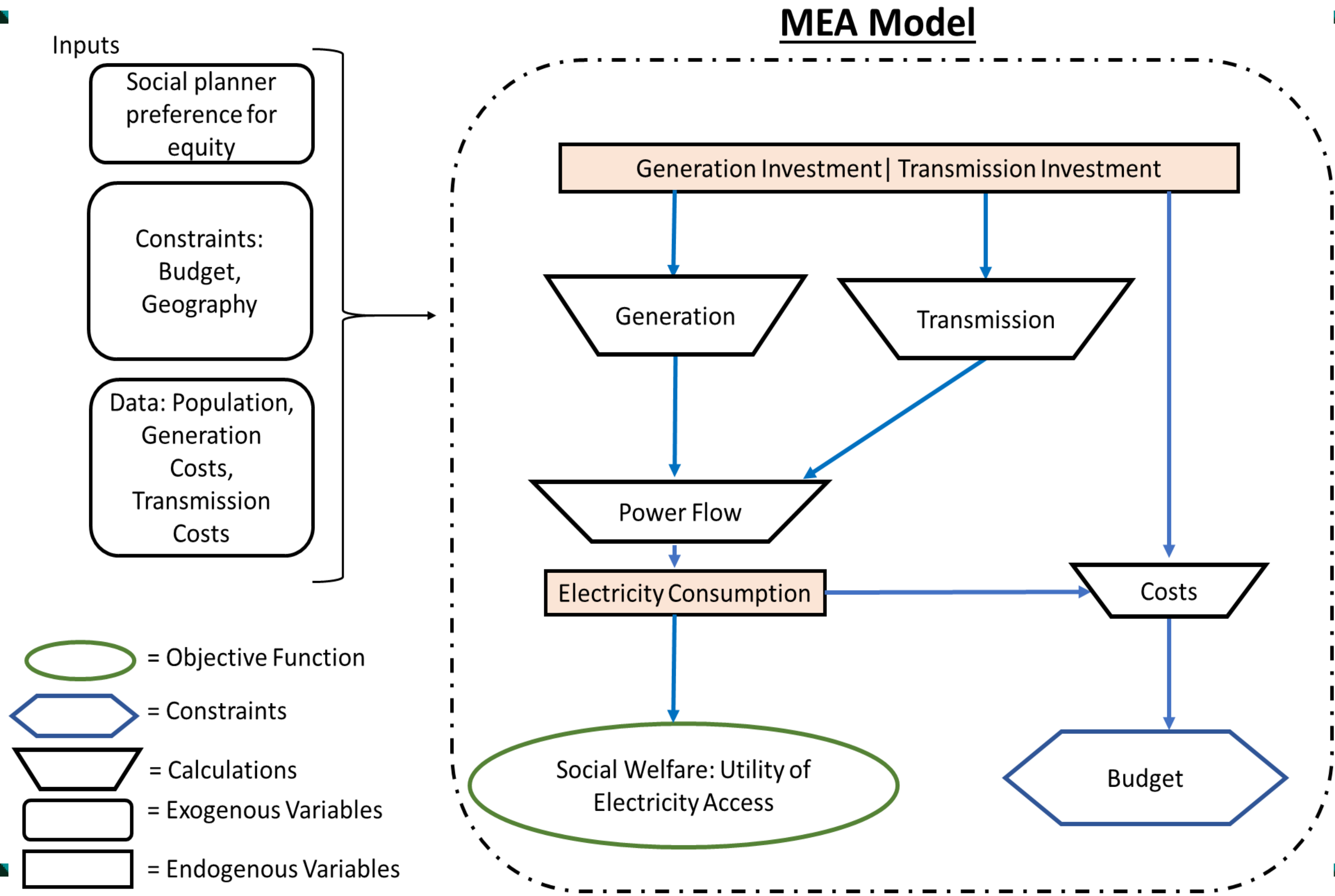
Full model published in Nock et al 2020 – Applied Energy

MEA Model - Flow of Information



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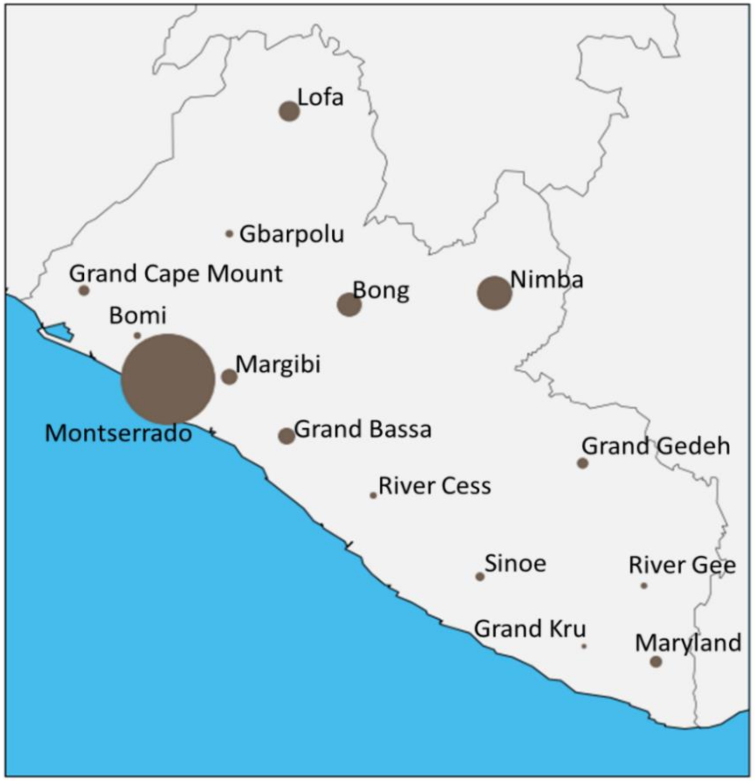
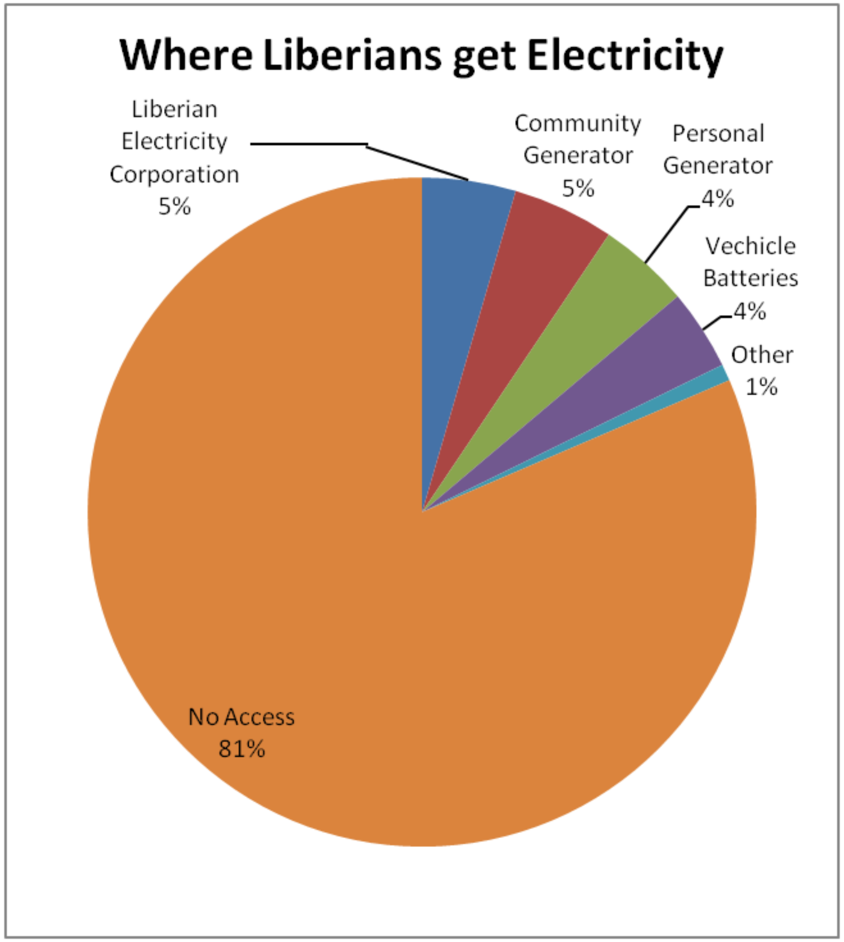
Nock et al 2020 - Applied Energy

The Initial Case Study: Liberia

- Population: 4,689,021 (2017)
- Electrification: 10%





Source: CIA World Factbook

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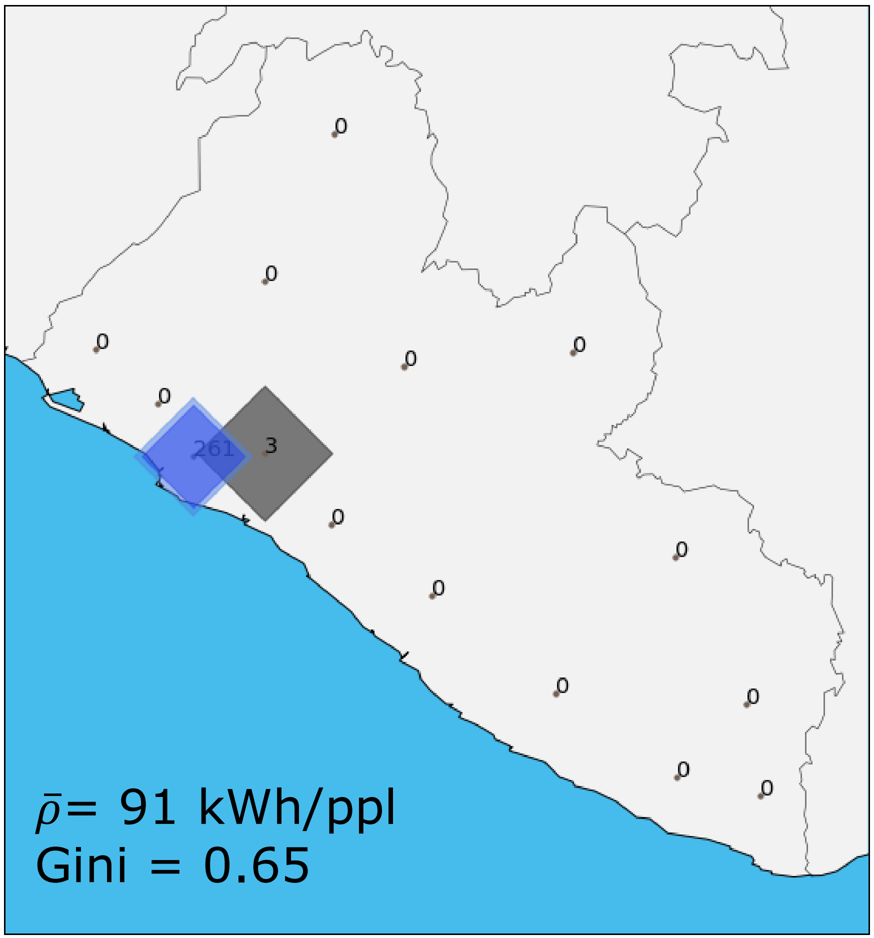
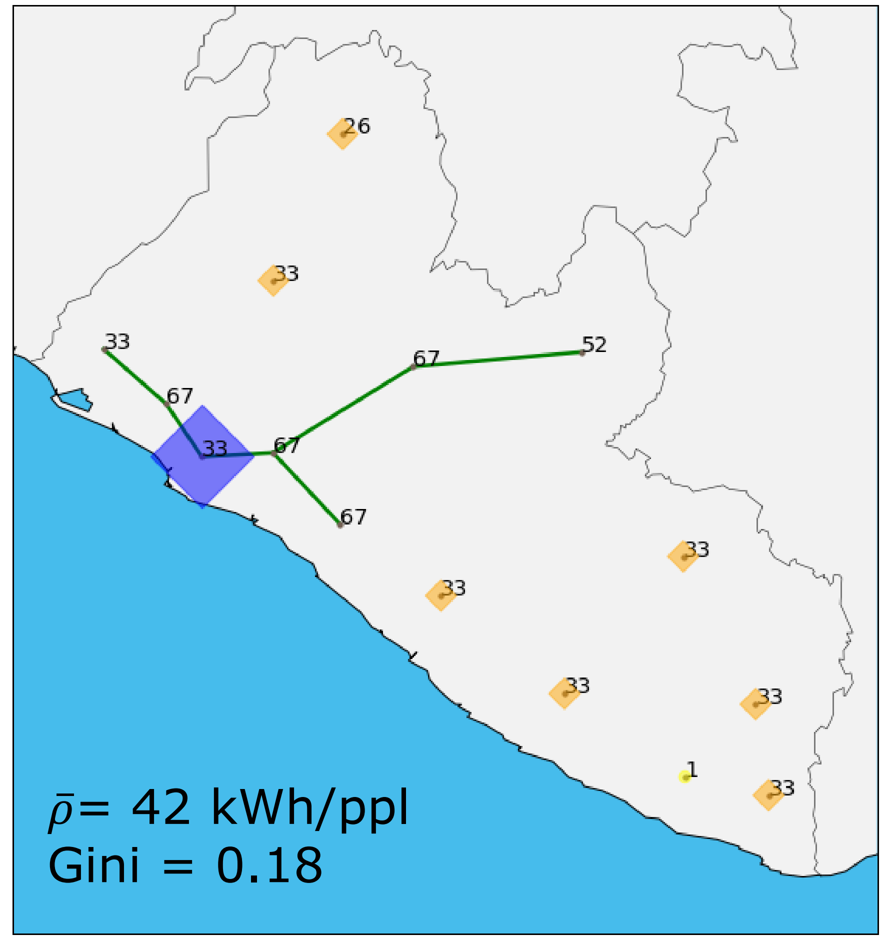
Electricity Infrastructure Investments Under Changing Equity Preferences. B = 10 million $/yr

Low Equality Preference (α = 0.10)



High Equality Preference (α = 0.86)



Hydro Centralized Generation
PV-diesel Mini Grid
Decentralized SHS Generation
No Generation Infrastructure
Low Voltage Transmission Line

Electricity Infrastructure Investments Under Changing Equity Preferences. B = 50 million $/yr

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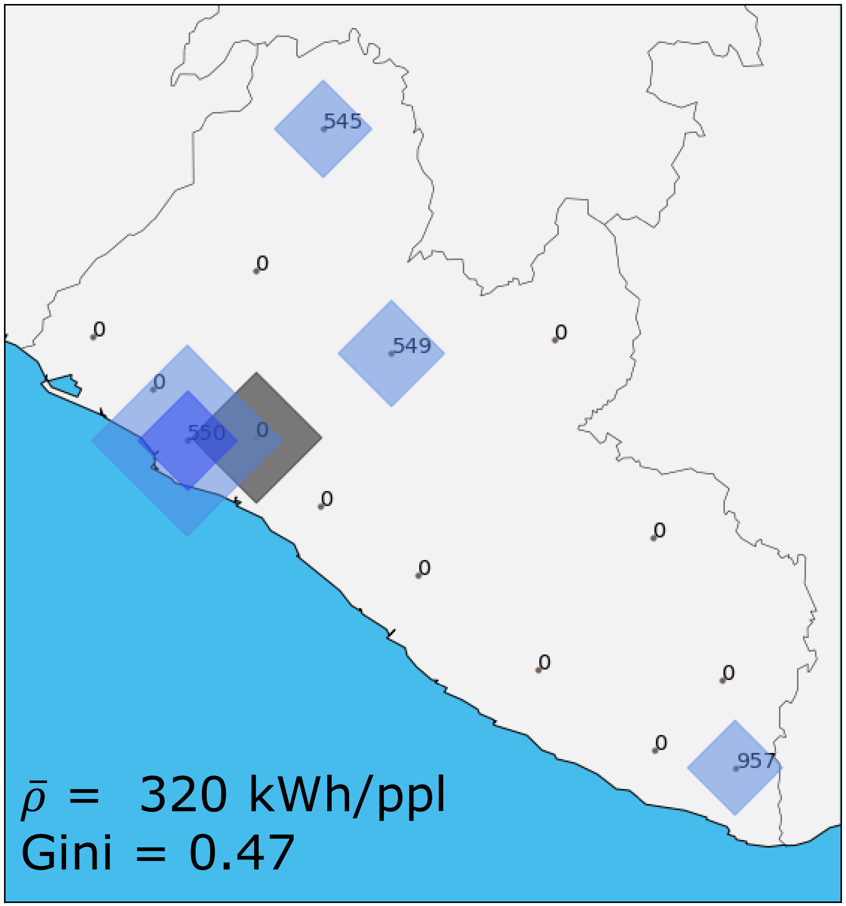

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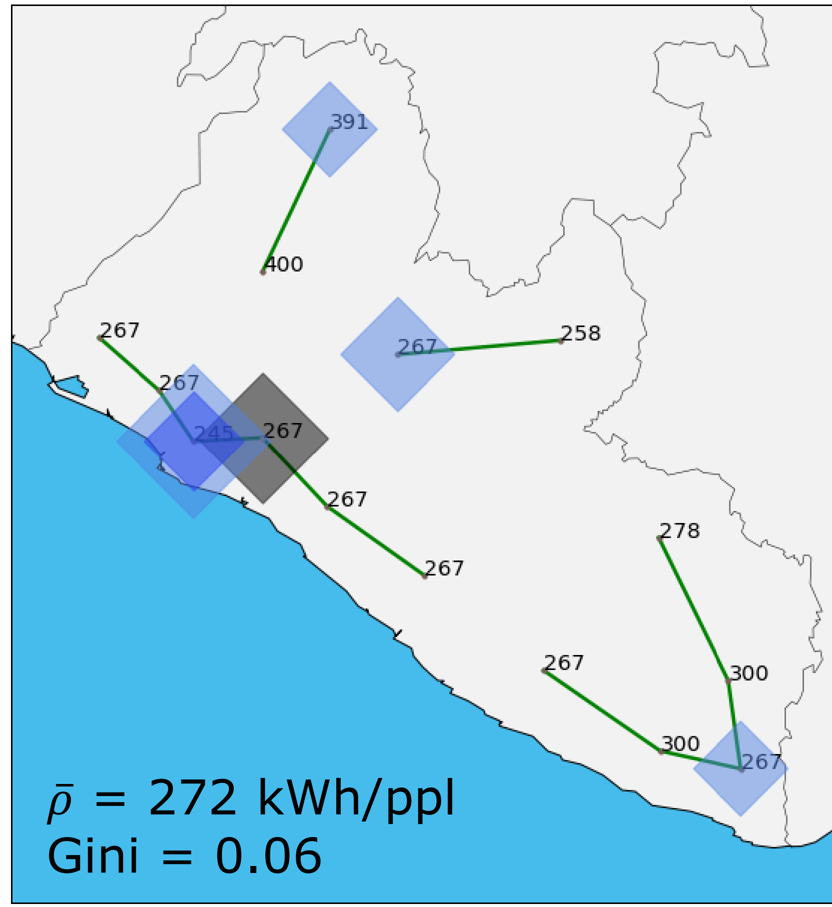

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PV-diesel Mini Grid

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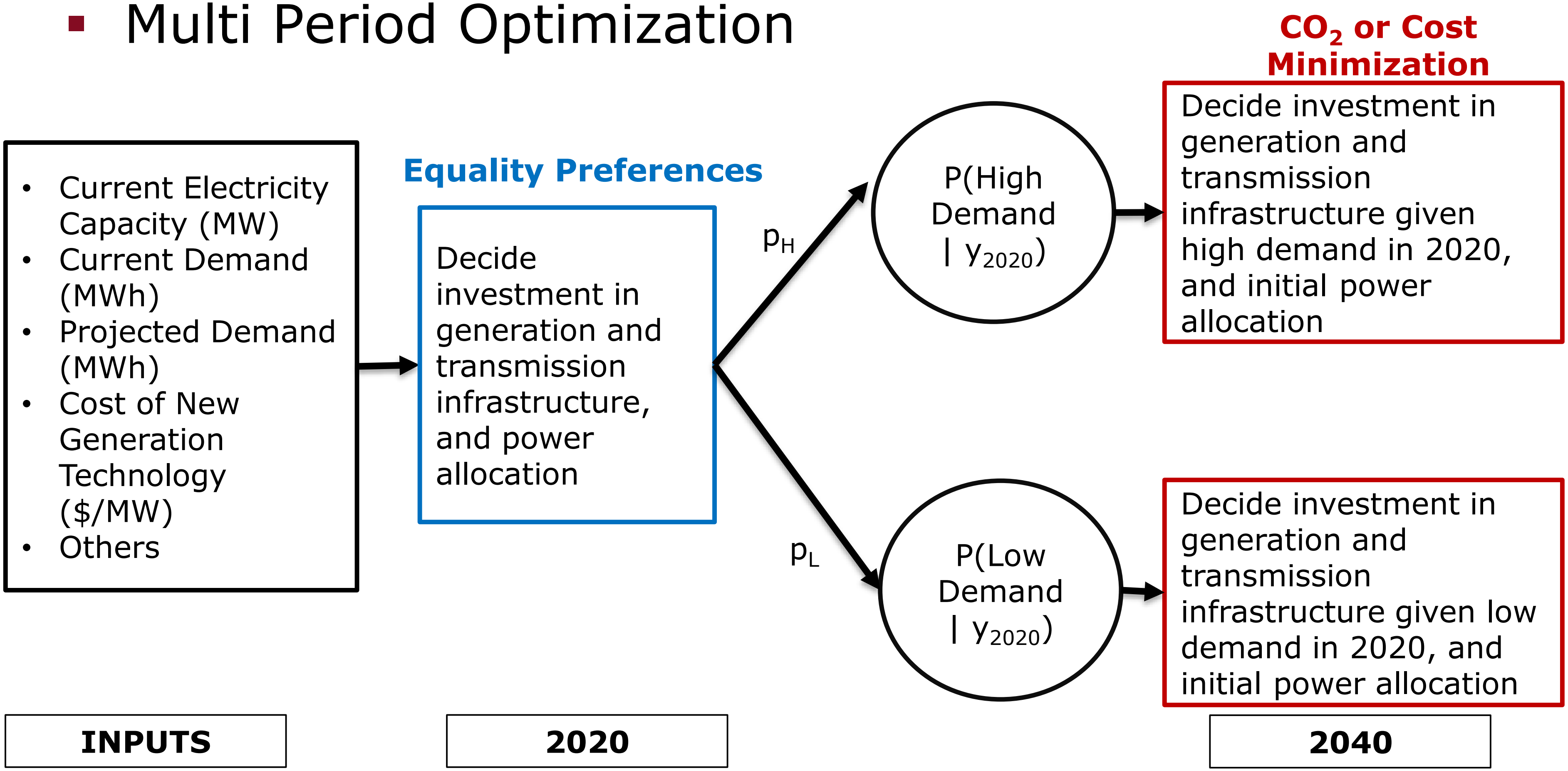
Future Work & Collaboration Opportunities

- Multi Period Optimization



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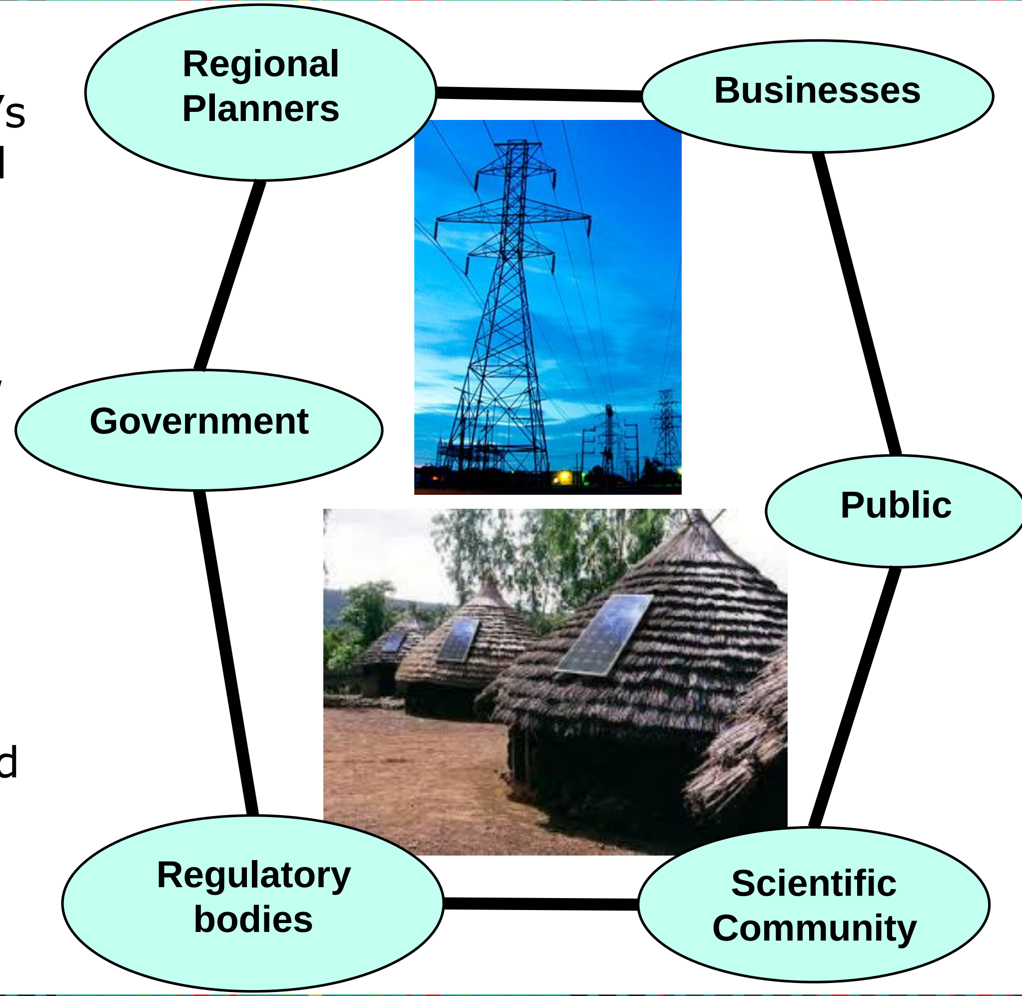
Overall Conclusions

- The model determines generation expansion plan under a stakeholder's preference for equity using potential electricity access as a proxy for human development.
- The information here illustrates how investment decisions change under stakeholder preferences.
  - Preferences Matter!
- Next steps: tie with a least cost model and understand how power expansion options could be impacted by preferences; integrate other preferences.



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  - Twitter: @destenienock

Key References

- Nock, Destenie, Todd Levin, and Erin Baker. "Changing the policy paradigm: A benefit maximization approach to electricity planning in developing countries." Applied Energy 264 (2020): 114583.

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  - Olivia Pfieffer, Ivan Norman, Ami Khalsa

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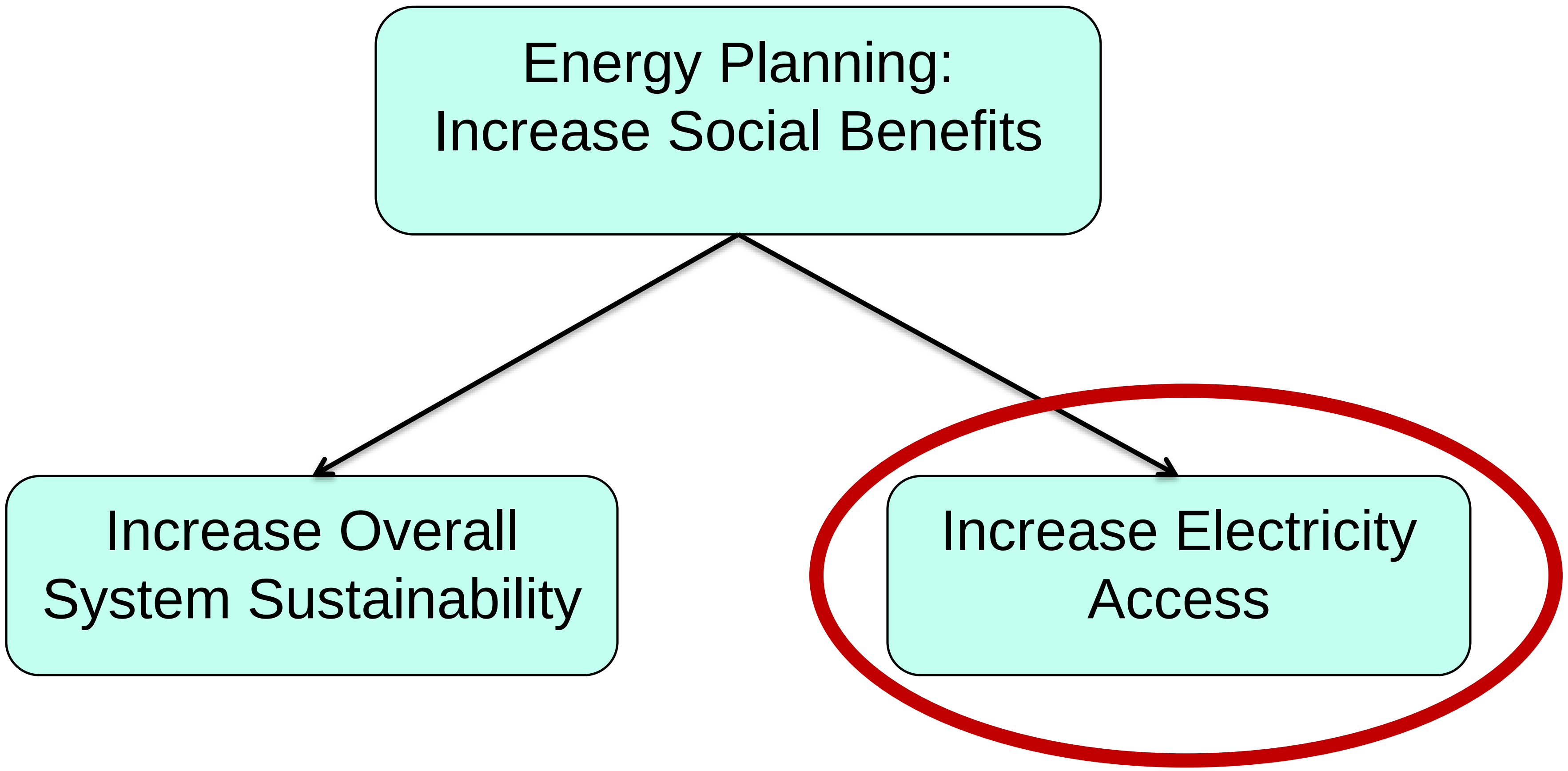
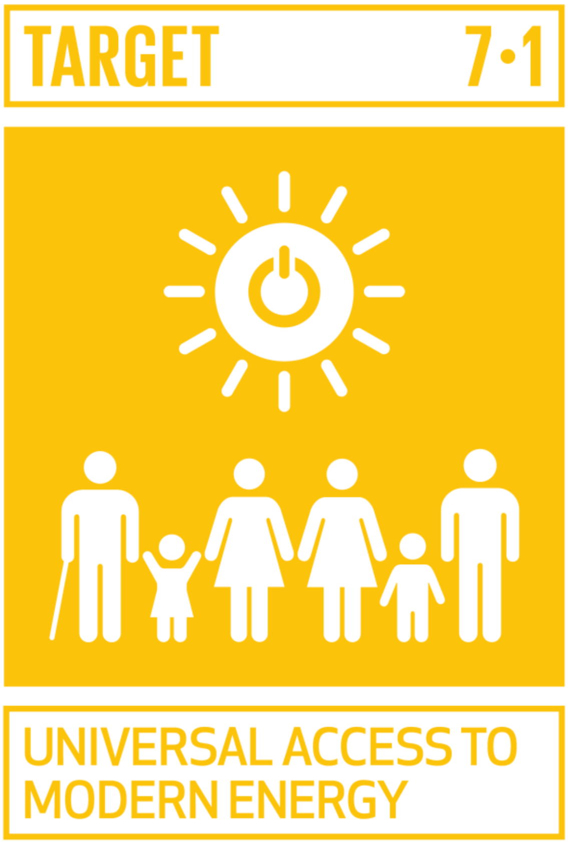
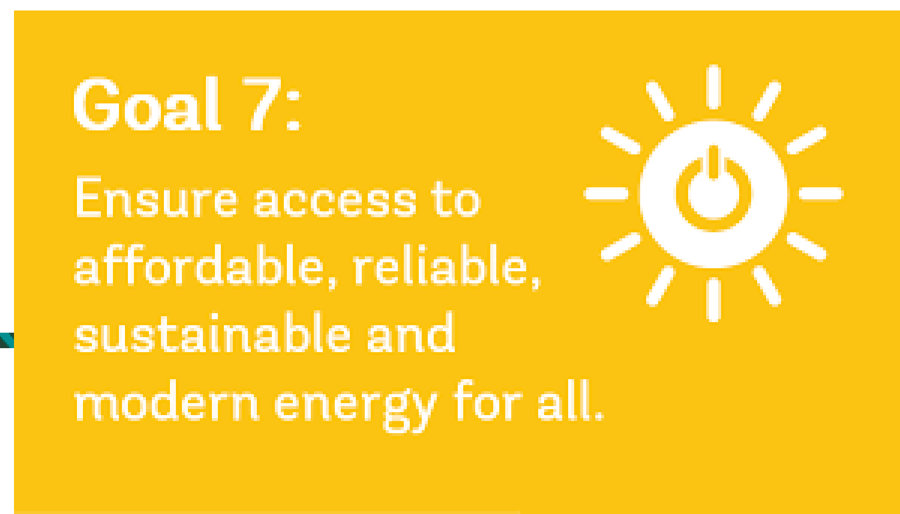
Motivation – Energy Planning



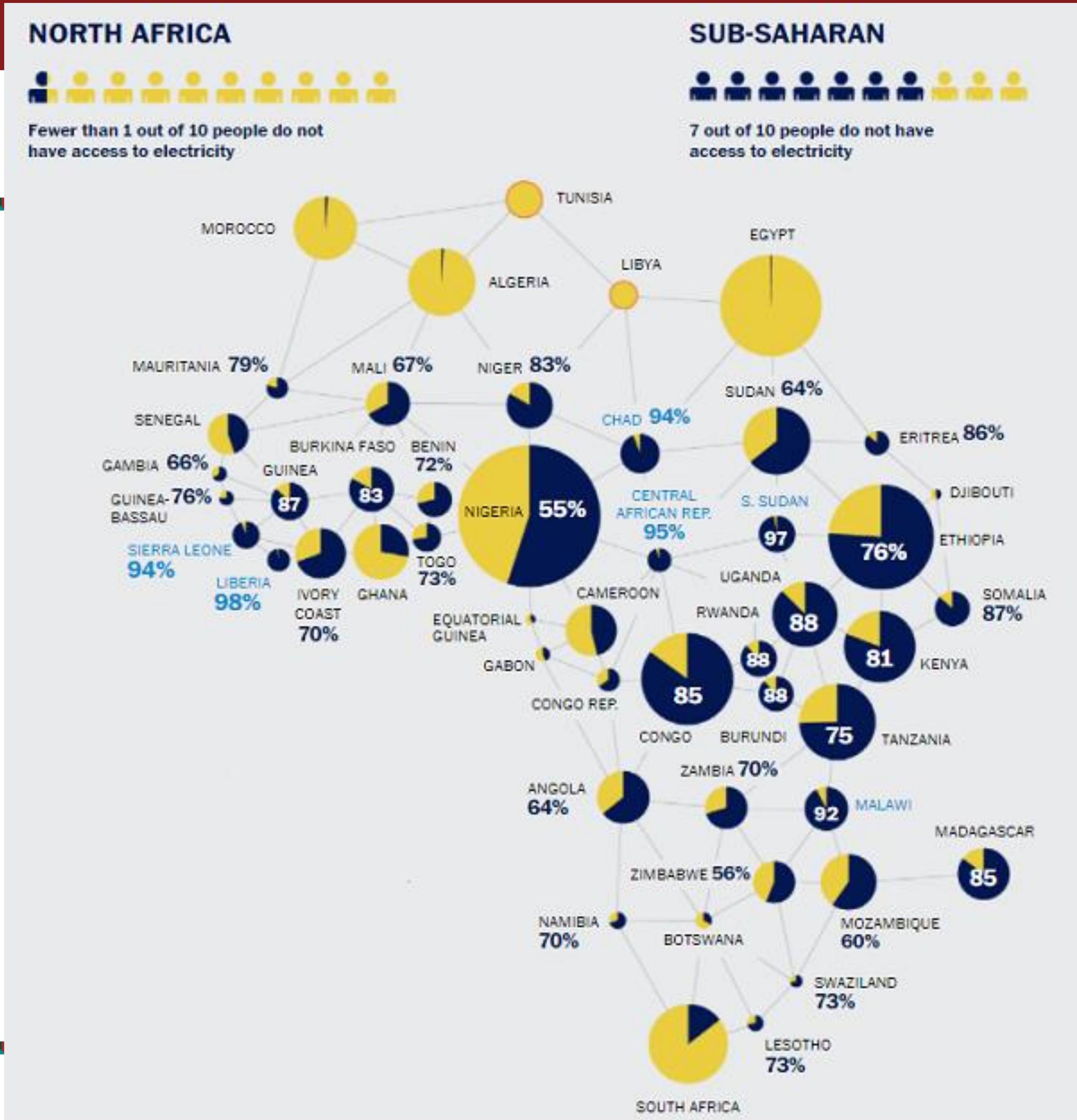
Motivation – United Nations 2030 Target





Equality Concerns

- Injustices in the energy sector occur at three scales (Sovacool et al, 2019).



Sources: Washington Post, International Energy Agency's electricity database and methodology, World Bank, Worldwatch Institute, NASA

Equality Concerns

- Micro Scale: such as local environmental impacts and exclusion of rural areas from benefits;

Photo of homes under power grid

Equality Concerns

- Meso Scale - national-scale issues such as unequal access to renewable technologies, ability to purchase low-carbon technology, and increasing electricity prices

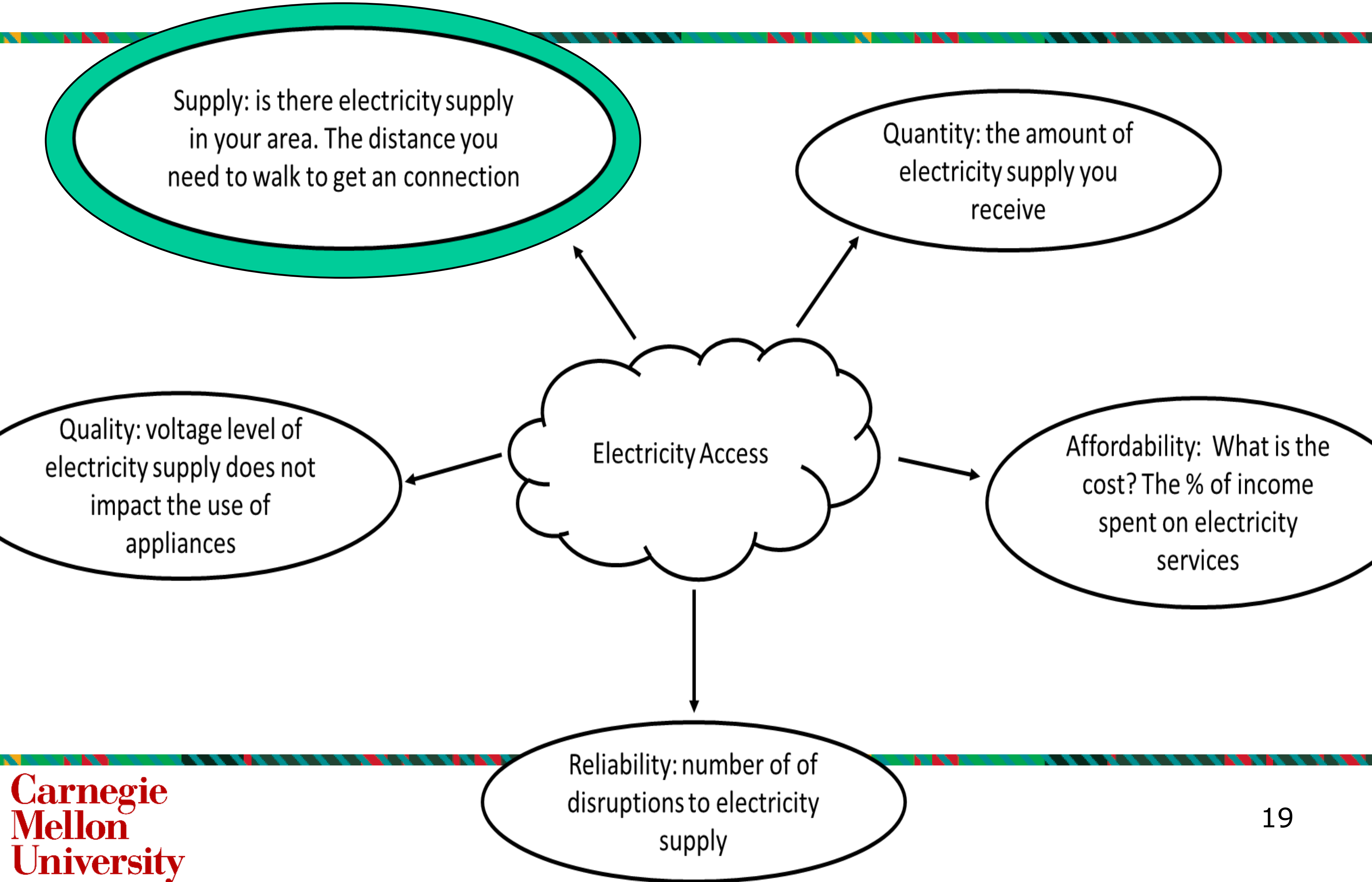
Equality Concerns

- Macro Scale –global level extraction of materials and global waste streams

We focus on the Meso Scale

- Meso Scale - national-scale issues of increasing electricity access

5 Facets of Electricity Access



MEA Model

- Objective: max $U\left(\mathbf{x},\mathbf{p}\right)$
- Budget Constraint

$$\sum_{(i,j)\in E}\left(C^{T,L}d_{i,j} * e^{L}_{i,j} + C^{T,H}d_{i,j} * e^{H}_{i,j}\right) + \sum_{i\in I,k\in K}(C_k{}^F G_{i,k} + C_k{}^V g_{i,k}) \leq B$$

Transmission Costs + Generation Costs < Budget

- Electricity Availability (Power Flow) Constraint

$$x_i \leq g_i + \sum_{j\in N} f_{j,i} - \sum_{j\in N} f_{i,j}$$

Electricity at node i < Generation at node i + Flow into node i – Flow out of node i

- Generation Constraints

$$g_i \leq \sum_{i\in I,k\in K_i} g_{i,k}$$

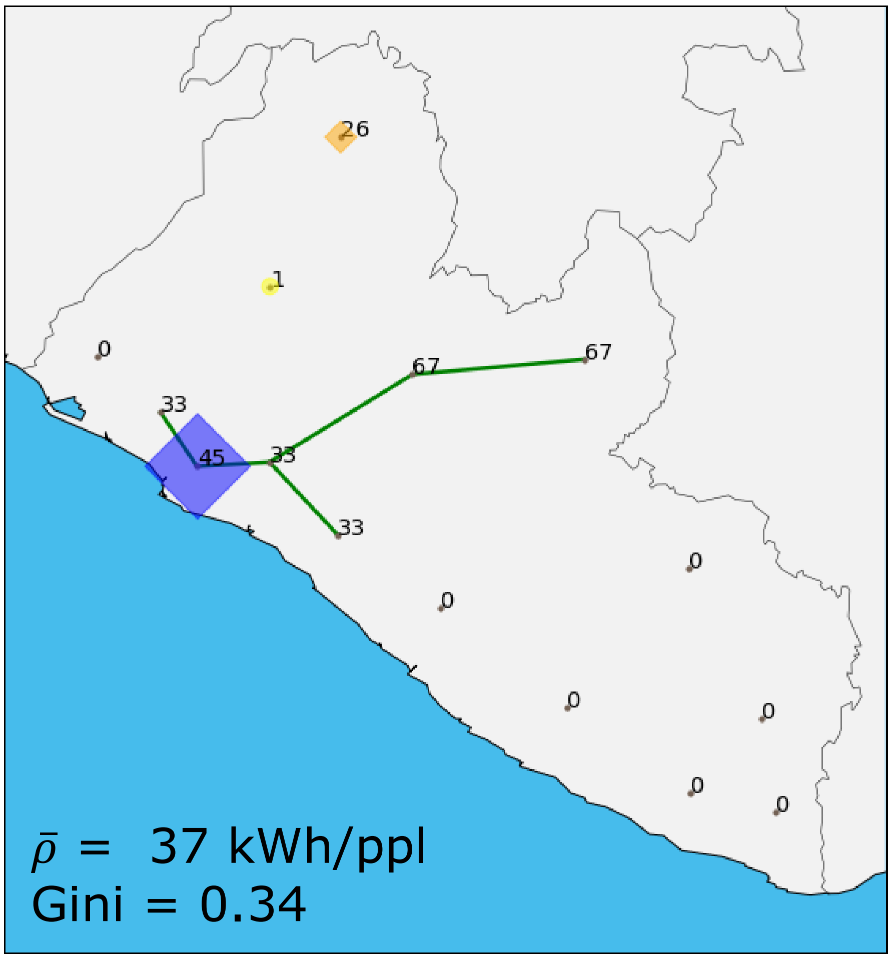
Generation at node i < Sum of all generation sources at node i

- Other Constraints: Transmission capacities and locations, Generation capacities and locations, non-negativity

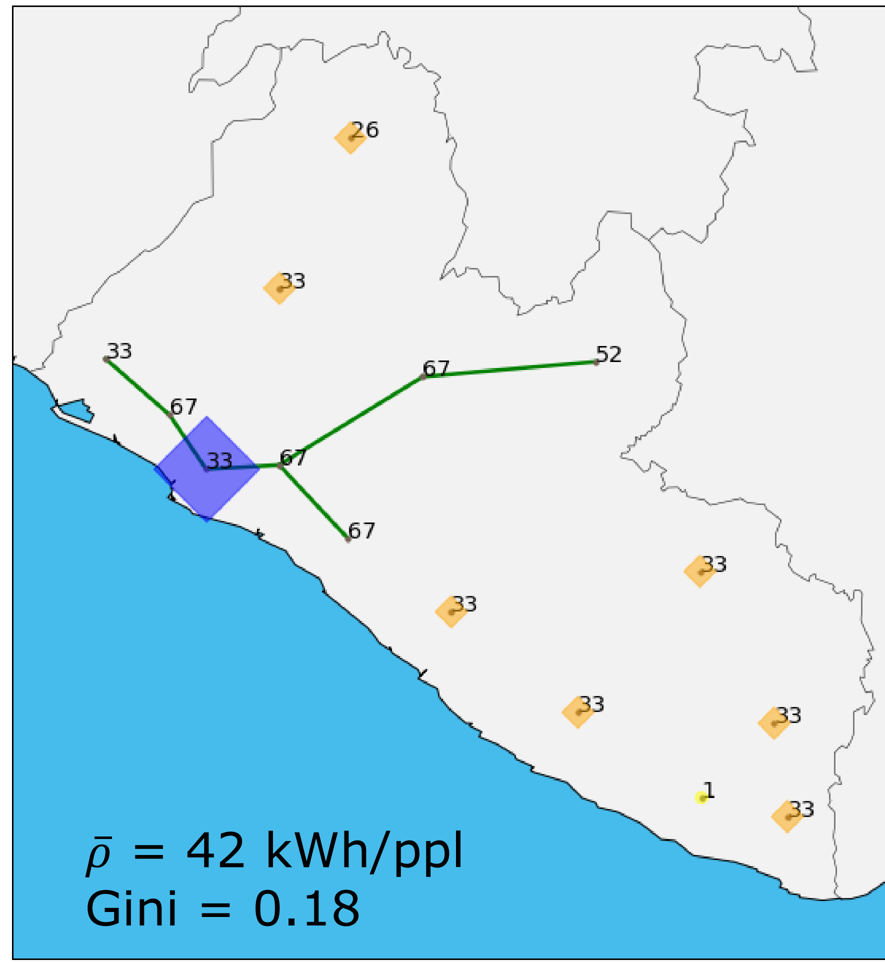
k = generation type i, j = node location

Electricity Infrastructure Investments Under Increasing Power Sector Budgets, High equality preference (α=0.86)

5 million $/yr



10 million $/yr



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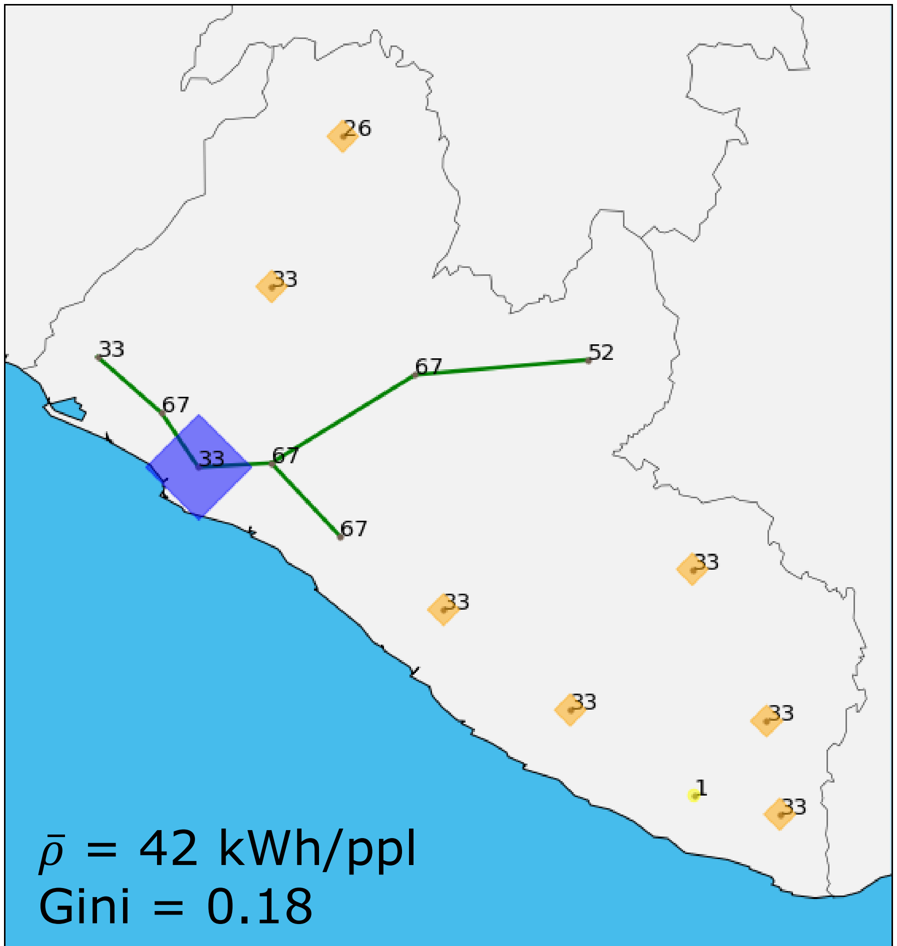
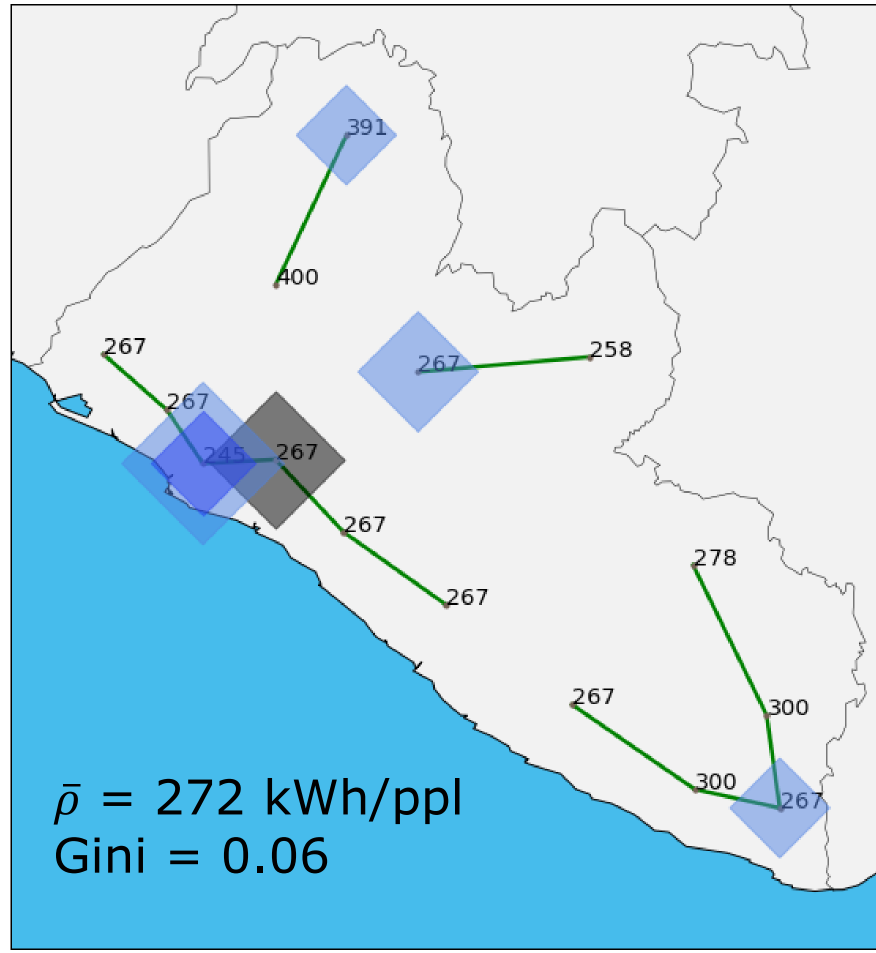


50 million $/yr



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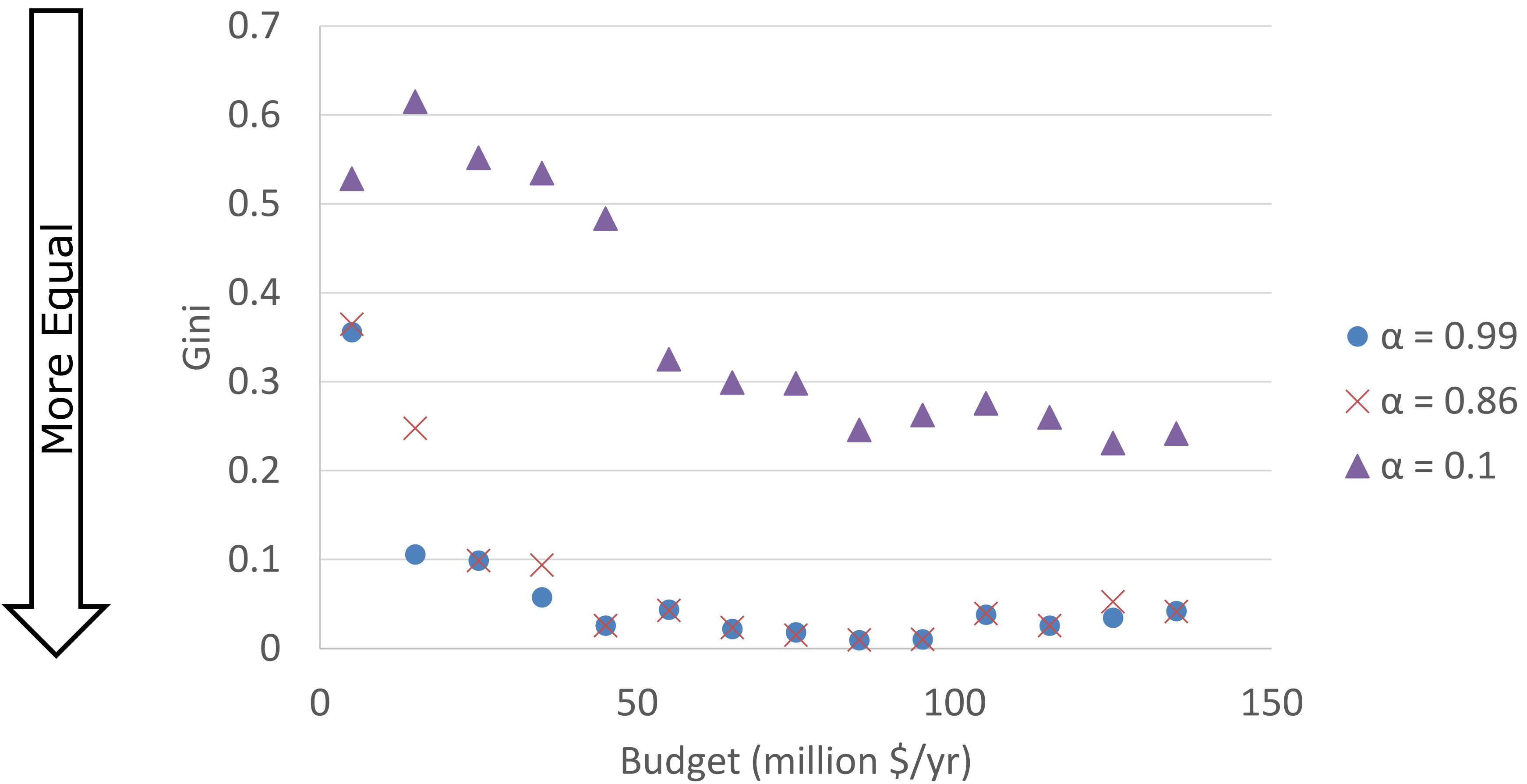
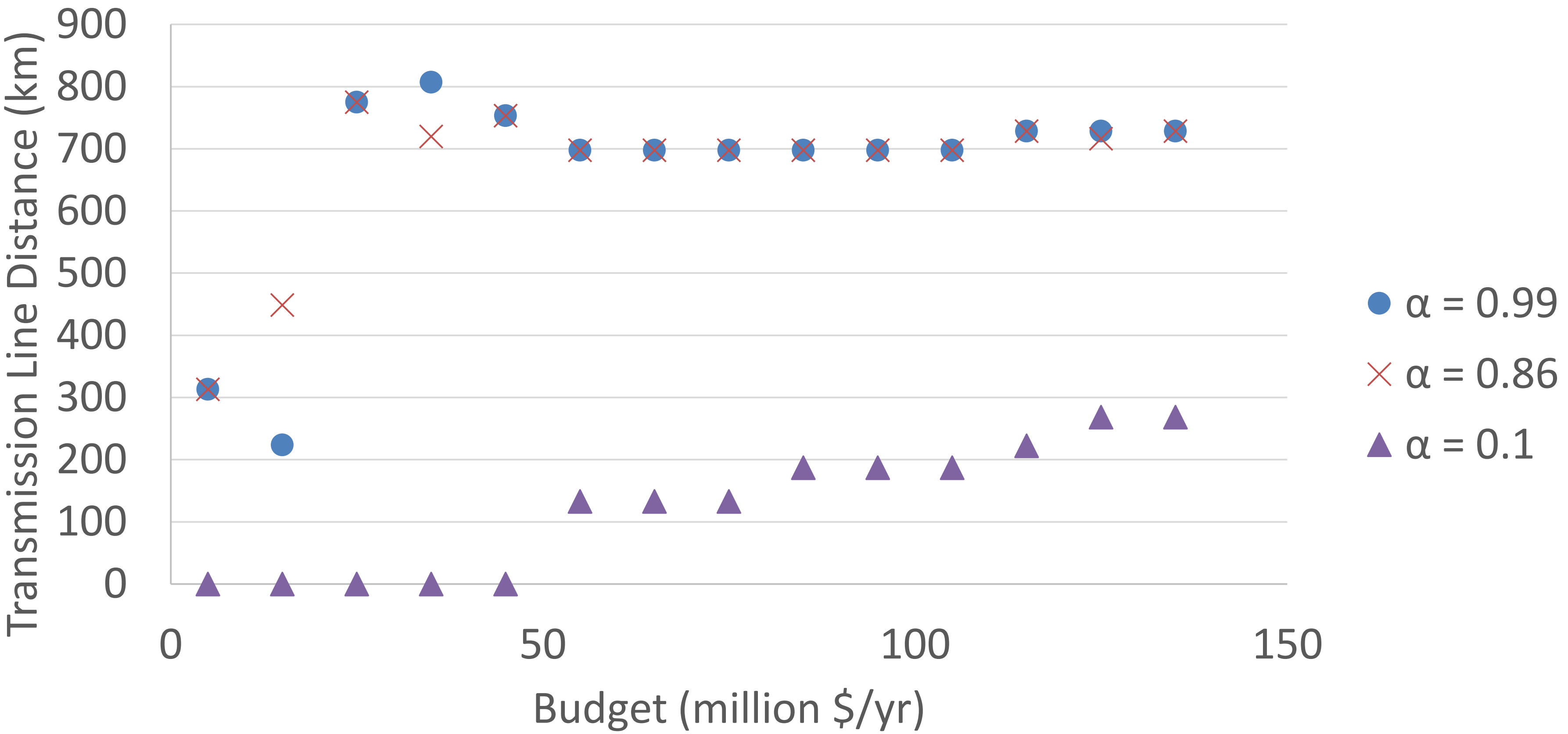
Equality Under Varying Preferences



SHS Unit Cost = 6,647 $/kW

Transmission Line Investment under Equality Preferences



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Decentralized Investments under Varying Solar Costs.

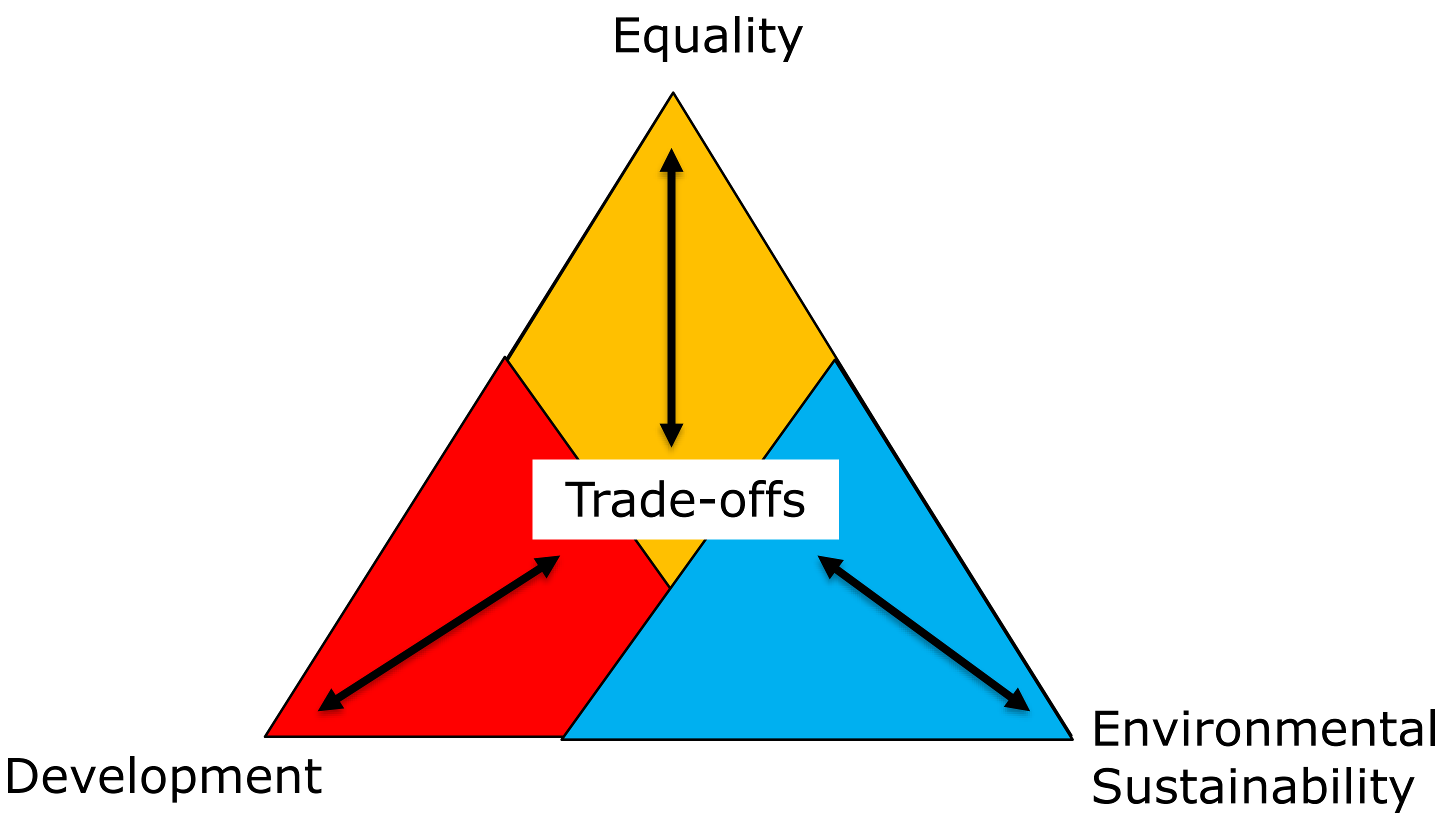
Tipping point for falling costs

Technology	SHS						PV-Diesel Mini Grid					
Budget	$50 million						$50 million					
Equality Parameter	0.10			0.86			0.10			0.86		
Minimum Capacity Penetration Threshold	0%	20%	40%	0%	20%	40%	0%	20%	40%	0%	20%	40%
Achieved Capacity Penetration	**0%**	**20%**	**49%**	**0%**	**21%**	**42%**	**0%**	**28%**	**71%**	**0%**	**20%**	**49%**
Energy Penetration	0%	4%	14%	0%	4%	11%	0%	29%	89%	0%	25%	51%
Cost Reduction Required	**0%**	**89%**	**90%**	**0%**	**86%**	**87%**	**0%**	**68%**	**71%**	**0%**	**65%**	**68%**
Gini	0.47	0.40	0.35	0.06	0.14	0.13	0.47	0.22	0.02	0.06	0.09	0.07

Equity better as costs fall in low preference

Equity has less clear relationship in high preference

Decision Analysis to Inform Sustainable Transitions



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Sustainability Concerns Stemming from Technologies

Air Pollution

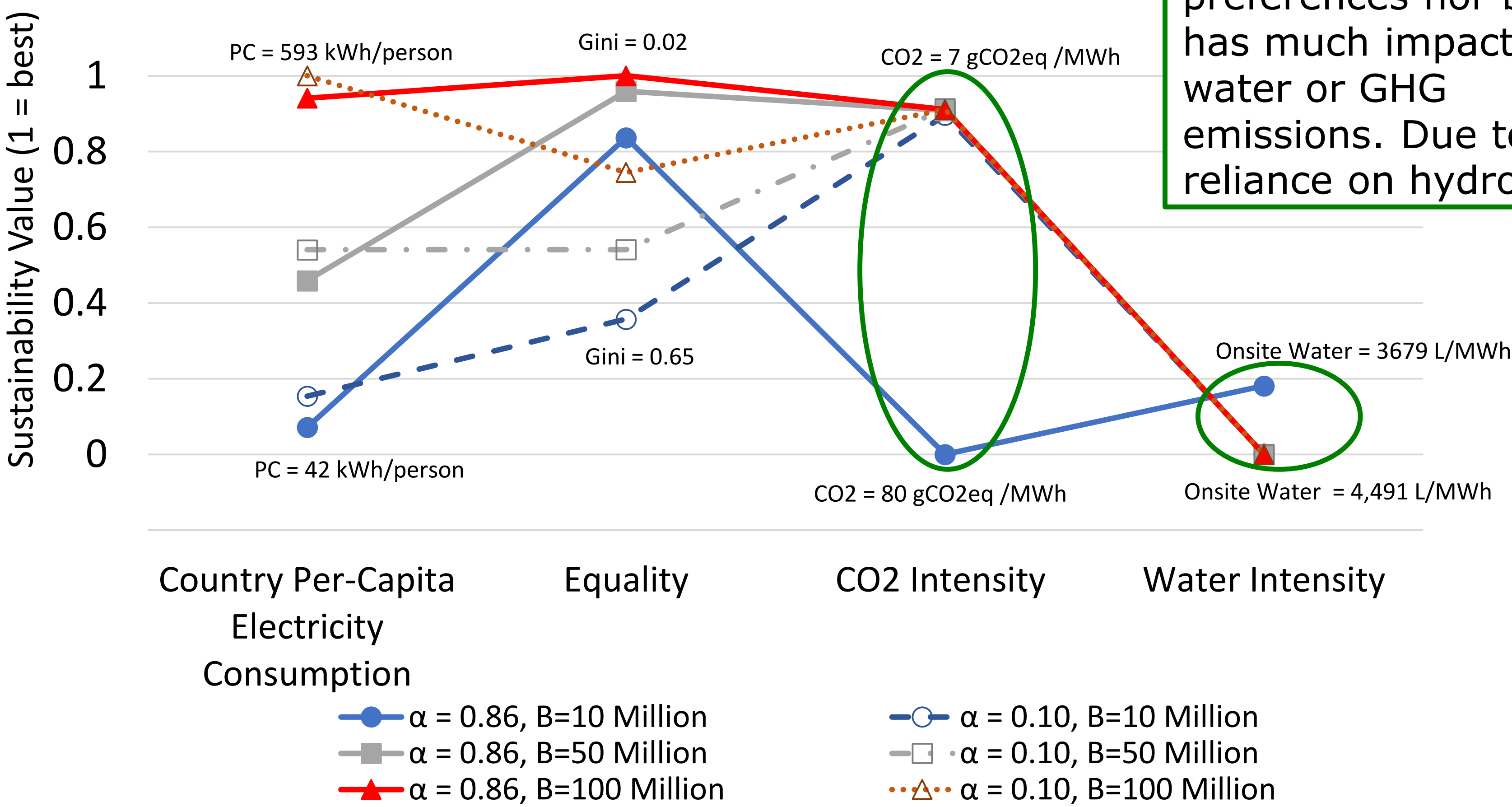
Scalability & Variability

Droughts and Water Use

Sustainability metric data for GHG emissions and water consumption

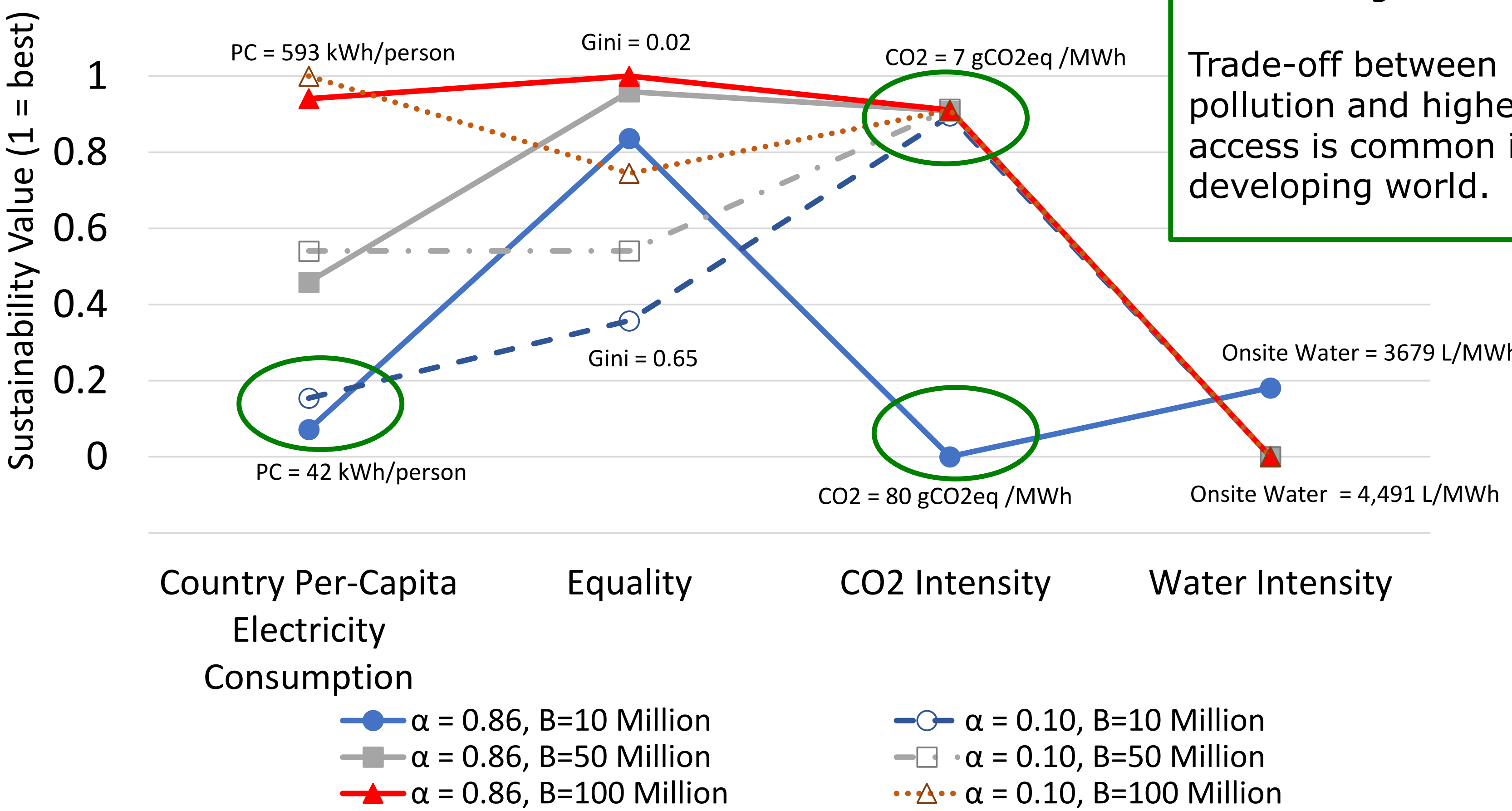
Technology	GHG (gCO_2eq/kWh)	Water Consumption (Direct On-site operational) L/MWh	Notes
Hydro	7	4491	
PV -diesel mini grid	413	11.5	Combination of 50% impact from PV utility and 50% impact from diesel.
SHS	41	23	
Oil	768	1893	Assumed to be same as coal

Sustainability Trade-offs



Neither equality preferences nor budget has much impact on water or GHG emissions. Due to reliance on hydro

Sustainability Trade-offs



Low budget case has most mini grids.

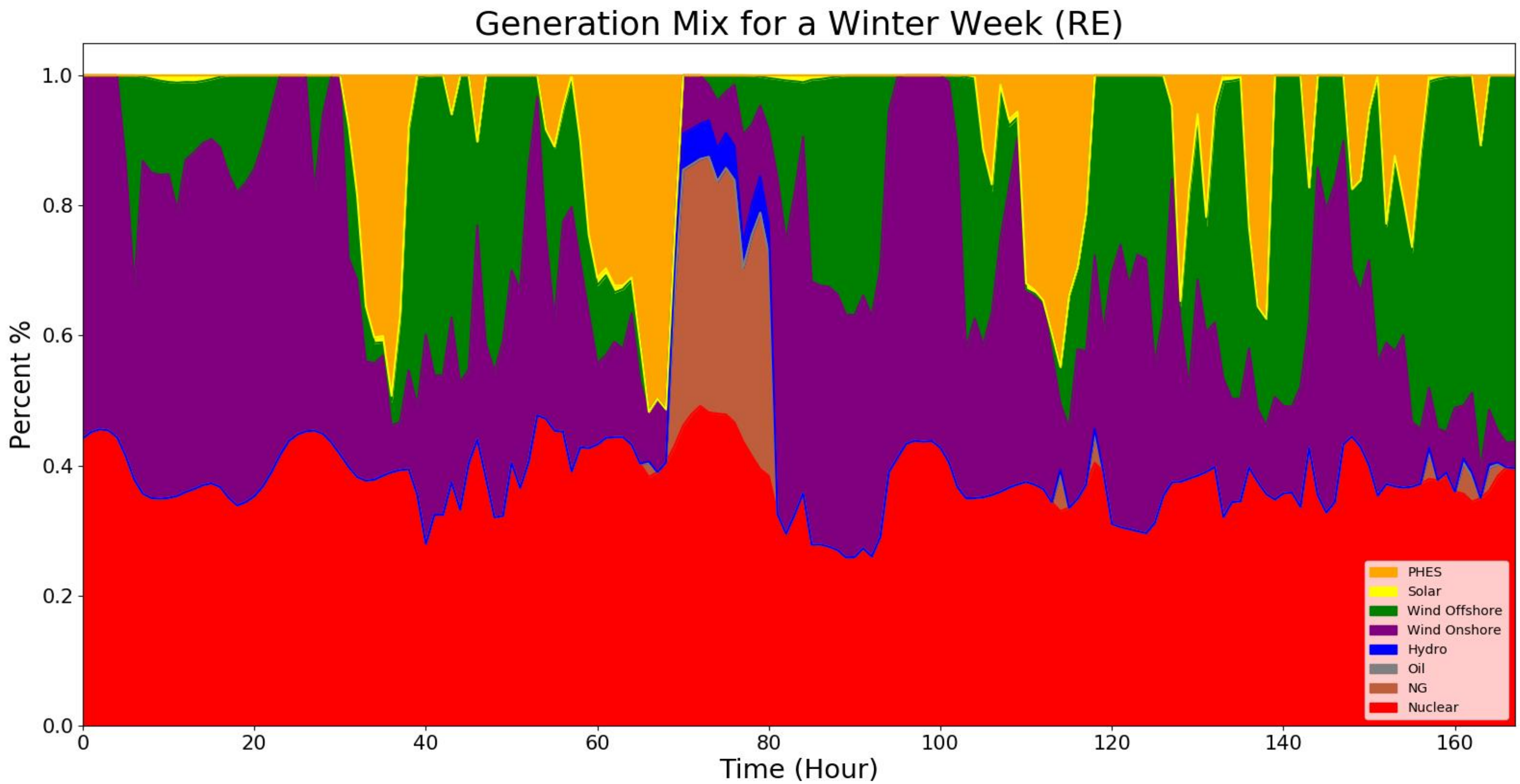
Trade-off between higher pollution and higher access is common in the developing world.

Future Work & Collaboration Opportunities

- Larger Scale Optimization
  - Distribution Network not currently modeled.
  - 15 nodes will not properly capture rural sparsity
  - At high resolution distributed generation could become more desirable

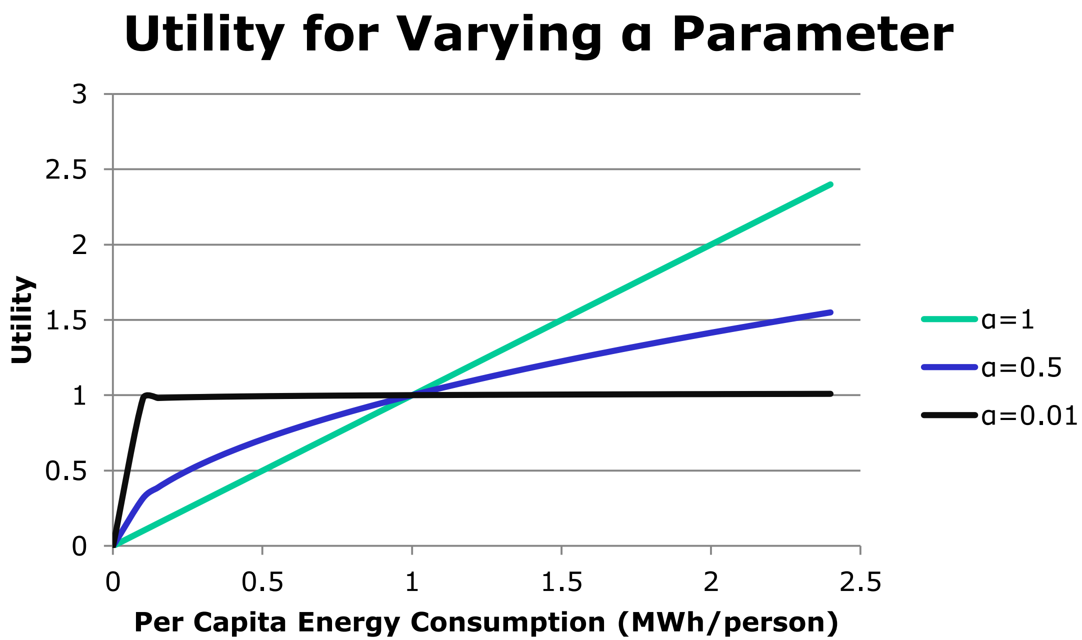
Future Work & Collaboration Opportunities

- Operational Optimization
  - Following generation capacity investment need to consider resource constraints (droughts), and operational concerns.
  - More technologies should be considered in analysis



α – Stakeholder Preferences

- α ⟶ 1 = more emphasis on the total quantity of generation supplied in the system.
- α ⟶ 0 = more emphasis on the distribution of electricity



Liberia Case Study: Assumptions

- No Pre-existing Generation
- Solar Home Systems can be built in any node
- Centralized Generation Capacity Options:

Location	Type	Min Capacity (MW)
Bomi	Hydro	10
Montserrado	Hydro	00
Nimba	Oil	40
Maryland	Hydro	10
Bong	Oil	40
Lofa	Coal	30

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Budget (million USD)	Stakeholder Equality Preference (α)	Country Electricity Consumption (kWh/ppl)	Equality (Gini)	CO_2 Emission Intensity (gCO_2eq/MWh)	Water Consumption Intensity (L/MWh)
10	High (α = 0.86)	42.3	0.18	80.8	3678.7
	Low (α = 0.10)	91.2	0.65	8.4	4486.4
50	High (α = 0.86)	272.1	0.06	7.4	4489.8
	Low (α = 0.10)	320.6	0.47	7.0	4490.9
100	High (α = 0.86)	558.1	0.02	7.2	4490.3
	Low (α = 0.10)	593.1	0.27	7.2	4490.2
Best (1)		*593.1*	*0*	*0*	*0*
Worst (0)		*0*	*1*	*80.8*	*4490.2*

Measure of Access Equality

The Gini coefficient used as a measure of distributional inequality

- mean of absolute differences between all pairs of individuals for some measure.
- interpreted as the electricity consumption gap between two individuals randomly selected from the population, and is defined using:

$$Gini = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} p_i p_j \left|\rho_i - \rho_j\right|}{2\left(\sum_{i=1}^{N} p_i\right)\left(\sum_{i=1}^{N} p_i \rho_i\right)}$$

where ρ is the per-capita electricity consumption in a node, and p is the total population at each node *i*. The indices *i* and *j* represent the population nodes.

Piecewise Linear Approximation

Here we detail the piecewise linear approximation formulation for our objective function. For a set of n points, a = [a_1, a_2, a_3, …, a_n] and b = [b_1, b_2, b_3, …, b_n], we define the piecewise-linear function, f(p) as follows:

$$f(\rho) = \begin{cases} b_1 + \dfrac{b_2 - b_1}{a_2 - a_1}(\rho - a_1), & \text{if } \rho \le a_1 \\ b_i + \dfrac{b_{i+1} - b_i}{a_{i+1} - a_i}(\rho - a_i), & \text{if } \rho \ge a_i \text{ and } \rho \le a_{i+1} \\ b_n + \dfrac{b_n - b_{n-1}}{a_n - a_{n-1}}(\rho - a_n), & \text{if } \rho \ge a_n \end{cases}$$

Here a_i are points that define the piecewise-linear function. These values must be in non-decreasing order. b_i are the values for the points that define the piecewise-linear function. The bi values indicate the corresponding utility values, u. The ρ is the per capita electricity available to be consumed at a node. In our model the piecewise-linear function was approximated using 6,000 points.

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Decision Analysis Equations – Normalizing the Scores

Where x_{max} is preferred

$$x_{i,j} = \frac{z_{i,j} - z_{\min}}{z_{\max} - z_{\min}}$$

Where x_{min} is preferred

$$x_{i,j} = \frac{z_{\max} - z_{i,j}}{z_{\max} - z_{\min}}$$

$$\begin{bmatrix} w_1, & w_2, & \cdots, & w_m \end{bmatrix} \times \begin{bmatrix} x_{11} & \cdots & x_{1I} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mI} \end{bmatrix} = \begin{bmatrix} y_{1,} & y_{2,} & \cdots, & y_I \end{bmatrix}$$

- $z_{i,j}$ is the raw score of portfolio i for criteria j
- $x_{i,j}$ is the normalized score of portfolio i for criteria j
- y_i is the weighted score for portfolio i
- for *m* criteria and *I portfolios*
- *w* is the preference scaling coefficients

Overall Trends

	With budget increase	With equality preference increase	With Solar cost decrease
Transmission	↑	↑	↓
Solar installations	↓	✥	↑
Equality (Gini coefficient)	↑	↑	✥
Total Electricity	↑	↓	↑

*Note that an upward (downward) arrow signifies an increase (decrease), and a cross signifies no relationship. Also, solar installations include both PV-diesel mini-grids and SHS.

Comments and Questions and Future Work from OpenMod online

- From Severin Ryberg to Everyone: 12:30 PM
  - Have you projected demand profiles? Or do you use historic profiles?
- From Daniel Olsen to Everyone: 12:31 PM
  - Have you projected demand profiles? Or do you use historic profiles?
- From Daniel Olsen to Everyone: 12:31 PM
  - Do you think this work is compatible with the inclusion of emissions/pollution for different kinds/penetrations of generation?
- From Niklas Nolzen to Everyone: 12:33 PM
  - Did you try a multiobjective optimization to see the trade-off between preferences and costs?
- From Santiago Peñate Vera to Everyone: 12:34 PM
  - Have you faced opposing stakeholder preferences? i.e. meeting CO2 targets with coal generation
- From Jacqueline Dowling to Everyone: 12:36 PM
  - Does this work support the idea that future equitable girds will be a hybrid between centralization and decentralization?

- From Me to Everyone: 12:38 PM
  - Yes it does. We find that the main solution is to build a centralized grid, and fill in with off-grid solutions. One policy implication was to build AC compatible off-grid solutions.
  - We have done opposing stakeholder preferences using an Multi-criteria decision analysis model, after the optimization is solved
  - Haven't done multi-obj yet, but that is next. Multi-Obj for Cost, and CO2 emissions

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