Changing the policy paradigm: A benefit maximization approach to electricity planning in developing countries

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HIGHLIGHTS
• Integrated stakeholder preferences towards equality into electricity planning.
• Framework for opportunity-focused approach for electricity planning.
• Novel combination of economics, utility maximization, and least-cost frameworks.
• Co-optimized generation and transmission investments under equality preferences.

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ABSTRACT
Access to electricity can lead to enhanced education, business, and healthcare opportunities. Governments in emerging economies are often faced with the challenge of increasing access to electricity and reducing system inequality, while operating under severe budget constraints. This paper develops a methodology for finding the optimal expansion of a power system under the objective of maximizing social benefit, as it relates to distributional equality for electricity access, subject to a budget constraint. This contrasts with traditional models, which minimize the cost of satisfying projected electricity demand. We formulate a generation expansion planning problem as a utility-maximization mixed-integer linear program and apply it to a case study analysis of a low-income country with limited electricity infrastructure. We focus our analysis on understanding how the optimal allocation of generation between centralized and distributed resources is impacted by stakeholder preferences toward equality and different budget levels. We find that a high preference for equality leads to lower overall electricity consumption levels, but improved electrification rates due to greater investment (300–750 km increase) in transmission infrastructure. If stakeholders move from a low to a high equality preference then they could see a 72–87% increase in energy access equality rating depending on the budget. Conversely, indifference to equality leads to higher overall consumption levels in urban areas but reduced electrification rates. This methodology can help decision makers evaluate the social trade-offs between improving energy access, reducing energy inequality and poverty, and increasing total electricity consumption when operating under budget constraints in their countries.

1. Introduction
Over 600 million people in sub-Saharan Africa do not have access to electricity [1]. Several studies have shown that access to electricity can provide a number of socio-economic benefits, including enhanced education, business, and healthcare opportunities [2,3]. A socio-economic impact study by the World Bank found a significant link between electricity access and educational achievement [4]. The United Nations (UN) has further cemented the interrelationship between equality, electricity access, and well-being through their Sustainable Development Goals (SDGs). Goal 7 of the UN SDGs focuses on providing access to affordable, reliable, sustainable, and modern energy for all. The metrics used to evaluate this goal include energy intensity (energy consumption per unit of GDP), renewable energy shares in total final energy consumption, proportion of the population with primary reliance on clean fuels and technologies for cooking, and...
proportion of the population with access to electricity by region [5]. There are a host of energy indicators for sustainable development that relate to equality and health, such as accessibility, energy resource risk, affordability, safety, and air quality [6,7]. This focus on universal electrification goals, equality and health highlights the need for a holistic electricity planning approach that considers not just cost and access but also equality in the level of access and how these are impacted by stakeholder preferences.

Electrification is considered essential for development, as areas without access are less developed than electrified regions [8]. Electrification can lead to improved economic output, clean sources for lighting and cooking, improved health, enhanced farm productivity, and convenience of household tasks (i.e., cooking), especially in rural areas. Previous literature has discussed the strong positive correlation between electrification and quality of life. It is well established that there is a correlation between per capita energy consumption and well-being indicators, such as the Human Development Index (HDI) [9,10]. While the specific mechanisms through which electricity access can benefit a region are complex, there tends to be agreement that expansion of a region’s electricity system will be one of the drivers of reducing poverty levels [11]. The association between well-being and electricity access is discussed further in Appendix A.

Several literature reviews have focused on the current trends and methodologies employed in generation and transmission planning problems. Kotsaklis and Dagoumas [12] review the generation planning literature, while Lumbreras and Ramos [13], along with Latorre et al. [14] review the transmission expansion literature. Hermmati et al. [15] discuss the combination of generation and transmission expansion planning.

Energy investment decisions are commonly modelled through the formulation of a mixed-integer linear program (MILP). Carvallo et al. [11] investigated low carbon electricity expansion options for Kenya using a MILP that estimates the least cost investment decisions to expand a power system subject to meeting load forecast and a host of operational constraints. Barteczko-Hibbert et al. [16] formulated a multi-period MILP for optimization of a system under cost and economic considerations. Pozo et al. [17] combined generation and transmission planning using a three-level MILP model. MILP has also been used to investigate other energy planning questions, as seen in Alizadeh and Jadid [18] who used MILP to account for reliability measures, Chen et al. [19] and Dong et al. [20] who investigated different types of uncertainties, Go et al. [21] who co-optimized generation, transmission and storage investments, and Bakirtzis [22] who used a MILP to combine generation expansion planning with scheduling decisions. MILP has also been used to address questions relating to renewable energy investments and impacts on the power system. Some studies have focused on centralized operational and investment decisions [23], and renewable impacts on thermal power plant efficiency [24].

From these review papers and MILP papers, we find that the question of how to expand the power system in emerging economies has been primarily addressed by economic decision criteria. A recent review found that 94% of the 306 studies included economic criteria in their electricity planning decision analysis for sub-Saharan Africa [25]. This review highlights that the majority of electricity generation expansion planning studies have been conducted from a least cost perspective.

The least cost approach focuses on minimizing the overall cost of expanding the power system, while satisfying a projected demand constraint. While this approach is common throughout the developed world, it presents unique challenges when applied in developing regions, where it is more difficult to forecast future electricity demand, particularly for populations who have not previously had access to electricity [26]. Future demand for electricity in developing countries is both uncertain and also in part dependent on the availability of supply. In particular, it is very difficult to estimate the suppressed demand for electricity from consumers who currently have no or little access to modern energy services, and how this demand will evolve over time as access improves. This often leads to models assuming higher electricity demand levels in urban areas, where access is already greater, which results in further increasing supply and access in these areas – in essence a self-perpetuating result. Furthermore, optimizing a power system to serve a particular pre-defined load profile provides insights into that specific situation, but only provides a limited contribution to a broader discussion of investment priorities under resource constraints.

When striving to achieve social objectives, one challenge of system planning is allocating limited resources between urban and rural population centers. Least cost approaches may not fully consider the social benefits of improving rural access and increasing consumption levels in these regions. Some studies have focused on rural electrification in developing countries in general [27] and specific regions such as Bangladesh [8], India [28], Liberia [29], and Nepal [30]. Others focus on the choice between grid expansion and decentralized options in Africa in general [31], and some look more specifically at regions such as Uganda [32], Kenya [33,34], and Liberia [26]. Both sets of analyses use a least cost perspective. Feron [27] investigated different indicators for sustainability of off-grid photo voltaic (PV) systems, but did not focus on the interplay between centralized and off-grid technologies. In regions without an existing power system infrastructure, research has indicated that decentralized electricity systems are more economically viable than centralized grids [35,36]. When stakeholders focus solely on increasing electricity consumption, they may disproportionately favor urban areas and increasing industrial production [37].

Even when least cost analysis deems distributed generation as the more cost-effective option for initial grid integration, the local population may view a connection to a reliable centralized grid as the preferred goal to provide the opportunity for increased future demand (Mehigan et al., 2018) [35]. In cases where the long-term, least cost plan requires a highly coordinated effort with years or decades of sustained funding, delays in implementation can be common, which may leave large quantities of demand unserved for extended periods of time [38]. These delays can diminish consumer utility, and such cases raise the question of whether limited resources could have been allocated more efficiently to achieve targeted social objectives. Auffel-Dadzie et al. [39] explored the impact of funding uncertainties by analyzing the role that periodic budget constraints and demand uncertainty play in the generation expansion problem.

While the studies mentioned above have analyzed electricity planning in developing countries, they have not explicitly considered often-stated preferences regarding equitable access to electricity in optimizing electricity system expansion. There are numerous places where preferences for equality are implied (i.e. World Bank’s energy tiers and rural electrification programs). Ignoring these preferences implicitly ignores the political climate and conflicting stakeholder objectives which can play a significant role in electricity investment [40] and subsequent power system development in sub-Saharan Africa [25], particularly when concerned about rural communities [41].

A recent review highlighted two major gaps in the electricity planning literature: (1) the lack of long-term optimization research applied to sub-Saharan Africa, and (2) the lack of a utility-maximization focused approach to long term energy planning [25]. Trotter et al. [32] partially addressed these gaps by designing a MILP specifically targeted for long-term energy planning in systems with little existing power infrastructure. Their multi-objective MILP focused on cost and regional inequality minimization. They found that solar energy could be the cost-minimization strategy for reducing electrification inequality. However, they do not represent a continuum of preferences around inequality, rather they simply minimize the discrepancy between rural and urban electrification. Another review investigated the models used for integrating renewable energy into the generation expansion planning literature, but none of the optimization models included in their review integrated stakeholder preferences for equity or equality [42].
Taken together, the key gaps in the literature have been created by
(1) a focus on cost minimization, which ignores the significant budget
constraints faced by many developing nations; (2) a reliance on demand
estimates, which are often very poor, and which implicitly favor regions
that are more developed; and (3) a dearth of electricity planning models
that explicitly include equality for electricity planning in sub-Saharan
Africa.

This paper addresses these gaps in the current literature by being
the first to explicitly integrate a stakeholder’s preference towards equality
into an electricity planning problem; by avoiding the need for esti-
mat ing demand, taking an opportunity-focused approach instead; by
considering cost through a budget constraint rather than through an
objective function; and by applying this to an under-studied system in
sub-Saharan Africa, Liberia. Although we demonstrate our model
through a case study analysis of Liberia, this method is applicable to
other countries with little to no electricity access such as Malawi, Sierra
Leone, Burundi, and Burkina Faso, where there are a combined 50
million people without access to electricity. Our methodology could
also be applied in island nations following a serious disaster, such as in
Puerto Rico following a massive hurricane. We note that while con-
sidering equal opportunity has been prevalent in other fields, such as
health (e.g. [43]), this approach is new to electricity system planning.

In the following section we present a methodology to determine the
electricity strategy— including investments in centralized and de-
centralized generation and transmission infrastructure— that maximizes
social benefit from the perspective of a central government or system
planner, for a given set of equality preferences and budget constraints.
We extend the previous work in MILP for energy planning analysis by
introducing the Maximize Energy Access (MEA) model, which de-
termines the optimal power system expansion plan by maximizing a
utility function that is based on electricity access and stakeholders’
preferences towards distributional equality. We determine the mix be-
tween centralized and decentralized generation, the layout of the power
system, and the choice of generation technologies, while maximizing
utility under different levels of equality preferences. This work provides
results on the tradeoffs between total system cost, the amount of gen-
eration capacity available, environmental sustainability criteria, and
distributional equality. These results can inform stakeholders, who face
complex decisions facing a broad range of tradeoffs needed at the local
and national level, and who can incorporate their assumptions about
economic growth.

In this work we do not use demand projections to determine the
electricification pathway. Even when the demand is measurable the
current consumption of many household services (e.g. heating and
cooking, lighting and potable water) may not reflect the real demand
for those services due to lack of infrastructure [44]. Instead, we build
on the idea that increased electricity access leads to improved quality
of life and social benefits. We model utility as a direct function of elec-
tricity access, measuring electricity access as potential per-capita elec-
tricity consumption at each node in the system. The potential con-
sumption depends on the generation portfolio and the transmission
infrastructure. A key distinguishing factor between our methodology
and previous literature is that we employ an opportunity-focused ap-
proach to electricity planning in low income countries with little to no
pre-existing infrastructure.

Our primary contribution to the electricity system planning litera-
ture is to illuminate how stakeholder preferences around equality in
electricity access impact the design of the electricity system under
budget constraints. In particular we analyze the impact of equality
preferences on the choice between pursuing primarily on-grid or pri-
marily off-grid electrification strategies, and also consider trade-offs
between different sustainability objectives. The methodology presented
in this paper is a novel combination of applied economics, utility
maximization, and least-cost frameworks. This unique combination al-
lows our team to take an equality focused approach to power system
planning in developing countries. This model is not intended to replace
detailed analyses of electrification pathways for a country, and cannot
be used as a stand-alone implementation tool. Instead it is intended to
guide discussions between various electricity stakeholders (i.e. donor
organizations, rural electrification agencies, power companies, and
Ministries), and illustrate a framework for taking a benefit maximiza-
tion approach to electricity planning.

Previous work has highlighted the importance of including multiple
objectives in water system planning [45]. Power systems, too, create
special problems that can make the application of classical optimization
methodologies misleading if they are not treated with considerable
insight. The large number of quasi-independent decision makers and
constituencies mean that multiple objectives are present. It is clear from
the United Nations Sustainable Development Goals and a host of na-
tional policies declaring universal access targets that there is a high
preference for equality of electricity access. Our work allows stake-
holders to explicitly examine the tradeoff between equality and eco-
nomic efficiency.

Following the methodology, we present a case study analysis of
Liberia to demonstrate the MEA model. While we use Liberia as a
backdrop, this approach has wider applications, and can support the
discussion revolving around how to best expand a nation’s power
system, particularly in cases where the electricity system is significantly
undeveloped and access is very low. The configuration of a regional
power system depends heavily on the underlying goals of the country,
stakeholder preferences, and the technology options available for pro-
viding electricity services [46]. While our methodology can be ex-
panded to include physics-based power flow constraints, we focus on
radial network systems since these are most appropriate to countries
with extremely sparse infrastructure and tight budget constraints. We
explicitly use the simplest reasonable network model to improve the
usability of our model in a region with limited electricity resources
[47,48]. This tool is best implemented as a preliminary assessment
capability tool for capacity building.

The remainder of the paper is organized as follows: Section 2 cov-
ersthe methods and approaches used in the models; Section 3 details the
case study assumptions and Section 4 discusses the results. We conclude
with some policy implications and general insights in Section 5.

2. Methodology

In Section 2.1 we describe the model formulation, Section 2.2 de-
tails the methods for the cost calculation, Section 2.3 discusses the
measure of distributional equality used to evaluate the population’s
resulting access to electricity, and Section 2.4 discusses the contrast
with least cost methodology. Section 2.5 concludes the section by dis-
cussing how we evaluate sustainability objectives after the optimization
is solved.

2.1. MEA model formulation

Designing an optimal power system is a complex spatial planning
problem. The MEA model is formulated as a bottom-up techno-socio-
economic MILP, maximizing consumer utility as a function of electricity
consumption subject to physical constraints on network flow and
budget constraints on the total cost of power system expansion and
operation. The objective of our model is to maximize the stakeholder’s
utility that is gained through electricity access. In our paper access is
measured as the maximum available per capita electricity consumption
within a node. Each node represents a location within the country. We
use a nodal representation of the geographic population distribution
and assume that the total consumer utility realized across an entire
country is equal to the sum of the utility of each individual consumer.
The model determines optimal investments in new generation and
transmission infrastructure, as well as the optimal allocation of elec-
tricity consumption across each node. The overall flow of the model is
presented in Fig. 1.
Similar to the studies from Deichmann et al. [49], and Abdul-Salam and Phimister [50] we determine the optimal power system for a static future year and therefore do not explicitly consider a temporal dimension in our analysis. We follow a methodology similar to Levin and Thomas [31] in the power grid formulation, which uses a simplified network flow representation of electricity transmission rather than explicitly considering the direct or alternating current power flow equations that govern how electricity flows through a connected power system. Our model differs from cost minimization models by addressing cost through a budget constraint. This is a type of multi-objective optimization model where the second objective (i.e. cost minimization) has been constrained. We emphasize that the system that results from the optimization represents the least cost way to achieve that level and distribution of electrification. We also note that by decreasing the preference for equality (i.e. alpha approaching zero) the model will seek to maximize total electricity consumption throughout the country while satisfying the budget constraint. This effectively minimizes the unit cost of electricity provision.

In the remainder of the section, we first present the overall model formulation, then discuss the objective function (Eq. (1)), budget constraint (Eq. (2)), power flow constraint (Eq. (3)), transmission constraints (Eqs. (4)–(7)), and generation constraints (Eqs. (8)–(11)). The variables and parameters used in the methodology can be found in Tables 1 and 2. The MEA model is formulated as follows:

Maximize

\[ U(x, p) = \sum_{i \in E} u(x_i, p_i) \]  

Subject to

\[ \sum_{(i,j) \in E} (C_{II}d_{ij}e_{ij}^L + C_{II}d_{ij}e_{ij}^H) + \sum_{i \in E, k \in K} (C_k G_{i,k} + C_k G_{i,k}) \leq B \]  

\[ x_i \leq g_i + \sum_{j \in \delta^+_i} f_{ij} - \sum_{j \in \delta^-_i} f_{ij} \quad \forall i \in I, (i, j) \in E \]  

The MEA model is implemented in Python using the Gurobi optimization solver. The non-linear objective function is approximated using a piecewise linear function, detailed in Appendix B. Electricity losses are integrated in to the peak factor, \( \gamma \). We do not consider Fig. 1. Flow of information within the MEA model.

*Table 1*  
MEA variables.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>( e_{ij}^L )</td>
<td>Indicates if a low-voltage or high-voltage transmission line is constructed between nodes i and j</td>
<td></td>
</tr>
<tr>
<td>( x_{ij} )</td>
<td>Average annual power flow from node i to node j</td>
<td>MWh</td>
</tr>
<tr>
<td>( F_{i,j} )</td>
<td>Peak annual electricity flow on edge (i, j)</td>
<td>MWh</td>
</tr>
<tr>
<td>( g_i )</td>
<td>Total generation in node i</td>
<td>MWh</td>
</tr>
<tr>
<td>( G_{i,k} )</td>
<td>Generation by technology k in node i</td>
<td>MW</td>
</tr>
<tr>
<td>( G_{i,k} )</td>
<td>Capacity of technology k installed at node i</td>
<td>MW</td>
</tr>
<tr>
<td>( \rho_i )</td>
<td>Per-capita energy consumption in node i</td>
<td>MWh/ppl</td>
</tr>
<tr>
<td>( x_i )</td>
<td>Electricity consumed at node i</td>
<td>MWh</td>
</tr>
</tbody>
</table>

\[ e_{ij}^L + e_{ij}^H + e_{ij}^F \leq 1 \quad \forall (i, j) \in E \]  

\[ F_{ij} = x_{ij} \quad \forall (i, j) \in E \]  

\[ F_{ij} \leq (T^L e_{ij}^L + T^H e_{ij}^H) \quad \forall (i, j) \in E \]  

\[ F_{ij} \geq -(T^L e_{ij}^L + T^H e_{ij}^H) \quad \forall (i, j) \in E \]  

\[ g_i = \sum_{k \in K_i} G_{i,k} \quad \forall i \in I, k \in K_i \]  

\[ G_{i,k} \leq G_{i,k} \quad \forall i \in I, k \in K_i \]  

\[ G_{i,k} \geq G_{i,k} \quad \forall i \in I, k \in K_i \]  

\[ x_i, G_{i,k} \geq 0 \quad \forall i \in I, k \in K_i \]  

D. Nock, et al.  
Applied Energy 264 (2020) 114583  
4
electricity theft explicitly, but this is captured in our estimate of system losses. We assume that all of the electricity available in the node will be consumed.

**Objective function.** In Eq. (1), $U(x,p)$ is the overall stakeholder utility that results from the electricity delivery and consumption profile determined by the model. $x$ is a vector of the electricity consumed (in MWh) at each node $i$, $p$ is the vector of populations at each node $i$, $p_i$ is the population at node $i$, and $J$ is the set of nodes in the system.

Utility increases with potential consumption, but with decreasing marginal utility. Thus, we assume that the utility at each node, $u(x_i, p_i)$, is a concave function of per capita electricity consumption at that node, scaled by the population of that node. In other words, consumers have decreasing marginal utility of electricity consumption. We use an isoelastic utility function as seen in Eq. (13) (adapted from Atkinson [51]).

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

where $\gamma = \frac{2}{\alpha}$ is the per-capita energy consumption in node $i$. The overall utility $U$ is equivalent to the equal-weighted sum of the individual utilities.

Stakeholder preferences for equality are modeled through the equality parameter $\alpha \in [0, 1)$, where a higher value of $\alpha$ represents a desire for more equality across the population. This is typically called an inequality aversion parameter in the economics literature [52–54] when it is applied to income; we focus on inequality of electricity consumption. As $\alpha$ approaches zero, there is more emphasis placed on the total quantity of generation supplied in the system, regardless of how it is distributed among consumers. As $\alpha$ approaches 1, the marginal utility of each additional unit of electricity supplied to a node approaches zero. As a result, the first unit of electricity consumption in a node provides far greater utility than an additional unit at higher consumption levels, meaning there is more emphasis placed on an equitable distribution of electricity, instead of the total quantity of countrywide consumption. We assume that within each node, there is uniform per capita electricity consumption. The value of $\alpha$ represents the social planner’s preference for electricity equality between individuals. The highest possible equality level occurs when each node receives the same *per-capita* quantity of electricity.

As a note one of the modeling challenges is the scalability of the model due to the non-linear objective function. This causes the computational cost of the model to increase with the stakeholder’s preference for equality. This can be addressed by altering the piecewise linear approximation, detailed in Appendix B.

While a fruitful direction of research would be to refine the non-linear objective function, the first question that will need to be addressed is the true functional form of the decision maker’s preferences. In practice it is difficult to capture stakeholder preferences towards equality, meaning that the objective function may take a different functional form than the one presented here.

**Budget constraint.** The budget constraint, Eq. (2), accounts for the annualized costs in the power sector. The annualization calculation, explained in more detail in Section 2.2, includes all fixed and variable costs of investment and operation over the lifetime of the facilities. We assume that existing generation and transmission infrastructure does not incur any capital costs.

The first summation in Eq. (2) accounts for the cost of building transmission lines. The set of edges, $E$, includes the possible connection sets between nodes. The binary variables, $e_{ij}^H$ and $e_{ij}^L$, are equal to one if a low-voltage or high-voltage transmission line is constructed between nodes $i$ and $j$, and zero otherwise. The parameters $C_{T H}$ and $C_{T L}$ are the annualized costs per km for low voltage and high voltage transmission respectively; and $d_{ij}$ is the length of the transmission edge connecting nodes $i$ and $j$. The second summation accounts for the cost of constructing and operating generation technologies. $C_{F k}$ is the annualized fixed cost (including capital and fixed operations and maintenance), per MW for generation technology $k$; note this factor will depend on the lifetime of the technology as well as the interest rate. These two parameters are discussed in more detail in Section 2.2. $C_{V k}$ is the variable cost (including fuel and variable operations and maintenance) of generating one MWh, for generation technology $k$; $B$ is the annual development and operations budget, assumed to be set by a social planner. We exclude household connection costs for both centralized and decentralized generation. Thus, we do not include the cost to connect individual households within a given population node; nor do we include balance of system costs (beyond storage) for decentralized solar home systems. $G_k$ is the installed capacity of technology $k$ at node $i$; and $g_k$ is the annual electricity generated by technology $k$ in node $i$.

**Power flow constraints.** Eq. (3) provides the power balance constraint for each node, ensuring that electricity consumption at each node ($x_i$) does not exceed the sum of energy generated at that node ($g_i$) and the net transmission flow into the node ($f_{i,j}^H, f_{i,j}^L$). Average annual power flow from node $i$ to node $j$ is represented as $f_{ij}$, and is positive if power flows from $i$ to $j$, and negative otherwise. This constraint ensures that power flow is balanced at each node. Fig. 2 illustrates the power flow constraints. Here node 1 contains a power plant that generates $g_1$ units of electricity. Node 1 consumes $x_1$ units of electricity and sends the remaining $g_1-f_{1,2}$ units of electricity to Node 2. Node 2 consumes $x_2$ and the remaining, $f_{1,2}-x_2$ is sent to node 3. The total electricity consumed by the nodes is $x_1 + x_2 + x_3$, which equals the total electricity generated by the power plant, $g_1$. Here $T_{ij}$ is the capacity of transmission edge $ij$. The factor $\gamma$ is explained in the following section.

**Transmission constraints.** If $e_{ij}^H$ ($e_{ij}^L$) is equal to one this means that electricity is transmitted from node $i$ to node $j$ across the low (high) voltage transmission edge, otherwise no electricity is transmitted across the edge. $T_{H}^\alpha$ and $T_{L}^\alpha$ are the transmission capacities of high-voltage and low-voltage transmission edges, respectively, in MW. The constraint defined in Eq. (4) ensures that there is at most one transmission line connecting any two nodes.

Power flow along transmission edges will vary through time, with the instantaneous flow being sometimes higher and sometimes lower than the average flow. The factor $\gamma$ is the ratio of peak flow to average flow, and is the mechanism used to account for reliability of the
centralized transmission system. The relationship between peak flow, \( F_g \), and average flow is presented in Eq. (5). Constraints 6 and 7 dictate that the peak flow on edge \((i, j)\) must be less than or equal to the transmission capacity on that edge.

**Generation constraints.** Eqs. (8) and (9) establish the relationship between annual generation and installed capacity. Total annual electricity generation in node \( i \), \( g_k \), is made up of the generation by all technologies \( k \in K_i \) installed at node \( i \). Annual generation \( g_{ik} \) by technology \( k \) in node \( i \), cannot exceed the capacity, \( G_{ik} \), of technology \( k \) installed at node \( i \), multiplied by the hours in a year and the availability factor, \( \alpha_k \), of technology \( k \).

The binary variable \( y_{ik} \) indicates whether or not new generation capacity \( k \) is built at node \( i \). Eq. (10) enforces a minimum bound, \( m_s \), on capacity, as some types of generation are inefficient below a certain level. Eq. (11) similarly enforces an upper bound, \( M_s \), on installed capacity.

**Other constraints.** Eq. (12) is the set of non-negativity constraints.

We make a simplifying assumption that electricity consumption is the same for each consumer within an individual node, although we recognize this is often not the case due to wealth disparities. In our model, we do not account for interconnections between countries, which would impact the amount of electricity available in nodes connected to the centralized power system. We do not investigate the impact of electricity prices in this model, instead we focus on the cost of building the system from a social planner’s perspective. There is no stochasticity considered in this model, but the reliability of the centralized power system is captured through the peak factor, and the reliability of generation supply is captured through the availability factor for generation sources. We leave the impact of stochastic outages as future work. We require all generation to provide similar services, thus solar systems have batteries to supply energy upon demand.

### 2.2. Methodology for cost calculation

We determine the annualized capital and operating costs incurred by each technology as outlined in Eqs. (14) and (15).

\[
C^k_c = C_{cap,k} \times CRF + C^k_{op,M,A,k} \\
C^k_{op} = C_{cap,k} + (C_{op,M,A,k} \times HR_k)
\]  

2.3. Methodology for evaluating equality

An important contribution of this paper is its consideration of the role of equality preferences in power system planning. To evaluate how equality preferences impact the development of power systems, we calculate the Gini coefficient as an informative metric after the optimization model is completed. It is not part of our model formulation, but rather a metric to evaluate the outcome. The Gini coefficient is a measure of inequality in society and is defined as the mean of absolute differences between all pairs of individuals for some measure, such as income, or in our case, electricity consumption. Here the Gini coefficient quantifies the disparity in electricity consumption within a given population and is defined using Eq. (17) (adapted from [56,57]):

\[
Gini = \frac{1}{2} \sum_{i=1}^{N} \sum_{j=1}^{N} p_i \left| p_i - p_j \right|
\]

where \( p \) 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. When the Gini coefficient is zero, there is perfect distributional equality; when the Gini coefficient reaches its theoretical maximum of 1 (i.e. complete inequality), all value accrues to a single individual, with all others having zero.

### 2.4. Contrast with least cost methodology

In this subsection we provide details regarding how our benefit maximization methodology differs from the least cost methodology. First, we address the role of costs in a different way. In least cost optimization, costs are accounted for in the objective function, whereas in the MEA model, the least cost objective function has been converted into a constraint. The value of the MEA model is that we can explicitly derive socially optimal solutions for a wide range of budgets. The budget limitation of the least cost method has been noted before by Afiful-Dazie et al. [39] who considered stochastic demand and budget constraints, over a multi-year planning horizon. Similar to our study, the authors investigate generation investment under varying budget constraints. Here we diverge from their work by
incorporating equality preferences.

Another contrast is the importance of demand projections in the least cost methodology where electricity demand is set as a constraint that must be met within an acceptable reliability tolerance. Thus, there is flexibility in how the electricity is generated and delivered, but not how much electricity is generated and where it is delivered. This is not always the preferred perspective in developing economies where system planners may wish to better understand optimal development pathways even if they cannot immediately meet all demand for energy services. Thus, the MEA provides an alternative analysis which enables system planners to optimally allocate the resources available to them.

Related to this, in a least cost framework, electricity demand projections exogenously determine the level of equality of access in a country. Therefore, equality preferences, e.g. between rural and urban users, are implicitly pre-determined by these projections, with rural users often assumed to demand far less electricity. Our model, in contrast, explicitly considers preferences for equality and how these impact optimal system planning and operations.

2.5. Environmental sustainability evaluation

Environmental sustainability scores are based on projected energy contribution per technology from the MEA model. The sustainability analysis framework is performed after the optimization is solved to determine how environmental sustainability is impacted by electrification pathway decisions. Here we focus on CO₂ emissions intensity (gCO₂eq/MWh), and water intensity (L/MWh) due to prevalence of these environmental criteria in the literature. CO₂ emissions intensity is defined as the total CO₂ emissions divided by the total energy produced. Water intensity is defined as the total direct on-site water consumption divided by the total energy produced. The data for the sustainability criteria can be found in Appendix D.

3. Case study description

We now present a case study analysis of the Liberian power system to demonstrate the capabilities of the MEA model and examine how the optimal system configuration is influenced by different choices of the equality parameter, the budget, and other key parameters. We start this section with a brief overview of the Liberian power sector, and then we delve into the model assumptions pertaining to the case study. This case study is meant to provide an illustration of how equality preferences impact power system development; a more detailed spatial analysis (i.e. resource availability, and preference elicitation) should be conducted before any development plans are implemented. Our primary purpose with this case study is to introduce, and provide a proof of concept for, our framework and the types of insights it can provide.

Liberia lies in West Africa along the Atlantic coast and, as of 2017, has a population of roughly 4.7 million people. USAID reports there is 126 MW of centralized installed capacity in Liberia, the majority of which is the Bushrod Island oil power plant (38 MW) and the Mt. Coffee hydro facility (88 MW). The Mt. Coffee hydro plant, however, is currently only operating at 22 MW capacity. Only 5% of the country, and less than 7% of the capital city, Monrovia, has access to grid connected electricity [58]. Currently, generation expansion projects are being pursued in Liberia to increase electricity access through constructing additional centralized oil generation, reconstructing the hydroelectric facility at Mt. Coffee, and developing interconnections to the West African Power Pool [59,26].

In this case study, both renewable and non-renewable technologies are considered for expansion of the Liberian power system. We assume a 15-node system in Liberia, based on the smallest division of the aggregated settlement population data from the Gridded Population of the World Data Set [60]. The 15 nodes represent the 15 counties in Liberia. Fig. 3 illustrates how the population is distributed between nodes in the country. Most of the population resides in the northwestern portion of the country, with a large majority residing in the capital of Monrovia, located in Montserrado county.

After a 14-year civil war, which ended in 2003, the hydropower plant at Mt. Coffee and the entire transmission and distribution network had been completely destroyed. While there have been many efforts to rebuild the power system, electricity access in Liberia is still extremely limited for much of the population. Thus, this paper aims to analyze how the power system could be rebuilt to maximize the benefits of electricity access under several different formulations of the social objective function, and can have wider applications to countries looking to rebuild systems after a man-made or natural disaster. The model is also applicable in regions with more developed electricity infrastructures, provided that data on the existing generation and transmission infrastructure are available. This analysis provides general insights into the role prioritizing equitable electricity access plays in expansion of the power system.

3.1. Generation assumptions and data

We consider two types of centralized generation (oil and hydro), and two types of decentralized generation (PV-diesel mini grids and solar home systems (SHS)). Decentralized solar costs are based on data from Liberia power sector analysis by Modi et al. [26] and global solar PV costs from Ilas et al. [61]. SHS costs include the cost of battery storage, which enables operation at night and increases the availability factor. We assume that solar-diesel mini grids and SHS can be built at any node. We exclude wind power from the generation options due to the low wind resource in the country [29]. While we focus on SHS, we note that small diesel generators can be modeled in the same way and are a substitute for SHS; thus, we account for this technology indirectly in our sensitivity analysis of SHS costs.

Due to the limited existing electricity infrastructure in Liberia, we demonstrate the model by assuming that there are only two pre-existing generation facilities, a 38 MW heavy fuel oil plant and a 22 MW hydro plant both near Monrovia, and no pre-existing transmission capacity in the country. We include the option to build up to eight large centralized generation plants, with possible locations listed in Table 3. The Montserrado, Margibi, and Maryland locations are chosen based on Liberia’s existing plans for increasing electricity access in the country, and the
Nimba, Bong, and Grand Bassa locations are chosen based on Liberia’s peak demand projections [26]. In two nodes, the most logical choice is hydro due to the location near rivers; in three nodes the choice is oil due to lack of hydro resources; and in the remaining node we allow for the choice between hydro and oil. We assume that the minimum capacity for hydro is 20 MW, oil is 30 MW, and PV-diesel mini-grids is 1 MW.

To limit the computation space of the model, the set E is limited to the transmission edges that connect each node i with its four closest nodes.

### 3.2. Cost assumptions and data

The cost assumptions for generation and transmission are based on a power expansion report for Liberia [26], a literature survey for generation and transmission costs in sub-Saharan Africa; and models that evaluate electricity planning options for Liberia [29,38], the World [61,62], and the USA [46]. All costs are presented in 2016 United States Dollars (USD). Oil fuel costs are sourced from the Liberian Ministry of Commerce & Industry [63], who reported that the price of fuel oil was 781.75 USD per metric ton in July 2018 (equivalent to 16.93 USD/MMBtu in 2016). Capital and operations and maintenance costs for oil are assumed to be similar to the median values of coal plants [62]. The technical and economic assumptions for the calculation are summarized in Appendix C.

For hydropower, Ilas [61] provides the total capital cost, defined as all of the costs of developing a project including interest during construction, project development costs, and upfront financing costs. Operating costs are sourced from Lazard [62] and Klein and Whalley [46].

Costs for SHS were sourced from Modi et al. [26]; then were projected to 2016 costs using a simple regression analysis from the weighted average of global solar PV costs from Ilas [61]. We assume that SHS capital costs will fall at a rate similar to the costs of utility-scale solar. We assume the storage component for SHS is a deep-cycle lead acid battery which must be replaced every 4 years [64].

In this paper we assume that for a PV-diesel hybrid system there will be equal amount of installed capacity for PV and diesel components. In other words, if there is 1 kW of PV capacity, then there will be 1 kW of installed diesel capacity. The even split between PV - diesel off grid investment stems from the need for supplemental generation with solar is not available (i.e. at night, and when it is cloudy). We assume that hybrid diesel-PV systems will be developed with equal installed capacity levels of each technology. This assumption is consistent with Yamegueu et al. [65] who show that for a PV - diesel hybrid system, the rated power of the diesel generator should be equal to the peak load to maintain reliability. Since we assume the maximum electricity available in the node will be consumed this leads us to size the diesel generator equal to the PV system. Similarly, we make an assumption that half of the energy will come from PV. We base this on a study of a solar-diesel hybrid system in Nigeria [66], see Table 4). While the Aini [66] system also has a battery, the direct energy from solar and diesel are about equal.

We analyze a range of annual budgets to evaluate how the system expansion plans change as investments increase. In 2017 Liberia had reported GDP of approximately $2 billion USD. Thus, we focus attention on the following annual budgets: $5 million (equivalent to 0.25% of GDP); $10 million (equivalent to 0.5% of GDP); $50 million (equivalent to 2.5% of GDP); and a very high budget of $130 million (equivalent to the 1.1 billion USD present value that Modi et al. [26] estimate will be required for power system expansion, and near 6% of GDP). The 1.1 billion USD projected by Modi et al. [26] included grid construction and household connection costs, but did not include the costs for power generation and high voltage transmission lines. The annualized budget is calculated from the present value estimated by Modi et al. [26] using a discount rate of 12% and a loan term of 30 years. We note that a budget of 130 million USD is very high for a country like Liberia, but the cumulative investment in Sub-Saharan Africa needed to reach the universal access goal could amount to 2.5 trillion USD [67]. Our inclusion of this scenario is not intended to represent any judgement regarding whether or not this is a realistic country-level objective. Rather we provide this case to demonstrate

### Table 3

Centralized generation options.

<table>
<thead>
<tr>
<th>Location</th>
<th>Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bong</td>
<td>Hydro</td>
</tr>
<tr>
<td>Grand Bassa</td>
<td>Oil</td>
</tr>
<tr>
<td>Lofa</td>
<td>Hydro</td>
</tr>
<tr>
<td>Margibi</td>
<td>Oil (existing)</td>
</tr>
<tr>
<td>Maryland</td>
<td>Oil</td>
</tr>
<tr>
<td>Montserrado</td>
<td>Hydro (existing)</td>
</tr>
<tr>
<td>Nimba</td>
<td>Oil</td>
</tr>
</tbody>
</table>

### Table 4

Nodal information for power system expansion under various budgets.

<table>
<thead>
<tr>
<th>Location (i)</th>
<th>B = 5 million</th>
<th>B = 10 million</th>
<th>B = 50 million</th>
<th>B = 130 million</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gini = 0.34, $\rho = 37 \text{ kWh/ppl}$</td>
<td></td>
<td>$\rho = 42 \text{ kWh/ppl}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Centralized Capacity (MW)</td>
<td>Decentralized Capacity (MW)</td>
<td>$\rho_1$ (kWh/ ppl)</td>
<td>Centralized Capacity (MW)</td>
<td>Decentralized Capacity (MW)</td>
</tr>
<tr>
<td>Bomi</td>
<td>–</td>
<td>33</td>
<td>–</td>
<td>67</td>
</tr>
<tr>
<td>Bong</td>
<td>–</td>
<td>67</td>
<td>–</td>
<td>67</td>
</tr>
<tr>
<td>Gbarpolu</td>
<td>–</td>
<td>1</td>
<td>–</td>
<td>33</td>
</tr>
<tr>
<td>Grand Cape</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>33</td>
</tr>
<tr>
<td>Mount</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>33</td>
</tr>
<tr>
<td>Grand Gedeh</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.06</td>
</tr>
<tr>
<td>Grand Kru</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>26</td>
</tr>
<tr>
<td>Maryland</td>
<td>–</td>
<td>33</td>
<td>–</td>
<td>67</td>
</tr>
<tr>
<td>Montserrado</td>
<td>22</td>
<td>45</td>
<td>22</td>
<td>33</td>
</tr>
<tr>
<td>Nimba</td>
<td>–</td>
<td>67</td>
<td>–</td>
<td>52</td>
</tr>
<tr>
<td>River Cess</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>33</td>
</tr>
<tr>
<td>River Gee</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>33</td>
</tr>
<tr>
<td>Sinoe</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>33</td>
</tr>
</tbody>
</table>
what might be accomplished with a budget on the order of the requirement provided by Modi et al. [26], and also to highlight the challenge faced in increasing average consumption levels and achieving the universal access target.

We source transmission cost estimates from [31] who performed a literature review of transmission line costs. We operate under the assumption that medium and low voltage transmission lines (< 66 kV) cost $90,000/km, and high voltage transmission lines (230–66 kV) cost $200,000/km. We assume the capacities of the transmission lines are 60 MW for medium and low voltage and 100 MW for high voltage transmission lines.

For the base equality preference, we assume that α is equal to 0.86, as this is the best fit of the well-known relationship between the country per-capita electricity consumption, and HDI [68,69], as described in Appendix A. We further assume that peak annual load in the system is 1.7 times greater than average load. (i.e. γ = 1.7). This is based on Rwanda’s peak-average power demand ratio [38].

We use a discount rate of r = 12%, consistent with the rate used in the economic analysis of investment operations in Africa by USAID and the African Development Bank [70]. We note that countries that have limited capital resources are likely to have a higher discount rate due to the higher economic opportunity costs of funds.

4. Results and discussion

In this section we explicitly provide the tradeoffs as part of our results, so that decision makers can weigh the importance of total cost, total electricity, and distributional equality. First, we detail how power system development is impacted by the budget. We then conduct a sensitivity analysis of two key parameters, stakeholder equality preferences and solar capital costs, to better understand how the power system development plan is influenced by changes in these parameters.

Impacts of the budget. Our baseline analysis assumes that the equality preference α is equal to 0.86. The resultant optimal expansion plans for various budgets are presented visually in Fig. 4, and with more detailed nodal information in Table 4. In Fig. 4, ρ represents the average per-capita electricity consumption in the country, and the Gini coefficient signifies the level of distributional equality in the country, with a lower value indicating greater equality. The numbers superimposed next to each node represent the per capita electricity consumption level at that node in annual kWh/person. To put these in context we note that, among those who have electricity access in Liberia, the average electricity consumption per capita is 58 kWh/ppl. In Ghana, a nearby country with 85% access and a GDP of 66 billion USD, the per capital electricity consumption is 315 kWh/ppl [71].

Here we see that investment in large centralized hydro generation and solar PV-diesel mini grids are the primary means of increasing the level of electricity access in the country. Of interest is that the existing oil plant is not used until the budget exceeds 40 million USD, due to the high variable costs of oil. Rather, it appears to be more beneficial to expand the Mt. Coffee hydro facility near the capital city and use PV-diesel mini-grids to provide initial electricity access. This result is consistent with Modi et al. [26], who suggest the Mt. Coffee Hydro Facility is rebuilt and expanded. Similarly, SHS are only used in the low budget scenarios (B < 16 million USD) since they can be built at a very small scale, but have higher costs per unit of energy. In the 130 million USD case we see an ambitious deployment of centralized generation and transmission infrastructure. The resultant country per capita electricity consumption level of 727 kWh per year is similarly an ambitious target, more than ten times greater than the current level in Liberia of 58 kWh/ppl per year and more than twice as high as the current level in Ghana of 315 kWh/ppl per year.

The maps reveal four distinct power systems in the north and south of the country, signifying that due to the sparse population in the middle of the country it may be ideal to develop separate power systems, as opposed to one large completely connected system. However, a more detailed power flow analysis may also find additional value in the reliability benefits associated with connecting these disconnected transmission segments. As mentioned previously we strongly recommend that such an analysis be conducted before any plans are implemented. This result is consistent with Modi et al. [26] who suggest stand-alone and off-grid systems for the less dense areas in the middle of the region. We see a very high usage of PV-diesel mini grids in the $10 million budget, but these are replaced by centralized generation and transmission lines in the $50 million budget. This suggests that PV-diesel mini grids could be a viable option for increasing access to electricity while the country is in transition to a larger centralized power system. From Table 4 we see that Montserrado always receives the highest level of investment due to the high population density. In Table 4, decentralized generation includes PV-diesel mini grids and SHS.

Impacts of equality preferences. Here we present the role that equality preferences play in the determining the optimal expansion plan for the power system. In Fig. 4 we saw a steady increase in equality as the budget increases, signified by a lower Gini coefficient. Fig. 5 provides more detail on this relationship and expands the analysis to different equality preferences. We see that equality is slightly non-monotonic in the budget, increasing for some budget increases, since the investment into centralized generation and transmission is lumpy. The lumpiness is caused by investments in large centralized generation, and PV-diesel mini grids that require a minimum investment. At low budgets, the model chooses to invest in transmission lines connected to the existing hydro plant, and PV-diesel mini grids, filling in with SHS with any left-over budget. The model will choose to continue building PV-diesel mini grids and expanding the transmission system connected to the existing hydro plant until the budget is large enough to meet the minimum capital requirements for a second hydro facility plant. At that point, the optimal investment plan is to reduce the size of the first plant and as well as transmission investments, and build the second power plant. In general, we find that the overall pattern is that equality tends to increase with the budget, regardless of the equality preferences, but this effect is not monotonic everywhere.

Fig. 6 illustrates how the power expansion plan changes when the equality preference is reduced from the baseline value of 0.86 to 0.10. Here we see that the low equality preference places more emphasis on increasing the total amount of power generation in the country, which results in allocating all generation from the existing hydro plant in Montserrado to the capital city Monrovia, without developing PV-diesel mini grids, or transmission infrastructure. In general, under lower equality preferences the optimal expansion plan involves building larger power plants near the capital city. As the equality preference increases, a larger share of the budget gets redistributed to develop transmission infrastructure that delivers electricity to other regions. This leads to lower levels of total countrywide electricity consumption but increased access. For example, under the $10 million/year budget every node receives at least some electricity when the equality parameter is 0.86, but only two nodes, near the capital city, receive electricity when the equality parameter is 0.10. On the other hand, twice as much electricity is available in the low equality case. At higher budgets, this tradeoff between increasing total electricity consumption and providing all nodes with at least some electricity access is much less pronounced, as universal access is achieved with a much smaller reduction in total electricity consumption. If a stakeholder was to move from a low (α = 0.1) to a high (α = 0.86) equality preference then Fig. 6 illustrates that they could increase the energy access equality rating (i.e. lower the Gini coefficient) by 72 – 87%, depending on the budget. We also find that the existing oil plays a larger role in the electrification plan produced under the low equality preference scenario. This is because, when equality preferences are low, the higher attention to the urban areas lead to higher use of the existing centralized oil generation facility.

In Fig. 7 we see that the relationship between increasing budget and transmission investment depends on equality preferences. Transmission investments mostly increase as the budget increases for any fixed
equality preference, but we see that increasing equality preferences has a non-monotonic relationship with transmission. This is because there are trade-offs between investments in PV-diesel mini grids versus transmission investments for large hydro generation facilities.

When the equality preference is low, the optimal system is largely disconnected with most electricity available in the same node where it is generated. This effect is indicated by the gap in transmission line investment between the scenarios with equality preferences of 0.10 and 0.86. If we move from a low equality preference ($\alpha = 0.1$) to the base equality preference ($\alpha = 0.86$) the increase in transmission line investment is between 313 and 775 km, which is a lower bound on the actual system investment needs.

While the equality preference impacts transmission investments, we find that these preferences have no significant impact on SHS investments. Under baseline SHS cost assumptions, the lower per-unit cost of hydro and PV-diesel mini grid generation causes the optimal investment strategy to include less than 4.86 MW of SHS capacity under all equality preferences and budgets included in this study. This finding is aligned with Azimoh et al. [72] who found that large scale deployment of SHS to be unsustainable business due to their limited direct economic benefits for households due to their limited capacity for productive and thermal uses. This model result is largely because PV-diesel mini grids are assumed to be a lower cost perfect substitute for SHS when there is more than 1 MW of installed capacity in a given node. This substitution is due to the low resolution in our model. We explore the impact of falling solar costs in the next section.

**Impacts of SHS and PV-diesel mini grid costs.** Here we present a sensitivity analysis for the impact of the costs of SHS and PV-diesel mini grids, under a budget of 50 million USD/year. This budget was chosen due to hydro generation dominating the system at this budget. In Table 5 we consider the reduction in cost that would be necessary to reach different capacity penetration goals. The table presents the results of the minimum cost reduction required to achieve a pre-determined capacity penetration threshold. We note that in many cases, due to the

![Fig. 4. Maps and electricity allocation under various budgets.](image-url)
lumpiness of investment, the actual capacity penetration is higher than the minimum threshold.

From Table 5, we see there tends to be a tipping point as costs reduce, with penetration of either solar technology increasing very rapidly once a certain cost reduction is met. For example, within the 50 million budget case, for SHS under low inequality preferences we see that an 89% reduction in costs is necessary to reach 20% penetration; whereas penetration jumps up to 48% when costs are reduced, only marginally more, by 90%. This pattern is repeated in all the cases.

Equality preference has a very small impact on these results. Regardless of preferences we see that SHS costs would need to fall by at least 86%, and PV-diesel mini-grid costs by at least 65%, for either of them to comprise at least 20% of the generation capacity mix. Note that these steep reductions are not required at low budget cases.

On the other hand, the relationship between falling solar costs and equality does depend on the stakeholder’s equality preference, further highlighting the importance of equality preferences in energy decision making. Falling solar prices leads to more inequality, but higher average consumption under the high equality preference case. This is because it shifts investment from transmission to generation. In the low equality preference case, this is reversed: falling solar costs lead to more equality. In this case, the base level of transmission is low; lower solar costs lead to larger investments in generation capacity around the country due to the modular nature of solar.

We note that these results are based on a low geographic resolution. It is possible that with increased resolution some of these results in infrastructure might change. For example, at higher resolution we expect that decentralized generation would become more widespread, particularly in rural communities. Also, at lower budgets a steep reduction in solar costs would not be required.

### 4.1. Sustainability trade-offs

Here we present trade-offs among sustainability and equality objectives using a MCDA framework. Fig. 8 visualizes the results. Each criterion has been normalized between 0 and 1, with 1 representing the best outcome (see Appendix E for methodology). Table 6 shows the raw values for each criterion and the values associated with 0 and 1. All cases except the high-equality, low-budget case ($\alpha = 0.86$, $B < 40$ million USD) are dominated by hydro (with small amounts of existing oil having little impact). Thus, neither equality preferences nor budget has much impact on water or GHG emissions. In the high-equality, low-budget case there is reliance on hybrid PV-diesel mini grids due to its modularity. This means that this case has significantly higher GHG emissions intensity (and local pollution), but marginally lower water consumption intensity. The trade-off between higher pollution (due to diesel) and higher access is not uncommon in the developing world. This analysis shows that it can be ameliorated to some extent, in countries like Liberia with significant hydro resources, through making greater investments in the electricity system.

**Overall trends.** In Table 7 we summarize the general findings of this analysis. In the table an upward (downward) arrow signifies an increase (decrease), and a cross signifies no relationship. We found that transmission investment increased with increasing budget, but was non-monotonic in equality preferences, and decreased with falling solar costs. Investments in PV-diesel mini grids increased with an increasing annual budget, up to a value of about $50$ million, but then decreased. SHS investments decreased with increasing budget, and rose slightly with decreasing component costs. In general, we find that SHS is non-monotonic in budget, and is a “filler” technology primarily used to spend extra money in the budget, prior to meeting the minimum capacity needed for a PV-diesel mini grid or a larger centralized generation facility.

Interestingly, in the 50 million annual budget case the relationship between installed solar capacity and the equality of electricity access, as quantified by the Gini coefficient, depends on the equality preference. This is caused by the trade-off between investments in decentralized generation and transmission infrastructure, and the low availability factor of solar. At low solar costs we see higher levels of generation concentrated at the demand centers. At the onset of falling costs the hydro generation in the capital city is much larger than the solar connected nodes. When solar costs have fallen to the point where we can have large scale deployment then the gap between consumption levels in the city and rural regions narrows.

**Limitations of current analysis.** We have demonstrated that the MEA model can be applied to provide useful insights into how socially-optimal electrification plans are impacted by changes in a number of key parameters, however the case study that we used to demonstrate the capabilities of this model also has a number of limitations.

A primary limitation of our analysis stems from the aggregation of the population into 15 nodes with relatively low spatial resolution, as we are unable to explicitly model the optimal development of transmission or distribution lines within any of these nodes. Utilizing a finer spatial resolution would likely increase the required transmission and distribution infrastructure investments and may therefore lead to greater investments in decentralized infrastructure in the rural communities. Because we assume that per capita electricity consumption is
constant within each node, increasing the number of nodes would also provide more detailed insight into electricity consumption and access inequalities; for example, highlighting specific small, remote villages that are particularly attractive candidates for decentralized infrastructure.

Another limitation comes from the limited data available on the cost of generation and transmission infrastructure in Liberia and other African countries.

The MEA model has 136 continuous and 118 integer (of which 95 are binary) variables. The base model with a budget of 50 million USD and \( \alpha = 0.86 \) takes 36.7 seconds to solve. As the integer variables that represent decision to build new generation increase, the required solve time increases logarithmically. One method for overcoming the computational burden could be to employ integer clustering method for handling discrete decision variables [73], which often provides a good approximation and a significant reduction of large-sized optimization problems [74].

5. Conclusions and policy implications

This paper presents a methodology for incorporating stakeholder equality preferences into generation and transmission expansion planning. We analyzed how investment in power system infrastructure is impacted by changes in stakeholder equality preferences, level of investment, and technology costs. This work provides a tool for decision makers to understand how their preferences towards equality can impact the optimal generation and transmission expansion plan in a region. To our knowledge, this work is the first to explicitly integrate stakeholder equality preferences into an optimization-driven decision-making process, offering a new perspective on resource allocation in the context of energy access and equity.
generation and transmission planning model, and has broad applications for countries looking to expand access to electricity, or rebuild systems after a disaster. Our results indicate that higher preferences for equality lead to a more interconnected power system. Under high equality preferences, investments in transmission infrastructure are made in lieu of building additional centralized generation capacity, as long as the budget is high enough. As a result, a greater fraction of the population receives electricity access under most assumptions. Under lower equality preferences, the system is more fragmented, with less transmission infrastructure, fewer mini-grids, and more investment in large power plants near larger cities. This results in higher total electricity consumption for the country, but a lower fraction of the population with electricity available for consumption as this consumption is more concentrated in urban areas. The overall pattern for electricity system development is that equality generally increases with the budget, regardless of the equality preferences, but this effect is not monotonic everywhere. In other words, the lumpiness of power system development costs causes inequality when budgets are small relative to the demand for services.

Reducing the cost of solar, either SHS or PV-diesel hybrid, leads to more investment in decentralized generation. This, however, often leads to less equality rather than more, particularly at low budgets. The availability of low-cost decentralized generation options means that it is optimal to invest in less transmission. This leads to some communities – those that get the solar – having more access to electricity, but fewer people overall getting access. At high annual budgets, however, the tipping point for solar dominating the optimal strategy is very steep.

Stakeholders’ equality preferences significantly impact the level of electricity access provided to different parts of the country. We would expect this observation to hold in other low-income countries. The specific results will depend on the existing infrastructure; regions that already have established transmission networks would likely rely even more heavily on a centralized generation and transmission model as the primary means for electrification. There is a connection between higher equality and higher pollution at low budget levels, but this ameliorated, in countries like Liberia with hydro, at higher budgets since it is optimal to move toward more central generation and away from diesel-supported small generation. In countries with fewer hydro resources this tradeoff may differ, particularly if the primary centralized generation technology relies on CO₂ emitting fossil fuels.

Future work involves modeling this generation expansion plan as a progression through time as opposed to a single static year, integrating it with physics-based network models for applications in regions with more-developed infrastructure, as well as considering a higher geographic resolution. Our analysis is intended to provide insight into the high-level impacts of large changes in annual budgets and equality preferences. Future work could focus on replicating this methodology at the distribution level and then potentially linking the transmission and distribution models. We recommend obtaining improved data on generation costs and population data with a greater spatial resolution before using this model to inform specific country-level development plans. Additionally, modeling power system expansions in developing countries is complex problem with many objectives. In the future this work would benefit from a multi-objective planning framework that combines the traditional least-cost, reliability, power quality, and the newly presented equality preference. Using a multi-objective approach, such as the weighting method, could further illustrate trade-offs between supplying electricity at low cost (for low income customers), sufficient reliability (for industrial customers), and meeting equality goals (for international investors and national universal electrification

![Fig. 7. Transmission line investment as a function of the budget for various equality preferences.](image)

<table>
<thead>
<tr>
<th>Technology</th>
<th>SHS</th>
<th>PV-Diesel Mini Grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Budget</td>
<td>$50 million</td>
<td>$50 million</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Equality Parameter</th>
<th>$50 million</th>
<th>$50 million</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10</td>
<td>0.86</td>
<td>0.10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Minimum Capacity Penetration Threshold</th>
<th>0% 20% 40% 0% 20% 40% 0% 20% 40% 0% 20% 40% 0% 20% 40%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Achieved Capacity Penetration</td>
<td>0% 20% 49% 0% 21% 42% 0% 21% 42% 0% 28% 71% 0% 20% 49%</td>
</tr>
<tr>
<td>Generation Penetration</td>
<td>0% 4% 14% 0% 4% 11% 0% 4% 11% 0% 29% 89% 0% 25% 51%</td>
</tr>
<tr>
<td>Cost Reduction Required</td>
<td>0% 89% 90% 0% 86% 87% 0% 68% 71% 0% 65% 68%</td>
</tr>
<tr>
<td>Gini</td>
<td>0.47 0.40 0.35 0.06 0.14 0.13 0.47 0.22 0.02 0.06 0.09 0.07</td>
</tr>
<tr>
<td>Average Per capita consumption (kWh/ppl)</td>
<td>321 314 313 272 284 286 321 313 324 272 297 306</td>
</tr>
</tbody>
</table>
One challenge that will need to be overcome as the model scales up is the nonlinearity of the objective function, which may prove to be computationally intensive. Thus, another fruitful direction of research would be to use a method other than piecewise linear approximations for integrating non-linear objective functions.

This work has been the first to explicitly integrate a stakeholder preference towards equality into the electricity modeling literature, thus opening the doors to a greater understanding of how political uncertainty regarding equality preferences would impact the optimal power system development, and providing a more holistic approach to electricity planning. While the preferences here are illustrative this work is an important step in understanding the role political climate and stakeholder preferences play in generation and transmission expansion planning. A fruitful direction of research would be to elicit stakeholder preferences and integrate this into the modelling framework, and incorporate a wider range of electrification objectives. Eliciting the true preferences of stakeholders could present modelling challenges due to the wide range of functional form, and the impact of their nonlinearity on the computational solve time.

This work will be of particular interest to policymakers and system planners with limited power system budgets. Specifically, it provides such policymakers and planners with a tool that can quantify the impact of preferences for equality in electricity consumption, thereby balancing the tradeoff between improving electricity access and increasing total electricity consumption in their system. These decision makers can gain insights into how changes in their equality preference will impact the overall allocation of resources within their system. From our work it is clear that stakeholders who have a strong preference for equality and a goal of increasing electricity access will benefit from more interconnected power systems. There is no single optimal approach to achieving universal access to electricity as this will depend on specific stakeholder preferences. However, regardless of these preferences, sound investments in electricity infrastructure will assist developing countries in reaching their sustainable development goals.

### Table 6

<table>
<thead>
<tr>
<th>Budget (million USD)</th>
<th>Stakeholder Equality Preference (α)</th>
<th>Country Per-Capita Electricity Consumption (kWh/ppl)</th>
<th>Equality (Gini)</th>
<th>CO2 Intensity (gCO2eq/MWh)</th>
<th>Water Intensity (L/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>High (α = 0.86)</td>
<td>42.3</td>
<td>0.18</td>
<td>80.8</td>
<td>4218.7</td>
</tr>
<tr>
<td></td>
<td>Low (α = 0.10)</td>
<td>91.2</td>
<td>0.71</td>
<td>8.4</td>
<td>4486.4</td>
</tr>
<tr>
<td>50</td>
<td>High (α = 0.86)</td>
<td>272.1</td>
<td>0.65</td>
<td>4.8</td>
<td>4489.8</td>
</tr>
<tr>
<td></td>
<td>Low (α = 0.10)</td>
<td>320.6</td>
<td>0.47</td>
<td>4.7</td>
<td>4490.9</td>
</tr>
<tr>
<td>100</td>
<td>High (α = 0.86)</td>
<td>558.1</td>
<td>0.02</td>
<td>7.2</td>
<td>4490.3</td>
</tr>
<tr>
<td></td>
<td>Low (α = 0.10)</td>
<td>593.1</td>
<td>0.27</td>
<td>7.2</td>
<td>4490.2</td>
</tr>
</tbody>
</table>

*Best (1) 593.1 0 0 0
Worst (0) 0 1 80.8 4490.2

### Table 7

Overall trends in model outputs.

<table>
<thead>
<tr>
<th>With budget increase</th>
<th>With equality preference increase</th>
<th>With solar cost decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission</td>
<td>![Upward Arrow]</td>
<td>![Downward Arrow]</td>
</tr>
<tr>
<td>Solar installations</td>
<td>![Upward Arrow]</td>
<td>![Upward Arrow]</td>
</tr>
<tr>
<td>Equality</td>
<td>![Upward Arrow]</td>
<td>![Upward Arrow]</td>
</tr>
<tr>
<td>Total Electricity</td>
<td>![Upward Arrow]</td>
<td>![Upward Arrow]</td>
</tr>
</tbody>
</table>

*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.
CRediT authorship contribution statement

Destenie Nock: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing - original draft, Data curation. Todd Levin: Conceptualization, Methodology, Formal analysis, Resources, Writing - review & editing, Supervision. Erin Baker: Methodology, Formal analysis, Resources, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Well-being and electricity access

We make two key assumptions in our model: that there is always sufficient demand to consume all electricity that is generated and delivered to each population node, and that this in turn will lead to increased utility through improvements in the quality of life. Regarding the first assumption, there is evidence that demand for electricity tends to increase rapidly once access is provided for the first time, provided there is sufficient access to electrical appliances [75–78]. We note here that the relationship between access and consumption will not be constant as access grows – there will be saturation in demand. Moreover, this assumption includes an implicit assumption that electricity demand is price inelastic. Nevertheless, we believe that this is a reasonable approximation in developing countries that currently have low levels of access.

Regarding our second assumption, there are two arguments for this. The first is that utility will depend on energy services, and total energy consumption is a good proxy for access to energy services. We note that utility does not inherently increase as electricity consumption increases, but is rather driven by utilization of the services that it provides, such as lighting. However, electricity consumption is a reasonable proxy for energy service utilization. This effect will be moderated by improvements in energy efficiency: utility will be higher for the same amount of energy consumption if appliances are more energy efficient. For a fixed level of energy efficiency, however, and in the absence of pure waste, utility will increase with increasing electricity consumption.

The second argument is more controversial, but important. It is the idea that energy access in developing countries contributes to economic growth and quality of life. It is well established that there is a positive correlation between per capita energy consumption and well-being indicators, such as the Human Development Index (HDI), the Physical Quality of life Index, infant mortality, and life expectancy [11,9,79,10,80,81]. A socio-economic impact study by the World Bank correlated electricity access to significant educational achievement [4]. In addition to well-being indicators, there is a host of energy indicators for sustainable development that relate to equality and health, such as accessibility, energy resource risk, affordability, safety, and air quality [6,7]. Alam et al. [10] established a logarithmic relationship between quality of life and per capita electricity consumption.

Fig. A1 illustrates how the HDI [68] is related to per capita electricity consumption at the country level [69] for the year 2014. Each data point represents a different country. The HDI is a composite statistic, developed by the UN, which measures achievement in three parts of human development: length and quality of life, education, and standard of living. The length and quality of life is determined through life expectancy at birth. The education indicator is derived from the mean number of years of schooling for adults aged 25 years or older, and the number of years of schooling a child is expected to receive once they enter school [82]. Gross national income per capita is used to evaluate standard of living. Fig. A1

![Fig. A1. The HDI compared to per-capita electricity consumption.](image-url)
shows that there is a logarithmic relationship between HDI and 2014 per capita electricity consumption, confirming the relationship identified by Kanagawa and Nakata [83] using 2002 data.

Although these correlations between energy consumption and well-being indicators are well-established, it is hard to determine the degree to which electrification causes increases in well-being, particularly for the economic development aspect of well-being [84]. Along with the normal challenges of establishing causation, predicting the impact of electrification has other difficulties, such as challenges in the reliability for electric supply and the rate at which electric appliances are adopted [85]. Parikh et al. [2], however, found evidence that providing infrastructure, including electricity, in Indian slums increases literacy, income, and health, particularly for women.

Finally, there is some indication that additional electricity consumption provides diminishing marginal returns after a certain level of consumption is achieved. The saturation effect is apparent in Fig. A1 and suggests that increased consumption at low levels may have a greater relative impact on socio-economic development, but this relationship may become less pronounced as the country becomes more developed and well-being is less dependent on energy consumption [86]. Martinez and Ebenhack [86] highlighted that the marginal returns to HDI from increased per-capita energy consumption became even more diminished when major energy exporting nations, such as OPEC countries, were filtered out.

There is evidence that, in general, stakeholders care about equality in terms of electricity access due to rural electrification programs and the UN SDGs. We also recognize that the benefits of increased electricity consumption have decreasing returns to scale due to the initial development gains, and energy efficiency allowing regions to maintain the same level of development, under lower levels of energy consumption. Thus, we model utility as a function of electricity access, using an isoelastic utility function, also known as the constant relative risk aversion utility function.

Appendix B. 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:

\[
f(p) = \begin{cases} 
    b_1 + \frac{b_2 - b_1}{a_2 - a_1}(p - a_1), & \text{if } \rho \leq a_1 \\
    b_i + \frac{b_{i+1} - b_i}{a_{i+1} - a_i}(p - a_i), & \text{if } \rho \geq a_i \text{ and } \rho \leq a_{i+1} \\
    b_n + \frac{b_{n+1} - b_n}{a_{n+1} - a_n}(p - a_n), & \text{if } \rho > a_n 
\end{cases}
\]

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 \( b_i \) values indicate the corresponding utility values, \( u \). The \( \rho \) is the per capita electricity available to be consumed at a node. The MEA model the piecewise linear function was approximated using 6,000 points.

Appendix C. Cost and parameter assumptions

The technical and economic assumptions for the MEA model calculations are summarized in Table C1.

### Table C1

<table>
<thead>
<tr>
<th>Parameters used to calculate costs of utility scale generation technologies.</th>
<th>Value</th>
<th>Units</th>
<th>Source</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discount rate (r)</td>
<td>12</td>
<td>%</td>
<td>[70]</td>
<td></td>
</tr>
<tr>
<td>Hours in a year (h)</td>
<td>8760</td>
<td>hr</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technology Specific</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydro</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capital Cost ((C_{\text{cap,k}}))</td>
<td>2562</td>
<td>$/kW</td>
<td>[61]</td>
<td></td>
</tr>
<tr>
<td>Fixed Operations &amp; Maintenance cost ((C_{\text{FOM,k}}))</td>
<td>22</td>
<td>$/kW-yr</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Variable Operations &amp; Maintenance cost (excluding fuel) ((C_{\text{VOM,k}}))</td>
<td>0</td>
<td>$/kWh</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Availability factor ((a_{\text{f}}))</td>
<td>81</td>
<td>%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lifetime ((y_{\text{f}}))</td>
<td>30</td>
<td>years</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capital Cost ((C_{\text{cap,k}}))</td>
<td>1033</td>
<td>$/kW</td>
<td>[40], [87]</td>
<td></td>
</tr>
<tr>
<td>Fixed Operations &amp; Maintenance cost ((C_{\text{FOM,k}}))</td>
<td>15</td>
<td>$/kW-yr</td>
<td>[87]</td>
<td></td>
</tr>
<tr>
<td>Variable Operations &amp; Maintenance cost (excluding fuel) ((C_{\text{VOM,k}}))</td>
<td>0.004</td>
<td>$/kWh</td>
<td>[87]</td>
<td></td>
</tr>
<tr>
<td>Availability factor ((a_{\text{f}}))</td>
<td>75</td>
<td>%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lifetime ((y_{\text{f}}))</td>
<td>40</td>
<td>years</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel cost ((C_{\text{fuel,k}}))</td>
<td>9.09</td>
<td>$/Mbtu</td>
<td>[40,87]</td>
<td></td>
</tr>
<tr>
<td>Heat Rate ((HR_{\text{f}}))</td>
<td>10,687</td>
<td>Btu/kWh</td>
<td>[40]</td>
<td></td>
</tr>
<tr>
<td>PV-Diesel Hybrid</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PV Capital Cost ((C_{\text{cap,k}}))</td>
<td>1800</td>
<td>$/kW</td>
<td>Taylor and Young So 2016</td>
<td></td>
</tr>
<tr>
<td>Diesel Capital Cost ((C_{\text{cap,k}}))</td>
<td>650</td>
<td>$/kW</td>
<td>[62]</td>
<td></td>
</tr>
<tr>
<td>Fixed Operations &amp; Maintenance cost ((C_{\text{FOM,k}}))</td>
<td>24</td>
<td>$/kW-yr</td>
<td>[61,62]</td>
<td></td>
</tr>
<tr>
<td>Variable Operations &amp; Maintenance cost (excluding fuel) ((C_{\text{VOM,k}}))</td>
<td>0.01</td>
<td>$/kWh</td>
<td>[62]</td>
<td></td>
</tr>
<tr>
<td>Availability factor ((a_{\text{f}}))</td>
<td>75</td>
<td>%</td>
<td>[62]</td>
<td></td>
</tr>
</tbody>
</table>

(continued on next page)
Appendix D. Sustainability metrics

Most of the sustainability metrics, presented in Table D1, are sourced from Klein and Whalley [46]. We note that metrics provided by Klein and Whalley [46] are based on data from the United States. The CO₂ and water intensity for Liberia will fluctuate based on the quality and efficiency of the power plants, as well as the efficiency of the electrical transmission and distribution system [91].

We assume that on-site direct water consumption by a SHS is the same as for utility scale PV, and that water consumption for diesel generators is negligible.

Table D1: Sustainability metric data for GHG emissions and water consumption.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
<th>Units</th>
<th>Source</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lifetime (y_k)</td>
<td>25</td>
<td>years</td>
<td>[62]</td>
<td></td>
</tr>
<tr>
<td>Fuel cost (C_{fuel,k})</td>
<td>18.3</td>
<td>$/Mbtu</td>
<td>[62]</td>
<td></td>
</tr>
<tr>
<td>Solar Home System (SHS)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Capital Cost for SHS System</td>
<td>4.25</td>
<td>$/W</td>
<td>[62,64,26]</td>
<td></td>
</tr>
<tr>
<td>Solar Capital Cost</td>
<td>3.5</td>
<td>$/W</td>
<td>[62]</td>
<td></td>
</tr>
<tr>
<td>Availability factor (a_{f,k})</td>
<td>17</td>
<td>%</td>
<td>[88]</td>
<td></td>
</tr>
<tr>
<td>Battery type</td>
<td>Deep-cycle Lead Acid</td>
<td></td>
<td>[64]</td>
<td></td>
</tr>
<tr>
<td>Battery Lifetime (y_b)</td>
<td>4</td>
<td>Years</td>
<td>[64]</td>
<td></td>
</tr>
<tr>
<td>Battery Capital Cost</td>
<td>213</td>
<td>$/kWh</td>
<td>[26]</td>
<td></td>
</tr>
<tr>
<td>Battery Sizing</td>
<td>3.5</td>
<td>kWh/kW</td>
<td>[64]</td>
<td></td>
</tr>
</tbody>
</table>

Appendix E. Normalization of electrification objectives

Each sustainability metric is normalized to allow for comparison across criteria resulting in each criterion being measured on a scale between 0 and 1. A measure of 1 reflects that this is the best calculated value of that metric across all portfolios being considered. A measure of 0 signifies the worst value.

The sustainability metrics are normalized using Eqs. (E1) and (E2).

\[
z_{ij} = \frac{\phi_{ij} - \phi_{min}}{\phi_{max} - \phi_{min}}, \text{ where } \phi_{max} \text{ is preferred}
\]

\[
z_{ij} = \frac{\phi_{max} - \phi_{ij}}{\phi_{max} - \phi_{min}}, \text{ where } \phi_{min} \text{ is preferred}
\]

where \( \phi_{ij} \) is the raw score of electricity mix i for sustainability metric j, \( z_{ij} \) is the normalized score of electricity mix i for metric j. Eq. (E1) is used where a higher value is most desirable (i.e. electricity consumption). Eq. (E2) is used for where lower value is most desirable (i.e. GHG emissions intensity, water consumption intensity, Gini).

References

[14] Latorre G, Cruz RD, Areiza JM, Villegas A. Classification of publications and models