Community-Based Microgrid Planning and Operation for Fostering Energy Justice

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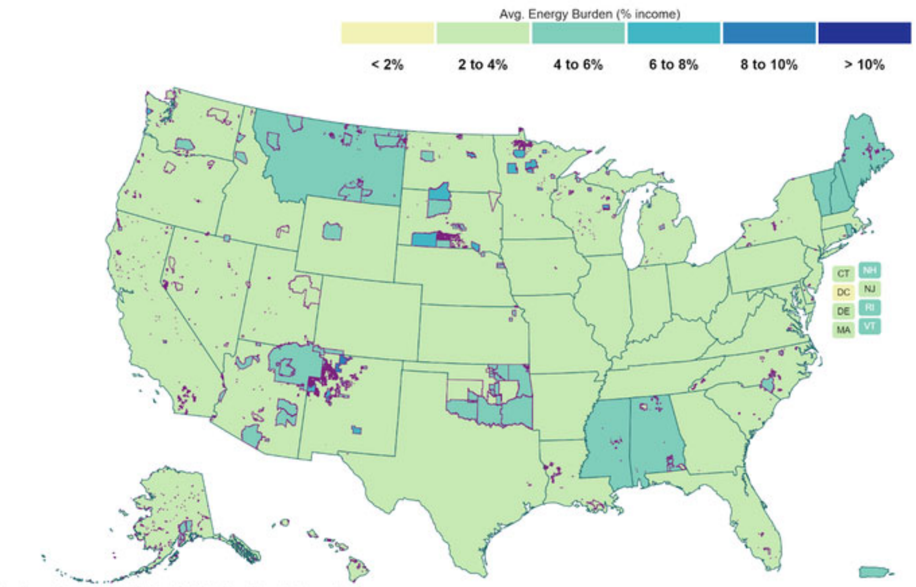
Table of Contents

Introduction-Background

- The average annual household energy costs in different states range between 1,638$ and 4,073$. Energy burden refers to the percentage of gross household income spent on energy expenses. Throughout the nation, the median energy burden is 3.1%, and the median energy burden for low-income households is 8.1% [1].

- Energy justice is the goal of achieving equity in both the social and economic participation in the energy system, while also remediating social, economic, and health burdens on those disproportionately harmed by the energy system [2]. The Justice40 Initiative requires that 40% of the overall benefits from certain Federal investments flow to disadvantaged communities.



Low-Income Energy Affordability Data Tool Map Export (https://lead.openei.org/)
Exported On: 8/26/2022
AMI: 0% - 30%, 30% - 60%, 60% - 80%, 80% - 100%, 100%+
Building Age: Before 1940, 1940 - 59, 1960 - 79, 1980 - 99, 2000 - 09, 2010+
Heating Fuel Type: Utility Gas, Bottled Gas, Electricity, Fuel Oil, Coal, Wood, Solar, Other, None
Building Type: 1 unit detached, 1 unit attached, 2 units, 3 - 4 units, 5 - 9 units, 10 - 19 units, 20 - 49 units, 50+ units, Boat/RV/Van, Mobile/Trailer
Rent/Own: Renter-occupied, Owner-occupied

Fig. 1. Energy burden for states [3]

Introduction-Motivations and Contributions

- **Motivations**
  - Energy cost is a major expense for U.S households.
  - Low-income households are suffering from a heavier energy burden.
  - Investing in distributed energy resources (DERs) is an efficient solution to reduce the energy burden of low-income households and improve energy justice.

- **Contributions**
  - A community-based microgrid planning approach is proposed to reduce energy burden of residents by investing in DERs while improving energy justice.
  - A multi-objective optimization problem is formulated to simultaneously reduce the energy burden and improve the electricity service resilience of low-income households.
  - Various case studies are analyzed to evaluate the significance of involving energy justice in the planning and operation problem.

Problem Description

- The considered community consists of both low-income households and high-income households.
- The planned DERs include small-scale diesel generators, solar generators, and battery energy storage.
- It is assumed that the community microgrid need to operate in islanded mode during extreme events.
- The goal of the planning problem is to reduce the energy burden of the community residents while improving the self-sustainability during potential islanded operation period with a focus on low-income households.

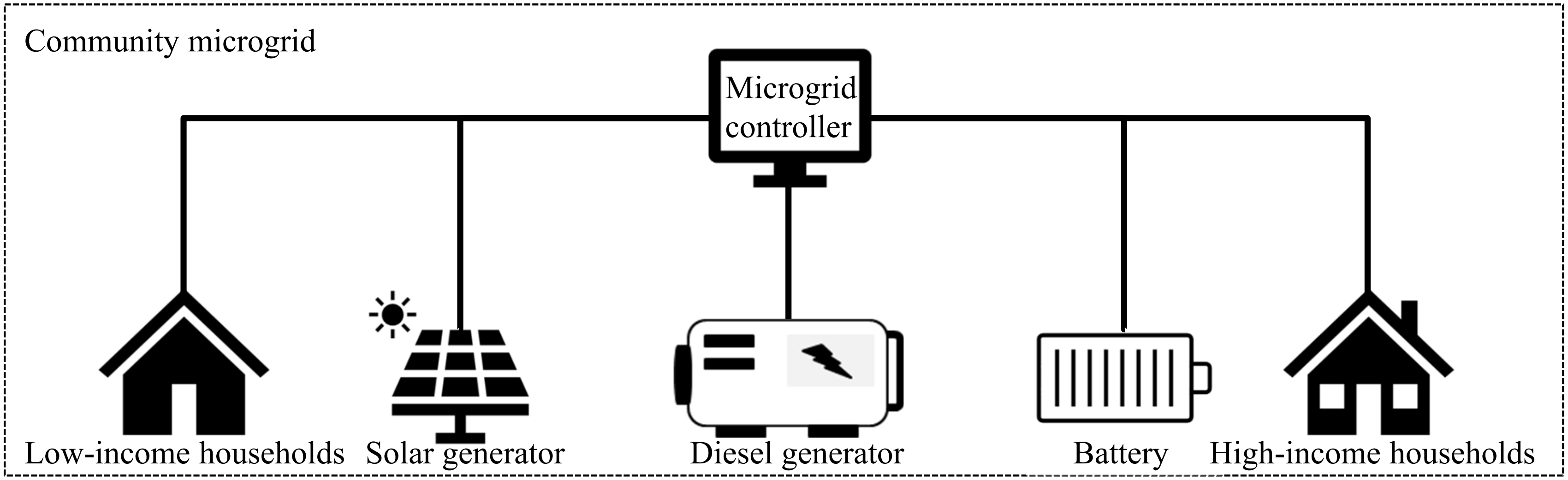


Fig. 2. System overview

Problem Formulation-Objective Function

- The problem objective has two components, including minimizing the energy costs during normal operation period and maximizing the power supply during resilience operation period.
- Different weights (w_c and w_r) are assigned to different goals to balance between energy costs and service resilience.
- Low-income households are given larger weights (w_i) than high-income households (w_j) to improve energy justice.

$$\min_{C^{solar},C^{battery},C^{diesel}} \left[\begin{array}{l} \pi_{connected} w_c \sum_{t \in T} \left(\sum_{i \in LIH} w_i P_{i,t} \lambda_t + \sum_{j \in HIH} w_j P_{j,t} \lambda_t \right) \\ -\pi_{islanded} w_r \sum_{t \in T} \left(\sum_{i \in LIH} w_i P_{i,t} + \sum_{j \in HIH} w_j P_{j,t} \right) \end{array} \right] \quad \begin{array}{l} \longleftarrow \text{Minimizing energy cost} \\ \qquad (1) \\ \longleftarrow \text{Maximizing energy supply} \end{array}$$

C^{solar}:	Solar generator capacity	λ_t:	Energy price at time t	$P_{i,t}$:	Load of low-income households
$C^{battery}$:	Battery capacity	$\pi_{connected}$:	Probability of connected operation	$P_{j,t}$:	Load of high-income households
C^{diesel}:	Diesel generator capacity	$\pi_{islanded}$:	Probability of islanded operation		

Problem Formulation-Constraints

- The problem constraints include planning constraints and operation constraints.
- The planning constraints include DER capacity constraints and the budget constraint.

$$C_{energy,min}^{battery} \leq C_{energy}^{battery} \leq C_{energy,max}^{battery}$$

(2) Battery energy capacity constraint

$$C_{power,min}^{battery} \leq C_{power}^{battery} \leq C_{power,max}^{battery}$$

(3) Battery power capacity constraint

$$C_{min}^{solar} \leq C^{solar} \leq C_{max}^{solar}$$

(4) Solar generator capacity constraint

$$C_{min}^{diesel} \leq C^{diesel} \leq C_{max}^{diesel}$$

(5) Diesel generator capacity constraint

$$C_{energy}^{battery}\lambda_e^b + C_{power}^{battery}\lambda_p^b + C^{solar}\lambda^s + C^{diesel}\lambda^d \leq B$$

(6) Investment budget constraint

λ_e^b: Battery energy capacity unit price

λ_p^b: Battery power capacity unit price

λ^s: Solar generator capacity unit price

λ^d: Diesel generator capacity unit price

B: Total investment budget

Problem Formulation-Constraints

- The diesel generator and battery are considered dispatchable units, and the solar generator is non-dispatchable.
- The operational constraints include technical constraints for the dispatchable DERs.

$SoC_{min}C_{energy}^{battery} \leq E_t^{battery} \leq C_{energy}^{battery}$	(7)	Battery energy level constraint
$0 \leq P_{charge,t}^{battery} \leq C_{power}^{battery}$	(8)	Battery charging power constraint
$0 \leq P_{discharge,t}^{battery} \leq C_{power}^{battery}$	(9)	Battery discharging power constraint
$P_{discharge,t}^{battery} \times P_{charge,t}^{battery} = 0$	(10)	Battery power constraint
$E_{t+1}^{battery} = E_t^{battery} + \eta P_{charge,t}^{battery} - P_{discharge,t}^{battery}/\eta$	(11)	Battery energy change constraint
$0 \leq P_t^{diesel} \leq C^{diesel}$	(12)	Diesel generator power constraint

SoC_{min}:	Minimum battery state-of-charge	$P_{charge,t}^{battery}$:	Battery charging power	η:	Battery dis/charging efficiency
$E_t^{battery}$:	Battery energy at time t	$P_{discharge,t}^{battery}$:	Battery discharging power	P_t^{diesel}:	Diesel generator power

Problem Formulation-Constraints

- The energy of the battery should be maintained after the operation of each day.
- The load and generation should be balanced at any time during the normal operation period.
- The electricity price is computed as the average price for supplying the loads at each time step.

$$\sum_{t \in T} \left(P^{battery}_{charge,t} \eta - P^{battery}_{discharge,t} / \eta \right) = 0$$

(13) Battery energy balance constraint

$$P^{solar}_{t} + P^{battery}_{discharge,t} - P^{battery}_{discharge,t} + P^{diesel}_{t} + P^{grid} = \sum_{i \in LIH} P_{i,t} + \sum_{j \in HIH} P_{j,t}$$

(14) Power balance constraint

$$\lambda_t = \frac{P^{diesel}_{t} c_{diesel} + P^{grid}_{t} c_{grid,t}}{\sum_{i \in LIH} P_{i,t} + \sum_{j \in LIH} P_{j,t}}$$

(15) Energy price calculation

c_{diesel}: Unit price of diesel generator fuel cost

$c_{grid,t}$: Unit price of energy procurement from the grid

Case Study

- The unit investment prices of DERs are set to 500$/kW for solar generation, 950$/kW for diesel generator, and 240$/kW and 270$/kWh for battery energy storage.
- On average, high-income households consumes more energy than low-income households
- The planning result gives an optimal capacity of 100 kW solar generator, a 205kW diesel generator, and a 35kW/155kWh battery.

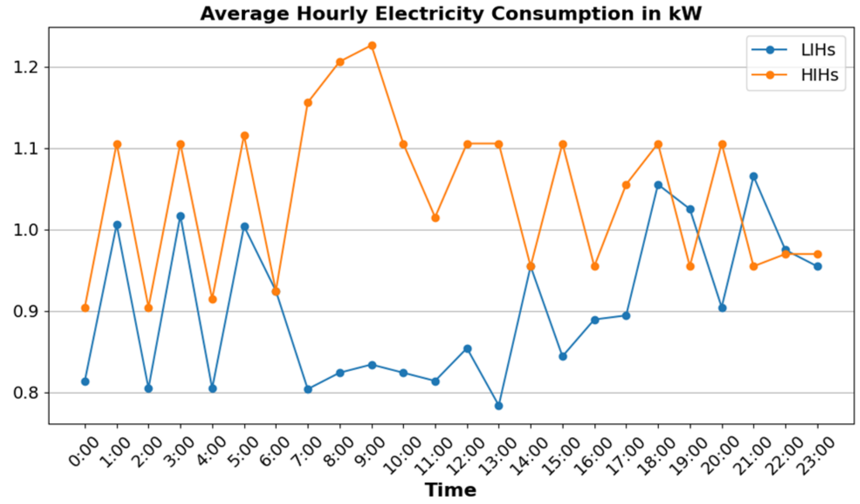


Fig. 3. Average load profiles for low-income and high-income households

Case Study

- The planned DERs can cover most energy demands to avoid importing energy from the grid and reduce energy cost.
- By using the invested DERs to supply the community load, the energy costs of low-income and high-income households are reduced by 14.16% and 14.04%, respectively.

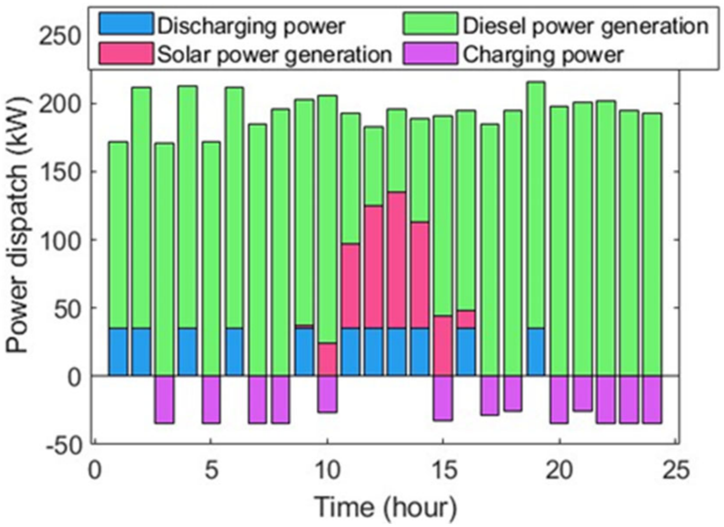


Fig. 4. A typical DER dispatching result

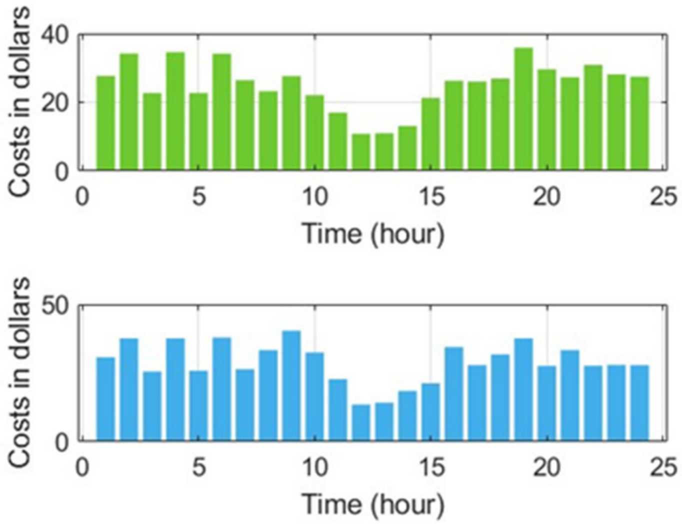


Fig. 5. Energy costs of different households

Case Study

- Solar generation is the major reason for electricity price reduction because it lowers the average electricity cost.
- Battery energy storage is dispatched to reduce energy price when the load of low-income households is high to improve energy justice.

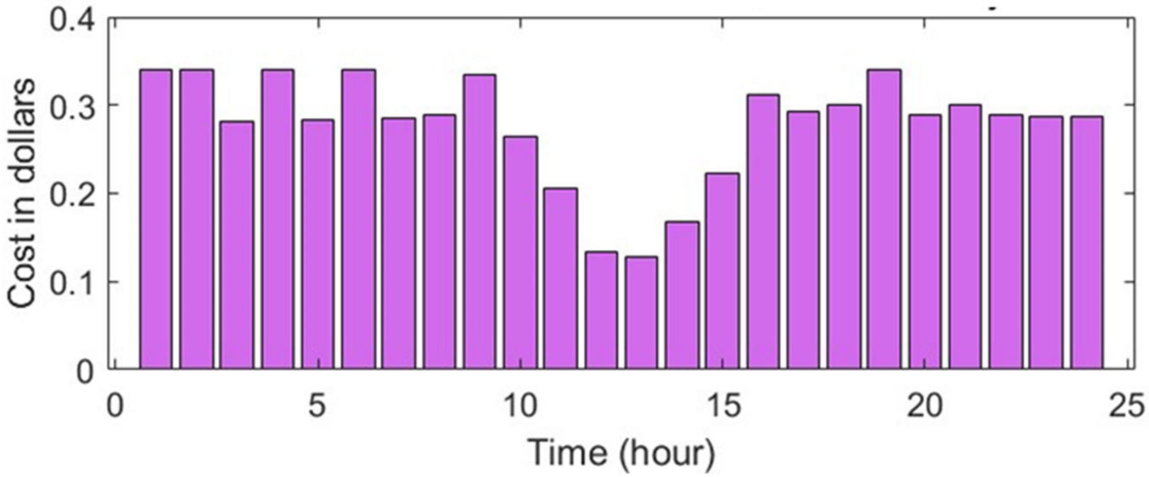


Fig. 6. Electricity price result

Case Study

- By assigning different weights to low- and high-income households, the obtained energy cost slightly changes.
- The total cost is the lowest when the weights for both types of households are the same (50% and 50%).

Table I: Energy Cost Summary

Case	w_i	w_j	Low-income household total energy cost ($)	High-income household total energy cost ($)	Total cost ($)
A	0%	100%	609.48	692.40	1,301.88
B	75%	25%	609.47	692.40	1,301.87
C	50%	50%	607.33	693.91	1,301.24
D	25%	75%	607.19	694.14	1,301.33
E	100%	0%	607.15	694.45	1,301.60

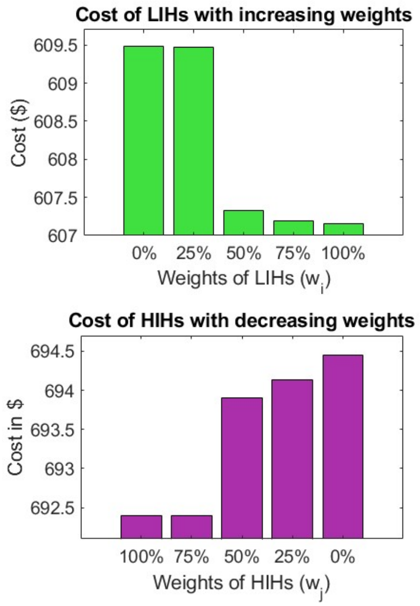


Fig. 7. Cost changes

Case Study

- During extreme events, the microgrid operates in islanded mode and energy from the grid is not available.
- The primary objective during extreme events is to supply as much load as possible.
- Because the low-income households have higher weights than high-income households, the energy demand of low-income households are satisfied in priority to high-income households. By varying the weights for different households, the energy supply changes significantly.

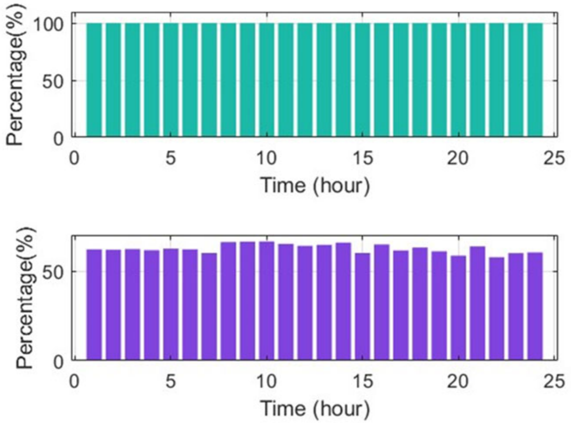


Fig. 8.Electricity supply during extreme events

Table II: Energy Supply Summary

Case	w_i	w_j	% of load supplied during extreme events for low-income households	% of load supplied during extreme events for high-income households
F	75%	25%	56.66	100.00
G	50%	50%	63.90	94.77
H	25%	75%	100.00	66.52

Conclusion and Future Work

- **Conclusion**
  - A community microgrid planning model is developed in this work with a focus on improving energy justice.
  - By assigning larger weights to low-income households, the low-income household energy cost is reduced, but the overall cost increases slightly.
  - Varying the weights for different households has a more significant impact on energy supply resilience than energy cost reduction in terms of improving energy justice.

- **Future Works**
  - The future work will enhance the planning model by considering network topology and constraints to evaluate the impact of network constraints on the planning and operation result.
  - The future work will include uncertainties like long-term demand growth, short-term load and solar generation variations to develop more comprehensive planning models.

References

1. American Council for an Energy-Efficient Economy, online, url: https://www.aceee.org/energy-burden
2. Energy Justice Dashboard (BETA), online, url: https://www.energy.gov/justice/energy-justice-dashboard-beta
3. Department of Energy Low-Income Energy Affordability Data(LEAD), online, url: https://www.energy.gov/scep/slsc/lead-tool

Thank You!
Q&A

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