A Bi-Objective Optimization Approach to Reducing Energy Poverty Through Biomass Gasification: The Case of Rural Colombia

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Problem Description

- **Energy poverty** is a major barrier to socio-economic development in off-grid communities;
- 10% of the world's population still lacks access to electricity, and 2.4 billion rely on fossil fuels, e.g., diesel or kerosene;
- These fuels are expensive and highly polluting;
- Biomass is cleaner and more abundant in rural areas;
- **But it remains underutilized for rural energization**.

Problem Description

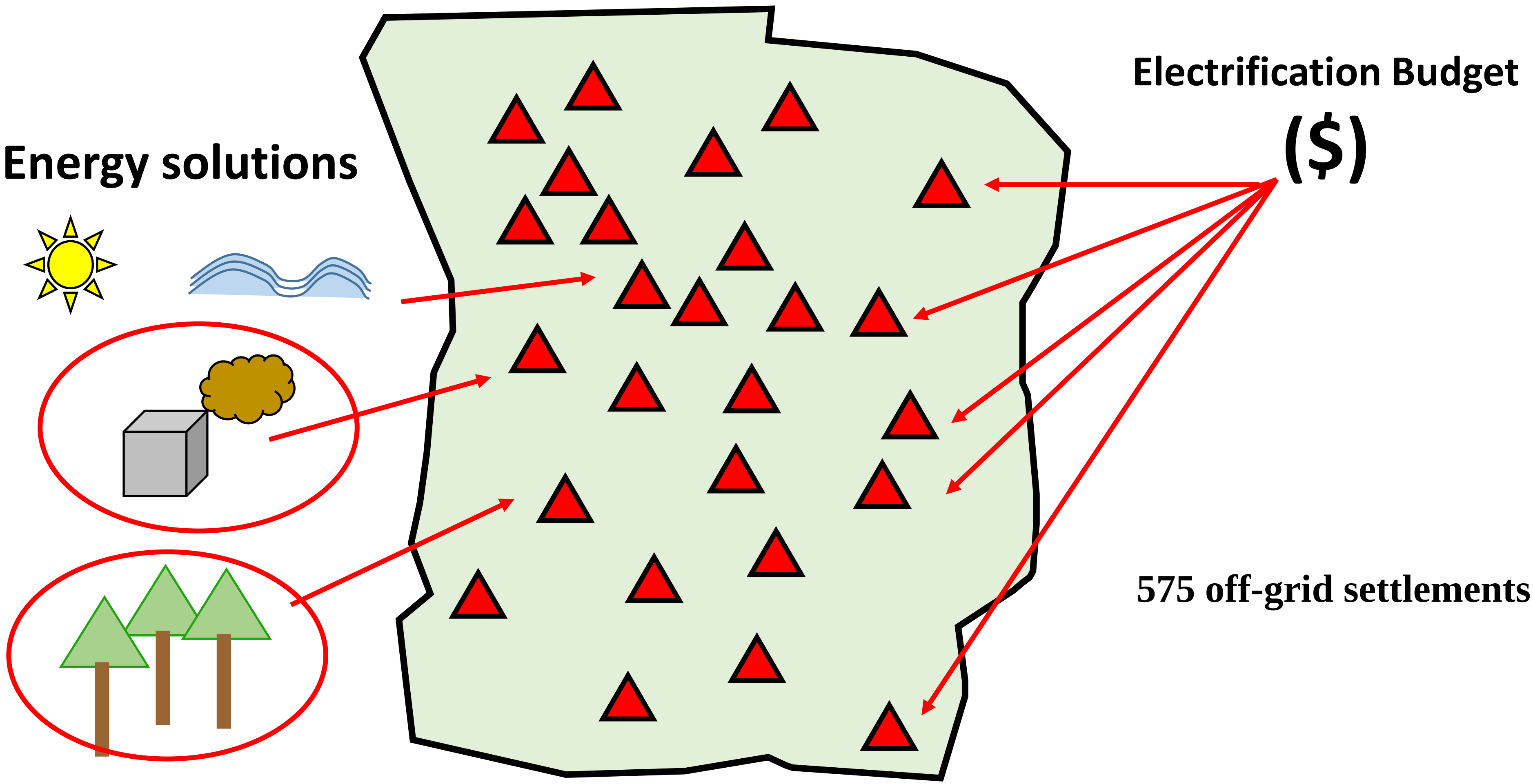
- **Regional rural electrification plans**—especially in Colombia—often subsidize inefficient and costly local power plants.
- Only **1.5%** of **off-grid energy** comes from biomass.
- Despite an estimated potential of 16 GW.

Literature Review & Research Gap

- A **literature review** was conducted around:
  - Most common rural energy planning problem: **local stand-alone**
  - **Energy poverty** indexes and composite indicators;
  - Common methodological approaches, e.g., single-objective optimization, MCDA, MO optimization – MILP.
  - Most frequently considered energy sources, e.g., solar PV!

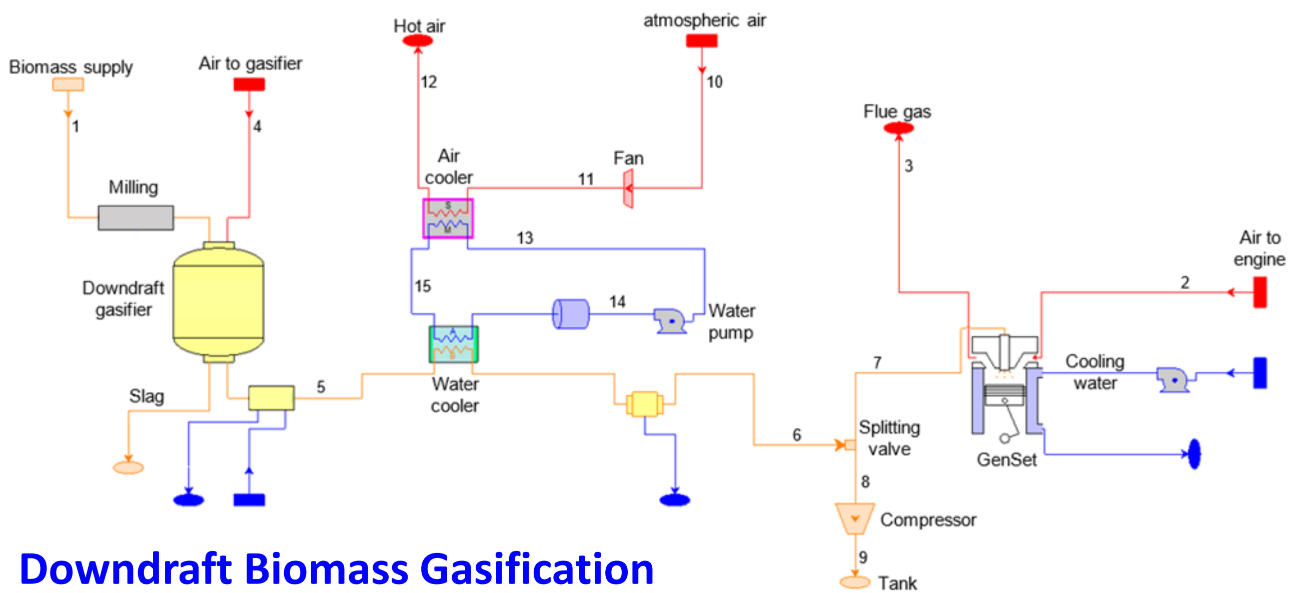
- **Identified Gap**:
  - Very few studies focus on **regional energy planning** incorporating **biomass gasification technologies** and **energy poverty indexes**.

Regional rural electrification plan



Case Study: Rural Colombia

Residual biomass by crop type	average share %	LHV [kJ/kg] (As received)	Production by crop type [tons/year]	Biomass production by crop type [tons/year]
rice	23.8%	13162	1268.93	3235.76
corn	4.4%	12800	474.46	668.99
banana	8.8%	1577	6176.26	37057.57
plantain	59.6%	1577	16685.85	100115.13
cane	3.2%	11700	921.82	5789.03
oil palm	0.2%	12790	1573.15	1337.18



Downdraft Biomass Gasification

Model

- We developed a **bi-objective optimization model** to assess the feasibility of biomass gasification as an alternative to diesel-based electrification;
- We wanted to explore to what extent biomass gasification could reduce energy poverty under **current rural electrification budget conditions;**

$$\min_{X} Z(X,Y) = \omega_1 f_1(X,Y) + \omega_2 f_2(X,Y)$$

$s.t.$

$$g_i(X,Y) \leq 0; \quad \forall\, i$$

$$h_i(X,Y) = 0; \quad \forall\, i$$

$$X \in \bar{X}, Y \in \bar{Y}$$

Model

energy access gap

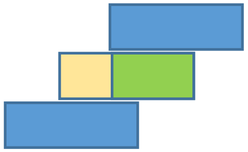
$$\text{Min } \textit{Energy Poverty Index} = \omega_1 * EAG + \omega_2 * ESO$$

EAG: the distance between the total energy amount supplied to a rural settlement with a given energy service (Ei), and the minimum amount they need for subsistence (173 kWh/month).

$$EAG = \frac{\sum_i EG_i * Users_i}{\sum_i Users_i}$$

$$EG_i = 1 - \frac{E_i}{ES * users_i} \;;\; \forall\, i$$

Energy service level



$$E_i = \sum_k \sum_j e_{ij} * X_{ij} * Y_{ik} \;;\; \forall\, i$$

Diesel and Biomass

Model

energy service overspending

$$\text{Min } \textit{Energy Poverty Index} = \omega_1 * EAG + \omega_2 * ESO$$

ESO: how close settlements are to reaching an excessive energy cost threshold (6% household income).

$$ESO = \frac{\sum_{i=1}^{l} EO_i * Users_i}{\sum_{i=1}^{l} Users_i}$$

$$EO_i = \frac{EBill_i}{EOT_{Colombia}} \; ; \forall\, i$$

$$EBill_i = \frac{E_i * COE_{ij} * (1 - Fsubsidy_i)}{Income_i} \; ; \forall\, i \; ; j = biomass, diesel$$

Model

Constraints:

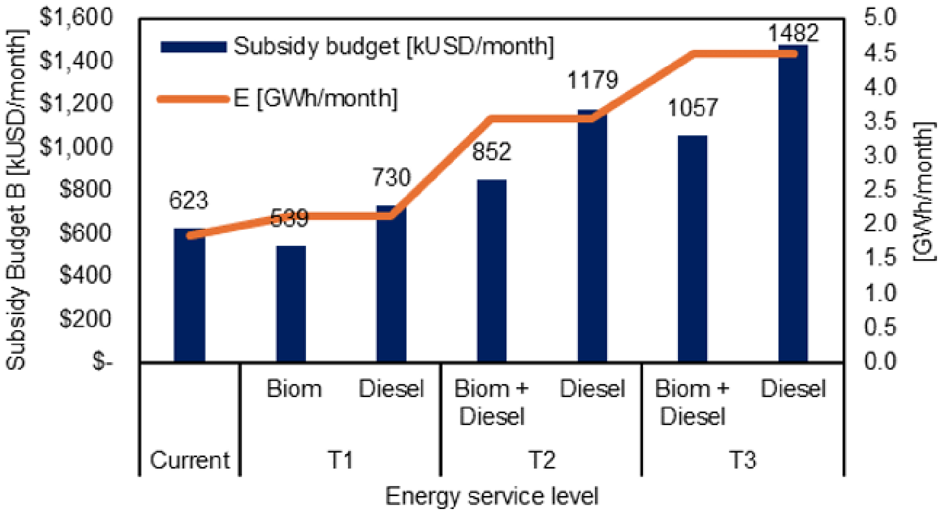
Each settlement receives at least the tier 1 energy service level

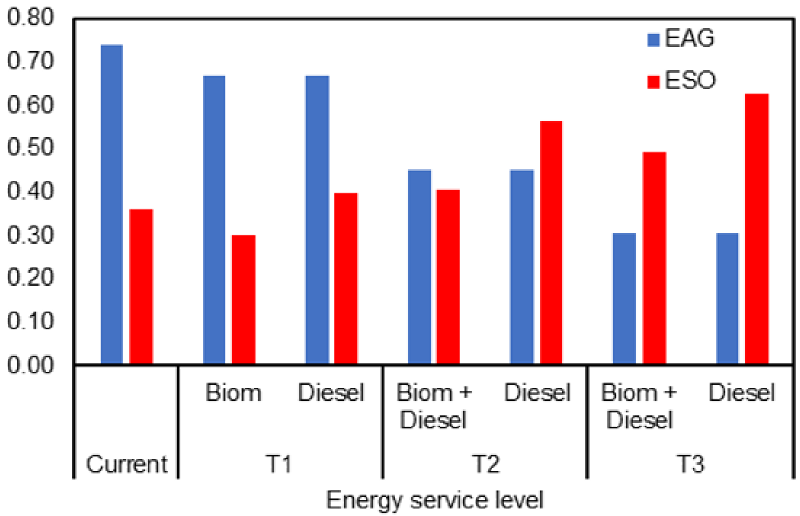
$$E_i \geq e_{i,1} * X_{i,1} * Y_{ik} \text{ ; } k{=}diesel \text{ ; } \forall\, i$$

Total subsidies should be less than or equal to the budget value B designated by the government, which in 2020 was 623,000 USD/month

Results

Baseline scenarios (no optimization):

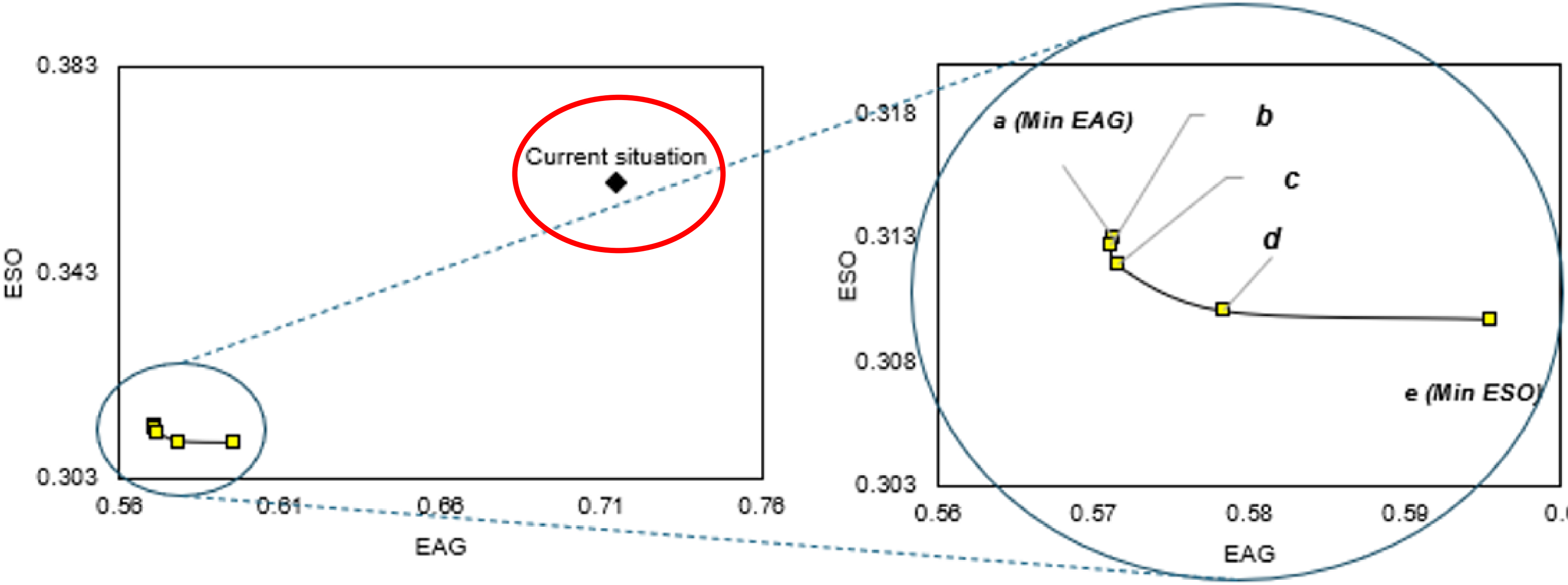




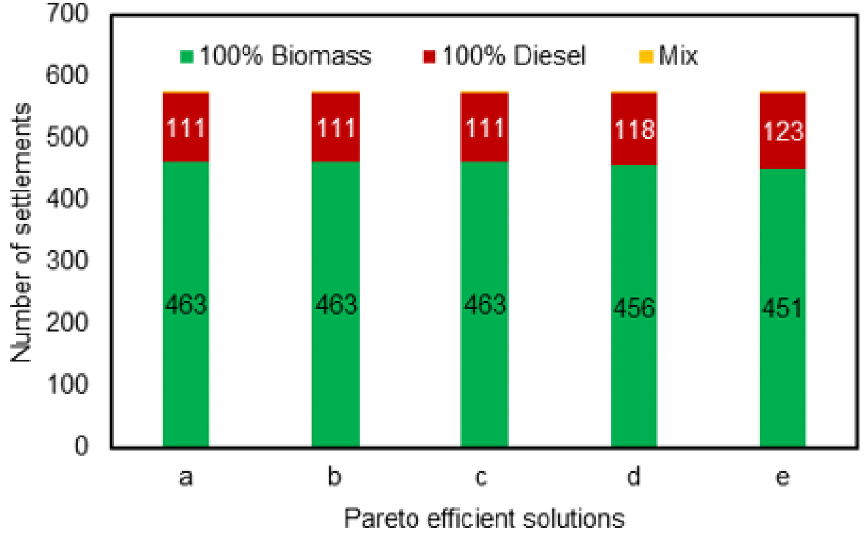
Results

Pareto efficient frontier at the current subsidy level of 623k USD/month

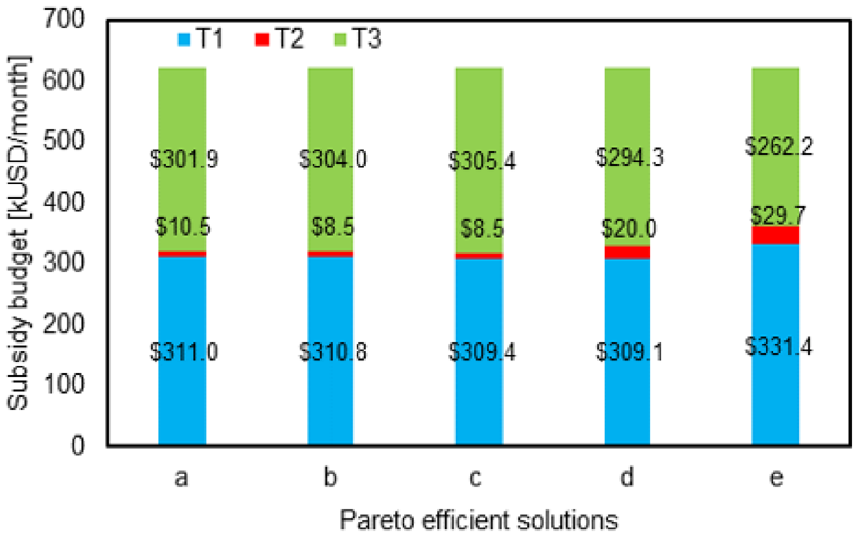
a ($w_1=1$, $w_2=0$), *b* ($w_1=0.75$, $w_2=0.25$), *c* ($w_1=0.5$, $w_2=0.5$), *d* ($w_1=0.25$, $w_2=0.75$), *e* ($w_1=0$, $w_2=1$)



Results



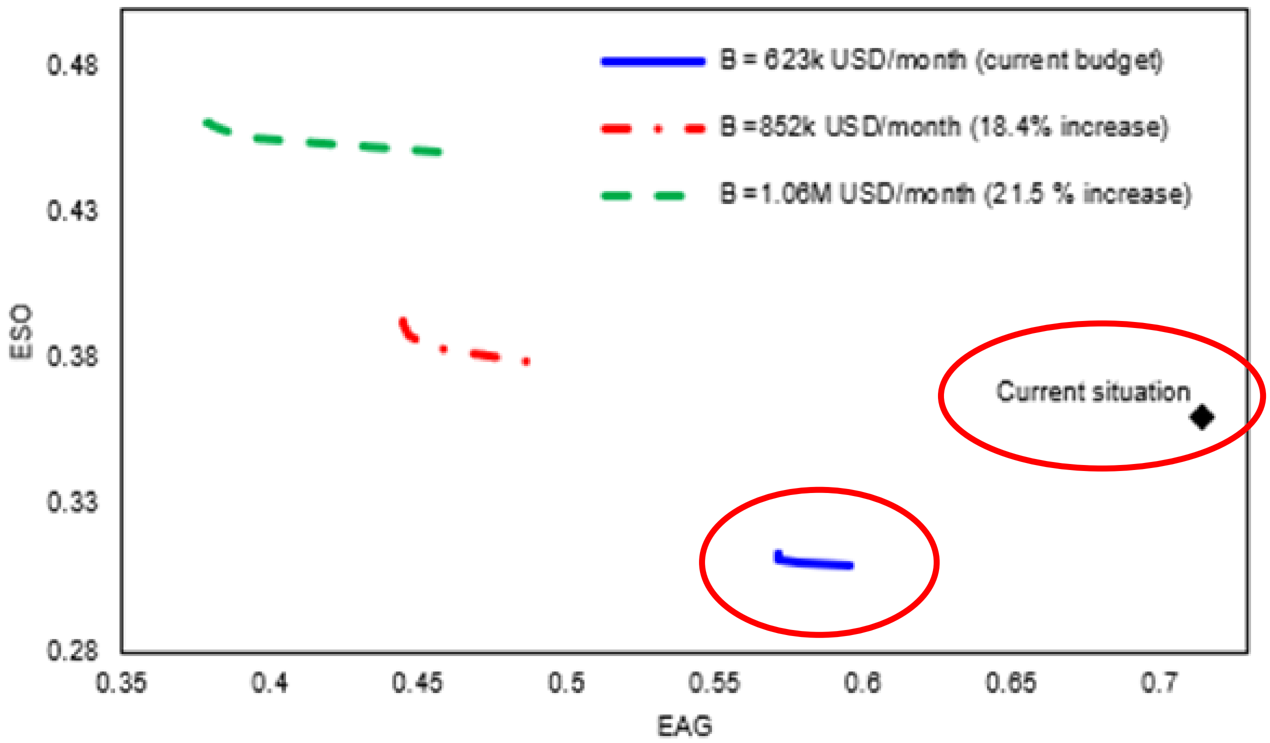
700
600
500
400
300
200
100
0
Number of settlements
100% Biomass
100% Diesel
Mix
111
111
111
118
123
463
463
463
456
451
a
b
c
d
e
Pareto efficient solutions



700
600
500
400
300
200
100
0
Subsidy budget [kUSD/month]
T1
T2
T3
$301.9
$304.0
$305.4
$294.3
$262.2
$10.5
$8.5
$8.5
$20.0
$29.7
$311.0
$310.8
$309.4
$309.1
$331.4
a
b
c
d
e
Pareto efficient solutions

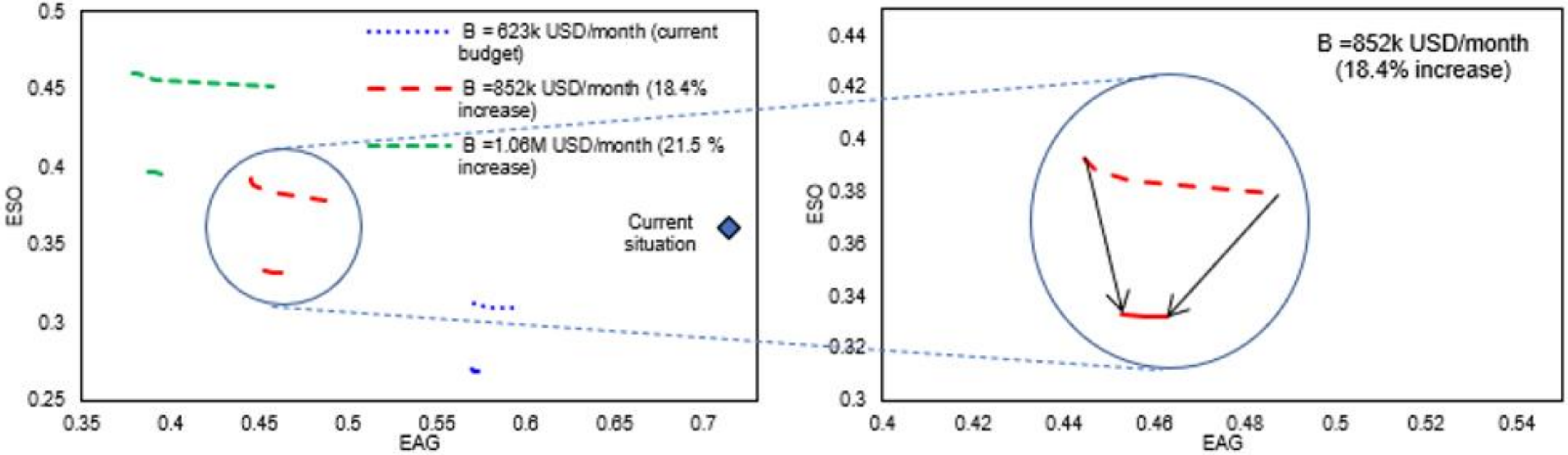
Results

Impact of subsidy budget (*B*) increases on the region´s Pareto efficient frontier



Results

Uniform Energy Bill Subsidy Policy of 85%



Conclusions

- The results demonstrate the potential of transitioning from diesel to biomass, reducing diesel by up to 89%;
- Biomass gasification can improve energy affordability and accessibility without requiring significant increases in subsidies;
- There is a trade-off between **energy access** and **energy cost -** a universal subsidy policy can reduce these trade-offs;
- A universal 85% subsidy policy can reduce such a trade-off, making energy more affordable and accessible for households;
- Prioritizing energy access (solution **a**) puts more users into higher service tiers, while focusing on costs (solution **e**) allocates users to lower service tiers;