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# Optimizing Rural Household Energy in Karnali through a Linear Programming Approach using Secondary Data

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## Abstract

This study employs a linear programming (LP) model to optimize the rural household energy consumption in Karnali Province of Nepal. The 80% households of karnali province still rely on the firewood as their primary energy source due to poor electrification rate. This study uses the secondary sources of data from the reliable sources such as government agencies, reports and publically available database. This study constructs a cost minimizing energy mix model of electricity, PV solar, LPG, and firewood. We have taken two scenarios for this simple optimization model of the energy mix. The one is with no restriction on the use of firewood and one restricting the use of firewood is in line with the forest conservation efforts. The result from the energy mix model shows that firewood as the cheapest energy source (NRs. 3.87/kWh), but its use is environmentally costly as it produces the 2.41 billion kg of CO2 annually that requires to cuts over 1.1 million trees each year in karnali. In the restricted model the households that relays on the firewood as energy sources is reduced by 98.7% that cuts the emission by over 2.37 billion kg CO2 per year by maintaining the affordable energy mix of electricity and solar with optimized cost of NRs. 671.72 per month per household. This study shows that transitioning to a balanced mix of electricity and solar energy is financially viable and environmentally critical which aligns with the SDG 7 Affordable and Clean Energy goal and with SDG 13 Climate Action goal. Since this study is aligned with the SDG's goal, it offers a replicable policy model for rural energy transformation.

***Keywords:*** *Linear Programming, Excel Solver, Optimization, Renewable Energy, Emission Reduction*

## 1. Introduction

Nepal's energy sector is mostly dominated by hydropower energy supply, but access to the rural region remains uneven. While the national energy mix is increasingly dominated by hydropower, over 25% of households in Karnali Province has no access to grid electricity and rely on traditional energy source (CBS, 2021). This has implications for health, environment sustainability, and economic development. Consequently, rural households in Karnali are highly dependent on traditional biomass sources, primarily firewood for cooking and heating purpose. It reports that the indoor air pollution mainly from solid fuel use like firewood is responsible for more than 13000 premature deaths annually in Nepal (WHO, 2023). Women and children are disproportionately affected, as they spend more time in indoors exposed to the traditional energy source. In addition to the to the health risks, firewood overdependence contributes to the deforestation. Data shows that Karnali households consume over 1.3 billion kg of firewood annually which is equivalent to the felling approximately 1.1 million mature trees each year (FA0 Estimate). This contributes to the massive carbon emission of around 2.41 billion kg $CO_2$ annually. Several studies have explored energy optimization using LP model. At national and urban levels to explore household energy transitions or electricity pricing strategies, linear programming model have been used (Koirala et al, 2020). However, this models often generalize demand, ignore localized constraints. This models rarely accounts for the specific vulnerabilities of rural, off-grid communities like those in Karnali as the Karnali terrain, economic, social behavior are significantly differing from urban contexts. Some paper has emphasized the use of optimization in rural energy planning across the Global South. The integrated role of planning models in achieving energy access for the poor, concluding that localized optimization frameworks outperform centralized strategies in addressing context specific barriers (Bazilian et al., 2012). The decentralized energy planning and found that linear and integer programming models can effectively guide the choice of off-grid solutions, particularly in geographically complex regions (Bhattacharyya & Timilsina, 2010). In Nepal, A fuzzy AHP model to evaluate rural energy options in Nepal, considering sustainability from economic, environmental, and social perspectives. While insightful, it lacked cost optimization, which this study addresses through LP modeling for monthly energy costs under strict constraints (Chhipi-Shrestha et al.,2015). A system dynamics approach to simulate household energy transitions in Nepal. Their findings affirm that restricting firewood and promoting cleaner alternatives reduces emissions aligning with the outcomes of this LP-based study focused on affordability and policy relevance (Adhikari & Mishra, 2021). Jha, R. (2021) provides a comprehensive review of household energy system optimization in Nepal, highlighting the technical, economic, and social barriers to clean energy adoption in rural areas. This study identifies the mismatch between top-down energy planning and household-level realities, particularly in regions with seasonal demand are fluctuating, poor infrastructure, and more informal energy practices. It emphasizes the need for locally adapted optimization models, such as LP and MCDA.

Households energy optimization is necessary for rural sustainable development in energy sector. This study fills that gap by applying a household-level LP optimization model specific to the rural socio-economic and infrastructural conditions of Karnali Province. By comparing energy mixes under two scenarios unrestricted and environmentally restricted firewood use it identifies affordable and practical solutions for minimizing household energy costs while ensuring policy compliance and environmental sustainability. This energy mix (i.e., Linear Programming) offers a mathematical method of optimizing energy to fulfill household energy demands with accessible resources. Based on the secondary data source, the study builds an LP model in excel to determine the cheapest mix of energy for domestic consumption in Karnali. This model can lead to more sustainable energy consumption patterns, reduce dependency on biomass and ensure a more reliable energy supply and replicates the frame work to support rurak energy transitions in line with Nepal's national goals and global commitments like SDG.

### 1.1 Objectives

1. To develop and LP model in excel for minimizing household energy cost.
2. To evaluate energy mix scenarios with and without firewood restrictions.
3. To provide policy recommendation for improving sustainable energy development.

### 1.2 Assumptions

a) Average household needs are taken constant with no significant changes.
b) Renewable energy solutions are feasible in this region.
c) Dry Season energy demand are taken for formulating mathematical model.
d) Seasonal variation in energy demand and supply are taken constant.
e) Only Photovoltaic solar energy supply has taken into consideration.

### 1.3 Limitation

a) Seasonal variations in energy supply and demand changes in actual that affect the optimize energy mix.
b) Limited access to up-to-date data on household energy consumption and household energy sources.
c) Economic factors, policy factors and feasibility of Renewable Energy restricts the actual implementation of optimized energy mix.
d) All the data are based on the secondary sources.

## 2. Methodology

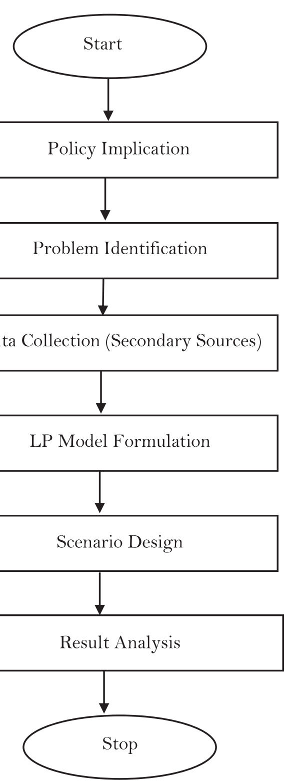


**Figure 1:** Flow Chart

For this case study, data has been collected from reliable sources such as government reports, public databases, and research institutions. Data were sourced from AEPC (2023), NEA (2023), NOC (2023), National Census (NPHC 2021), WHO (2023). These organizations provide valuable insights into electricity access, renewable energy adoption, and energy consumption patterns in Nepal. NEA's annual reports offer details on electricity tariffs and supply, while AEPC provides information on off-grid solar and micro-hydro projects.

**Table 1:** No of Household by type of fuel usually used for cooking (NPHC 2021)

| Area | Total | Type of fuel | | | |
|---|---|---|---|---|---|
| | | Wood | Liquefied Petroleum Gas | Electricity | Other |
| **Karnali Province** | 366037 | 300962 | 61727 | 353 | 2995 |
| **Surkhet District** | 97822 | 59269 | 37600 | 109 | 844 |

**Table 2:** No of Household by type of fuel usually used for Heating (NPHC 2021)

| Area | Total | Usual source of lighting | | | |
|---|---|---|---|---|---|
| | | Electricity | Solar | Bio gas | Other |
| **Karnali** | 366037 | 181676 | 175306 | 145 | 8910 |
| **Surkhet District** | 97822 | 67096 | 28905 | 11 | 1810 |

Using the Nepal's per capita average electricity consumption was around 245kWh annually, and applying and assumed average household size of 4.8 persons, it translates to approximately 94kWh monthly per households. As, there is rise in demand for household we have used the maximum load demand of 100kWh per month per house for this case study.

*Annual household consumption*

$$=245kWh\ /person/year \times 4.6\ person/\ household$$

$$=1127\ kWh/household/year$$

*Monthly household consumption=93.9kWh*

Based on per capita income of Karnali region for the fiscal year 22/23, each household can spend up to NRs. 14111anually on energy consumption. So, monthly each can spend approximately about NRs. 1175 on energy. However, for the case study we have taken monthly expenses limit of NRs. 2000.

Table 3 Electricity Tariff Data for Single Phase Low Voltage (230V) 15 Ampere according to NEA.

| kWh (Monthly) | Monthly Minimum Charge | Energy Charge (Nrs)/kWh |
|---|---|---|
| 0-20 | 50 | 4.0 |
| 21-30 | 75 | 6.5 |
| 31-50 | 75 | 8.0 |
| 51-100 | 100 | 9.5 |
| 101-250 | 125 | 9.5 |
| Above 251 | 175 | 11.0 |

According to Nepal Electricity Authority, The Surkhet district of Karnali Province is connected to the national grid and receives electricity through 33kV and 11kV lines. As of the fiscal year 2020/21, the Surkhet

Distribution Center reported the energy sales of 108,729 MWh (megawatt-hours) annually. Thus, the Surkhet Distribution Center supplied approximately 9,061,000 kWh of electricity per month to consumers during the 2020/21 fiscal year, while the total electricity supplied (including losses) was around 10,617,000 kWh per month. This data includes households, businesses, and institutions. So, taking that this 80% of the supply of electricity is supplied to household. So, on average each household can receive around 211kWh of electricity per month.

According to NOC, the retail price of a 14.2 kg LPG cylinder in Surkhet is NRs. 1,800. This makes the cost per kilogram of LPG is as approximately NRs. 127. According to the CBS, an average household uses 1 to 1.5 cylinder of LPG per month which is around 17.04 kg. Using energy conversion factor, 1 kg of LPG contains 12.9 kWh energy.

*nergy consumption from LPG per month per household=12.9×17.04*

*=219.82kWh*

$$Cost\ per\ kWh = \frac{Cost\ of\ 1\ kg\ LPG}{Energy\ from\ 1\ kg\ LPG} = \frac{127}{12.9} = NRs. 9.84$$

According to AEPC, Karnali region receives 3.6-6.2 kWh/m2/day solar radiation and 300 sunny days annually which is ideal for solar energy. AEPC's Gutu Solar Mini-grid has capacity of 100 kWp. kWp means kilowatt peak power output of solar. This Gutu Solar Mini-grid with a peak power of 100 kWp working at its maximum capacity for one hour produces 100 kWh energy.

$$Annual\ Output\ (kWh)$$
$$= System\ Size\ (kWp) \times Average\ Solar\ Hours\ per\ Day$$
$$\times No. of\ Sunny\ Days = 100 \times 4.9 \times 300 = 147000\ kWh\ per\ year$$

$$Monthly\ Output = \frac{Annual\ Output}{12} = \frac{147000}{12} = 12250\ kWh\ per\ month$$

Considering every household uses the PV solar energy. So, when this energy distributed equally each household can receive only about 0.15 kWh per month. The cost of solar energy in Nepal is based on the Levelized cost of Energy(LCOE) which typically ranges from NRs. 7 to 9 per kWh. Taking NRs. 8 kWh for this case study. These calculations are based on standard assumptions, and actual figures may vary depending on system performance, maintenance, and local conditions.

The Karnali region energy sources is fully based on the local fuel like firewood. The MoFE says that, the firewood costs between NRs. 25 to NRs. 50 per kilogram. The firewood consumptions are based on the regional geographical conditions, family size but for Karnali region it has reported that average household consumption ranging from 8.4 kg per day to 12.1 kg per day. For monthly, it ranges from 252-363 kg. Considering an average consumption of 300kg per month per households with average rate of NRs. 50 per kg. Using energy conversion factor, 100kg equals to 4GJ and 1GJ equals to 277.778 kWh.

$$1kg\ of\ firewood = \frac{4}{100} = 0.04\ GJ$$

$$300\ kg\ of\ firewood = 300 \times 0.04 = 12\ GJ\ per\ month$$

$$kWh\ per\ month\ per\ household\ from\ firewood = 12 \times 277.778 = 3333.336\ kWh$$

$$Cost\ per\ kWh = \frac{Cost\ of\ 1\ kg\ Firewood}{Energy\ from\ 1\ kg\ Firewood} = \frac{50}{12.9} = NRs. 3.87$$

Considering various laws, we estimate that each household can use up to 4 kg of firewood per month, priced at NRs. 50 per kg. The energy generated by 4 kg of firewood is approximately 44.44 kWh using the same relation as used above. This means the cost per kWh of energy from firewood is NRs. 3.87.

### 2.1 Data Limitations

This study is fully based on the secondary data from government agencies such as AEPC, NEA, CBS, NOC. These sources are generally reliable with certain limitations. Such as, the firewood consumption may be underreported due to unregistered household level use in remove areas. The assumptions such as constant monthly energy demand that may not completely capture the seasonal variations, which are acknowledged and mentioned into the model assumption section above in 1.2.

### 2.2 Tool Justification

The tool Microsoft excel solver was chosen for its wider accessibility and transparency. This is wider used by local policymaker and planners in the world who may have lack of access to the tools like Python, Julia or LEAP. This tool remains a practical and replicable tool for the municipal level energy planning and prototyping.

### 2.3 Linear Programming Optimization Model

Linear programming (LP) in Excel Solver involves optimizing a linear objective function, subject to a set of linear constraints. Using Solver, we can define decision variables, set an objective to maximize or minimize, and input constraints (e.g., resource limitations) in the form of linear equations or inequalities.

**Decision Variables:**

$X_1$=*Electricity consumption from Grid (kWh)*

$X_2$=*Solar Energy Consumption (kWh)*

$X_3$=*LPG Consumption (kWh)*

$X_4$=*Firewood Energy Consumption (kWh)*

**Objective Function:**

Minimize total Cost $(Z)=C_1 X_1+C_2 X_2+C_3 X_3+C_4 X_4$..............................(1)

Where;

$C_1$=*Cost per kWh electricity from grid=NRs.9*

$C_2$=*Cost per kWh energy from solar=NRs.7*

$C_3$=*Cost per kWh energy from LPG=NRs.9.84*

$C_4$=*Cost per kWh energy from fuel wood=NRs.3.87*

**Constraints (1st Case Scenario):**

1. $X_1+X_2+X_3+X_4=100$*kWh per month (Demand)*
2. $C_1 X_1+C_2 X_2+C_3 X_3+C_4 X_4 \leq$ *NRs.2000 per month (Budget)*
3. $X_1 \leq 211$*kWh per month (Electricity Supply)*

4. $X\_2 \leq 0.15kWh$ *per month (Solar Supply)*
5. $X\_3 \leq 219.82kWh$ *per month (LPG Supply)*
6. $X\_4 \leq 3333.33kWh$ *per month (Fire wood Supply)*

**Constraints (2nd Case Scenario):**

1. $X\_1+X\_2+X\_3+X\_4=100kWh$ *per month (Demand)*
2. $C\_1\ X\_1+C\_2\ X\_2+C\_3\ X\_3+C\_4\ X\_4 \leq NRs.2000$ *per month (Budget)*
3. $X\_1 \leq 211kWh$ *per month (Electricity Supply)*
4. $X\_2 \leq 0.15kWh$ *per month (Solar Supply)*
5. $X\_3 \leq 219.82kWh$ *per month (LPG Supply)*
6. $X\_4 \leq 44.44kWh$ *per month (Fire wood Supply)*

## 3. Result and Discussion

Using Microsoft excel solver for the both scenario i.e., with restricted firewood uses and without restricted firewood uses which are based on the current business overview for the Karnali region of Nepal. The linear programming equation given in the section 2.3 above were formulated in the excel as an optimization model, the following result are found and discussed below.

### 3.1 Scenario 1: Without restriction on firewood as energy source.

**Table 5:** Optimized table for firewood without restriction scenario

| | Sources of Energy (kWH) Per Households | | | | | |
|---|---|---|---|---|---|---|
| Parameter | Electricity consumption from Grid | Solar Energy Consumption | LPG Consumption | Firewood Energy Consumption | Utilized | Available |
| Optimized (kWh) | 0 | 0 | 0 | 100.00073 | 100.0007 | 100 |
| Cost (NRs per kWh) | 9 | 7 | 9.84 | 3.87 | | 2000 |
| Available Per month (kWh) | 211 | 0.15 | 219.82 | 3333.33 | | |
| Minimize (Objective Function) | 387.0028251 | | | | | |

Based on the Excel solver results, each household in Surkhet spends NRs. 387 per month to consume 100 kWh of energy from various sources. With 97,822 households in the district, the total monthly energy consumption is **9,782,200 kWh**, with a total expenditure of **NRs. 37,857,116.8**. However, the optimization suggests that firewood is the most cost-effective energy source, which is not a viable solution due to environmental regulations such as forest conservation laws and concerns about deforestation.

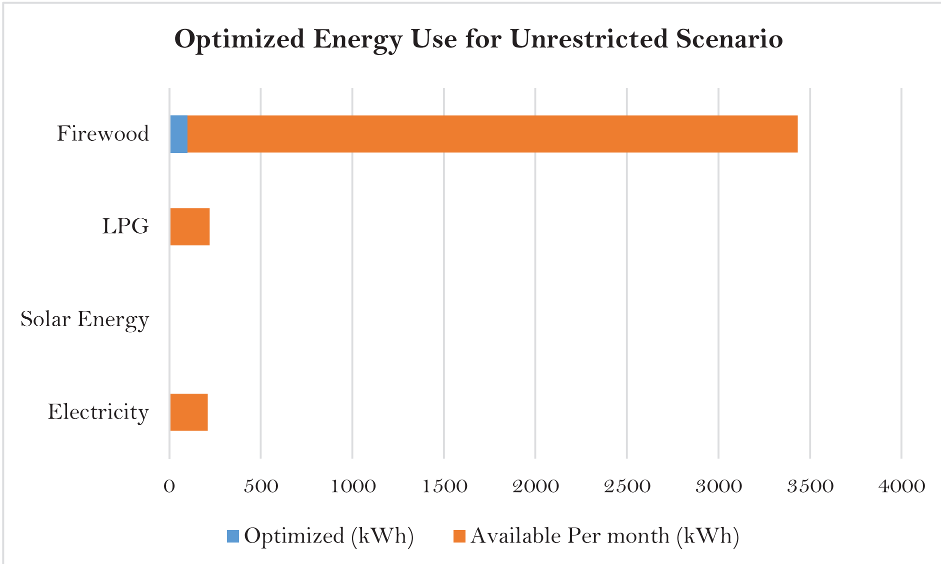


**Figure 2:** Stacked bar diagram for optimized energy use for unrestricted scenario

### 3.2 Scenario 2: With restriction on firewood as energy source.

**Table 6:** Optimized table for firewood with restriction case scenario

| | Sources of Energy (kWH) Per Households | | | | | |
|---|---|---|---|---|---|---|
| Parameter | Electricity consumption from Grid | Solar Energy Consumption | LPG Consumption | Firewood Energy Consumption | Utilized | Available |
| Optimized (kWh) | 55.41 | 0.15 | 0 | 44.44 | 100 | 100 |
| Cost (NRs per kWh) | 9 | 7 | 9.84 | 3.87 | | 2000 |
| Available Per month (kWh) | 211 | 0.15 | 219.82 | 44.44 | | |
| Minimize (Objective Function) | 671.7228 | | | | | |

Based on the Excel solver results, each household in Surkhet spends NRs. 671.72 per month to consume 100 kWh of energy from various sources. With 97,822 households in the district, the total monthly energy consumption is **9,782,200 kWh**, with a total expenditure of **NRs. 65,709,267.70.** The optimization suggests that alternative energy sources should be fully utilized, excluding the use of LPG.

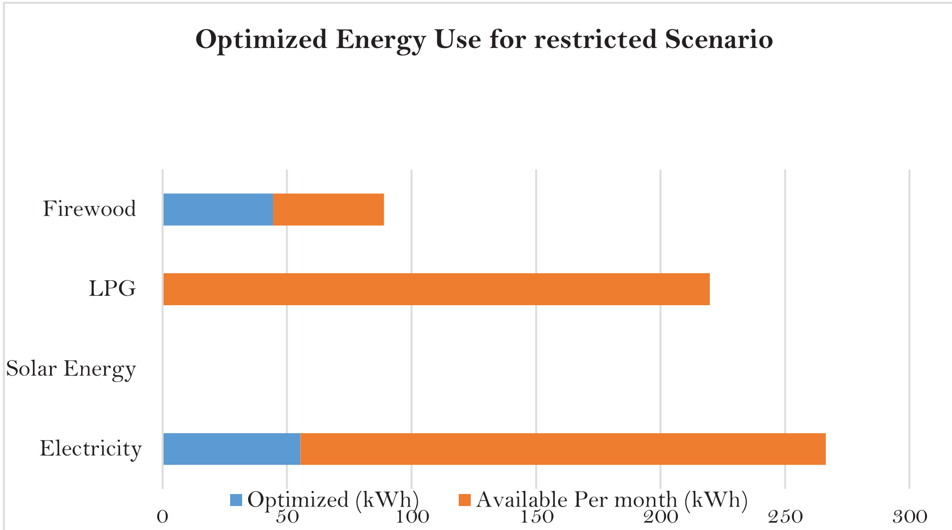


**Figure 3:** Stacked bar diagram for optimized energy use for restricted scenario

## 3.3 Comparison between Scenario 1 and Scenario 2

In rural region like Karnali Province of Nepal, households primary source of energy is firewood due to the limited grid access and energy affordability. This heavy dependence on a firewood contributes to deforestation and indoor pollution that links to over 13000 deaths annually in Nepal by WHO. This scenario analysis compares two energy strategies such as unrestricted versus restricted firewood use to demonstrate how the constraints can influence cleaner and more balanced household's energy mixes.

**Table 7:** Comparison of Optimized result between Scenario 1 and Scenario 2

| Energy Source | Scenario 1: Unrestricted Firewood (kWh) | Scenario 2: Restricted Firewood (kWh) |
|---|---|---|
| Electricity | 0 | 55.41 |
| Solar | 0 | 0.15 |
| LPG | 0 | 0 |
| Firewood | 100 | 44.44 |
| **Total** | **100** | **100** |

According to the data from table 7, for scenario 1we can see that the firewood dominates the required energy demand of 100kWh. This also shows that if the government allows the use of firewood as much as the household wants, the other sources like grid electricity, Solar and LPG are not required to meet the demand. This data came from the optimization LP model that accounts only the firewood as this is cheapest source of energy. For scenario 2, Electricity uses is mow became dominating energy source with 55.41 kWh, firewood uses are limited to 44.44 kWh. The solar as energy source contributes the minor amount to meet the demand around 0.15 kWh that aligns with local generation limits of PV Solar power plant which suggest government and responsible agency to promote the infrastructure development and feasibility study program for PV Solar power plant. The second scenario shifts to a more diversified and cleaner energy mix under the affordability.

The below stacked bar chart strongly supports the policy argument restricting firewood use to encourages clean energy adoption taking the costs of energy as feasible as before.

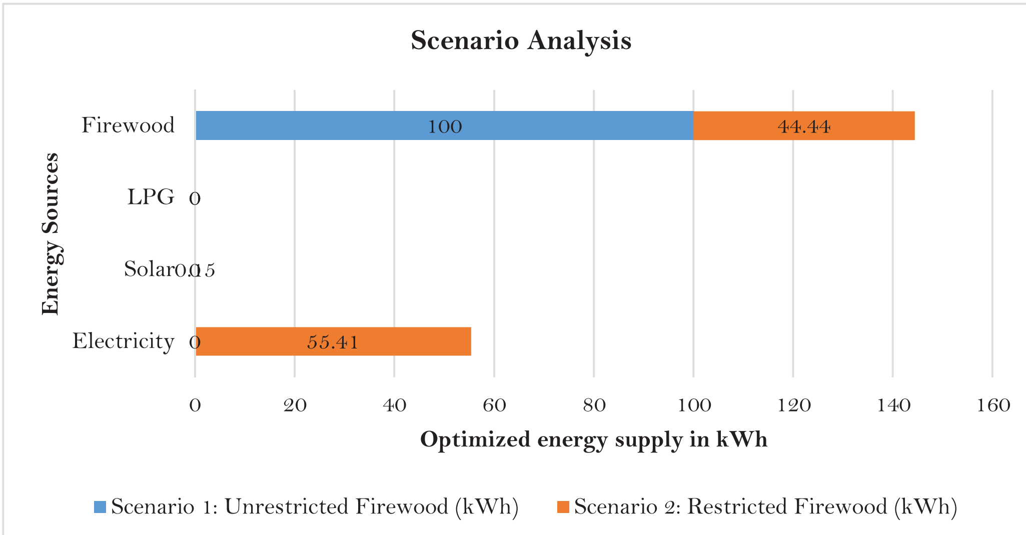


**Figure 4:** Stacked bar diagram of comparison between scenario 1 and scenario 2 for optimized energy supply from sources

## 4. Conclusion and Recommendation

This study shows that Linear Programming modeling in Excel can effectively guide energy planning. This LP framework can be scaled and adapted for broader energy optimization in rural Nepal. The second case optimal solution involves using all available resources efficiently, ensuring cost-effectiveness, and environmental sustainability. By comparing the two scenarios, the study confirms that significant reductions in $CO_2$ emission are achievable while staying within household energy budgets. Specifically, it is seen that firewood consumption is dropped by 98.7% with electricity and solar as an alternatives source. Households can reduce the use of LPG by following electric and solar cooking. Government and Policymakers should promote subsidies for solar and electric cooking while regulating firewood use. The results suggest that cleaner energy transitions are not only technically feasible but also financially accessible with proper policy support.

The LP model developed in this study is scalable to other rural regions of Nepal including the Himalayan and terai belts. The energy demand profile for terai region and the Himalayan region are different due to the climate, terrain and economic capacity of household. For Himalayan region, adaptations can include the seasonal heating demand and low solar intensity where as in Terai region, the greater LPG access or biogas use could be integrated into the model. So, the model structure remains adaptable with region specific constraints like solar irradiance, grid availability.

Maintenance and logistics challenges in remote areas are the major problem in case of solar energy mostly in Himalayan region to replace the traditional source. Inconsistent electricity supply from the grid could discourage people to shift from the firewood as energy source especially in off-grid zones. In some rural region the cultural preferences of the native people can slow down the shift of energy sources from biomass to electric or solar energy source for cooking. To account this, government and responsible agency should promote the awareness program targeted to this region.

We can develop the dynamic LP model that account for the seasonal energy demand and price volatility in future with the primary data which are collected from the on field survey. We suggest that hybrid optimization methods also can be used through which we can analysis the more complex constraints.

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