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Design of decentralized energy systems for rural electrification in developing countries considering regional disparity

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A B S T R A C T

Decentralized electrification using local resources can reduce regional disparity in rural and remote areas in terms of supply reliability and cost, as well as promote income generation. In this research an optimization energy model is introduced for designing decentralized energy systems using biomass for rural electrification in developing countries. Regional disparity is incorporated disaggregating electricity demand into urban, rural and remote areas. The model has been applied for designing a decentralized system using agricultural waste and forest biomass in a region in Colombia, South America. The resulting design includes biomass technologies in remote areas, reducing supply cost by 30% in this region. Using agricultural waste for electricity generation increases unit costs by 25% and reduces 15% of CO_2 emissions compared to the current energy system. Using all biomass to meet current demand lowers the efficiency of the system, resulting in high system costs and emissions reduction. Reduction of disparity in electricity access among regions using local biomass needs to balance the increase in energy system costs and CO_2 emissions reduction. For instance, using 30% of available biomass reduces 22% of system CO_2 emissions, and provides 121 USD/house/yr and 99 USD/house/yr of additional income in rural and remote areas, respectively. Design of the energy system considering regional disparity shows that fuel transportation costs and efficiencies of biomass conversion technologies have significant impact on system configuration and performance.

1. Introduction

Better access to modern energy sources such as LPG and electricity is a necessary condition for improving living conditions and reducing poverty in rural areas of developing countries. Currently over 1.3 billion people living in rural areas have no access to electricity. They represent 80% of the world population without the service [1]. In countries with a large share of urban population and a small participation of the agricultural sector in the national economy electrification needs focus on the reduction of disparity between rural and urban areas. Access and quality of energy supply, as well as the consumption patterns of households present considerable differences between these regions. A graphic representation of regional disparity in energy supply in developing countries is showed in Fig. 1. In urbanized countries rates of electrification in urban areas are close to 100%, different to countries where access to electricity is small in both urban and rural areas. On the other hand, electrification rates in rural areas are disproportionately low. Even when electricity supply is available, the service is unreliable and expensive. For example, electricity supply is limited to a few hours a day, with high losses in transmission and distribution, frequent blackouts and power fluctuations. Moreover, electrification of remote areas is largely unachieved in these countries due to the deficient transportation infrastructure [2,3].

An alternative for electrification of rural and remote areas is the introduction of decentralized conversion technologies using resources locally available. Decentralized electrification can provide a more reliable supply and generate income derived from the use of local resources [3,4]. For example, the use of agricultural and forest wastes, as well as other biomass resources in combustion technologies for electricity generation decreases the dependence on foreign fuels and can provide income to local communities derived from biomass collection and transportation.

In addition to increasing access to electricity, the design of decentralized energy systems for rural electrification in developing countries must consider regional disparity. The large differences between urban, rural and remote areas can be interpreted beyond the geographical location including income disparity. Disaggregating the demand side of the energy system into different regions helps to describe the income opportunities according to the availability of biomass energy resources. Incorporating income differences allows the characterization of the energy system's performance based on the impact of electricity costs on energy expenditure in households with different incomes. Several energy

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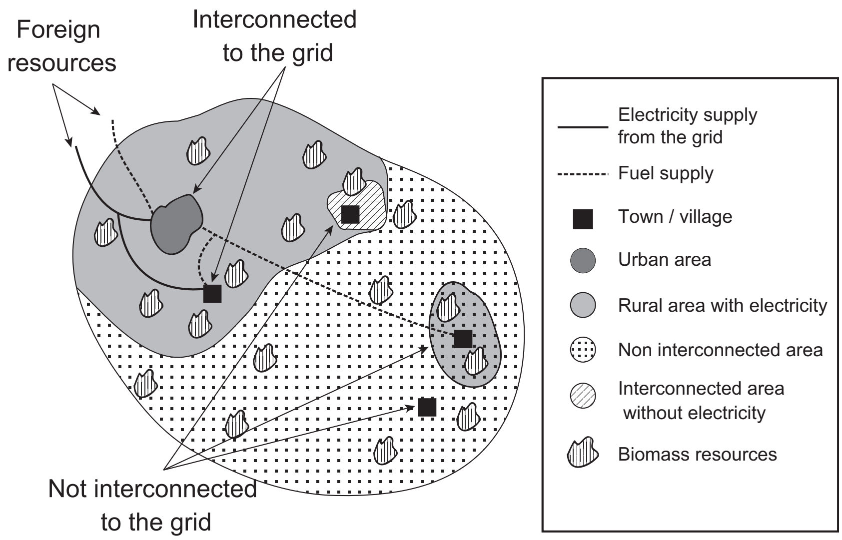

Fig. 1. Regional differences in energy supply for electrification in developing countries.

models analyze the use of biomass in rural areas of developing countries applying optimization methodologies [5,6]. However, few applications consider regional differences and the income generated by using biomass energy resources.

In this research a linear programming (LP) model has been developed in order to design decentralized energy systems for rural electrification using local biomass resources, considering disparity in energy consumption between urban and rural areas. A third region, referred to as remote areas, and which describes areas located outside the service area of the electricity grid, has been introduced. The performance of the system is evaluated based on the financial viability from the perspective of electricity producers, the local income and energy expenditures in households, and the mitigation of CO_2 emissions. The energy system analyzed considers the use of agricultural wastes and forest wastes for electricity generation by means of several energy conversion technologies using biomass (direct combustion of biomass in boilers and gas turbines coupled with gasification unit). The target area is a region in Colombia, South America, characterized by abundant biomass resources in the form of agricultural wastes, with partial coverage of the electricity grid, where over 15% of population has no access to electricity. Currently, electricity from the grid covers the interconnected area, and diesel generators using diesel fuel supply the non-interconnected area.

2. Design of rural energy systems for rural development

2.1. Promotion of rural development with biomass based electrification

Access to electricity is an important component of rural development. Better access to electricity has been correlated to the improvement of living conditions in several aspects, such as education and income generation [7]. Electrification in rural areas of developing countries, and in particular in the case of remote areas, is difficult due to low population densities, highly dispersed location of populated centers, low energy consumption levels per capita and poor road infrastructure which constrains transportation [2,3]. This makes conventional rural electrification programs based on extension of the electricity grid and decentralized schemes with foreign fuels expensive or even economically not feasible. Rural electrification programs often require direct governmental support in the form of subsidies. In rural areas where energy resources are widely available in the form of agricultural wastes and forest biomass, decentralized electrification using local resources is more suitable as an alternative for electrification [4]. This scheme avoids the necessity of extending transmission lines to dispersed populated centers, reduces the dependence on foreign fuels within these areas, and promotes local development through the introduction of the production chain of biomass energy. As illustrated in Fig. 2, biomass resources collected in rural and remote areas can be sold to companies generating electricity from these resources. Thus, households involved in the biomass supply chain would get an income surplus equivalent to the total cost of biomass resources paid by electricity suppliers. The actual worth of the local income benefit can be weighted against the electricity bills paid by households. Moreover, biomass for electricity generation, in contrast to diesel generation and other fossil fuel based electricity supply methods, does not contribute directly to climate change since it is considered a neutral source of carbon emissions. Although electrification based on biomass energy has lower conversion efficiencies and higher investment costs compared to conventional electricity generation schemes, it has more significant impact on rural development due to the generation of new income opportunities from the use of local resources. Thus, the introduction of these systems can help reduce the gap in development that exists between rural and urban areas. There are several examples of biomass applications for decentralized electrification in developing countries, especially in Asia and some Latin American countries. Small scale applications for rural electrification using biomass gasification processes exist in Thailand, India, China and Brazil, among other countries [8–10].

2.2. Application of energy models for the design of rural energy systems

The design of decentralized energy systems for rural electrification using biomass resources in developing countries have to consider certain characteristics of energy systems in these countries. Many of these features, presented in Table 1, have been commonly overlooked in the literature dealing with energy planning supported by mathematical models [11]. It is worth noting that among these factors off-grid renewable energy, rural energy programs and energy issues related to poverty aspects are rare among applications [12].

Most models applied for designing decentralized energy systems describe the optimal mix of energy resources and

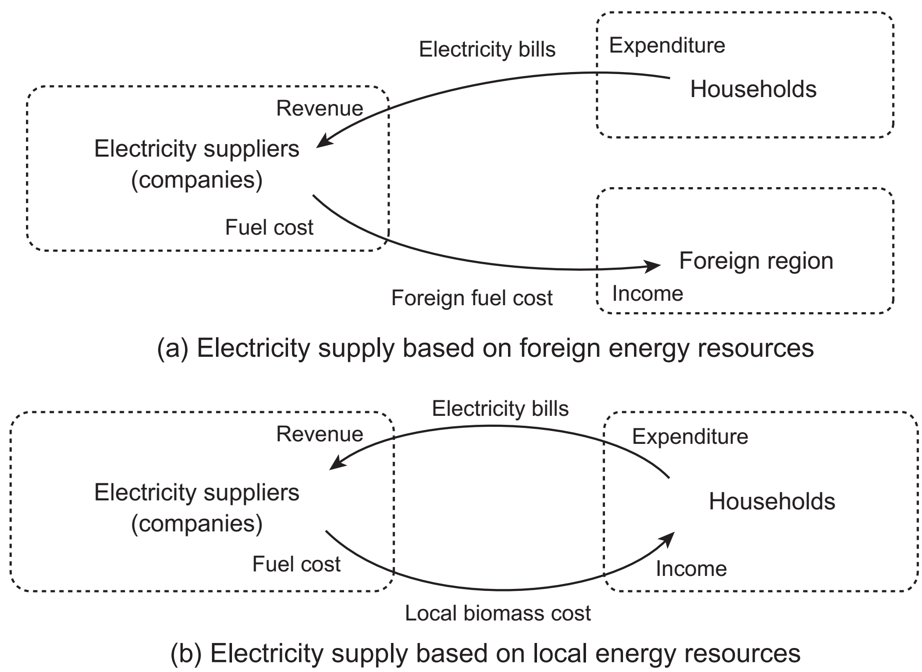

Fig. 2. Cash flow associated to electricity supply and consumption.

Table 1
Features of energy systems in developing countries.

Feature	Examples
Performance of power sector	Sub-optimal system configuration due to plant breakdown, outages and voltage fluctuations
Supply shortages	Poor condition of equipment, inadequate operational and maintenance performance, organizational and technical problems
Electrification	Lack of electricity access in many areas
Traditional bio-fuels	Traditional biomass (firewood, dung, agricultural wastes) are predominant fuels
Urban–rural divide/ urbanization	Drastic differences in rural and urban areas (services and infrastructure)
Informal economy	Non-monetary transactions, illegal activities, tax evasion
Structural economic change	Rapid shift from agricultural to services economy
Investment decisions	Inadequate planning techniques
Subsidies	Abuse or inadequate use of subsidies

Adapted from [11].

technologies under a certain objective function and set of constraints. For example, minimum system costs and minimum level of emissions stemming from system operation are common objective functions. The analytical approach generally used in these models is single-period optimization [13–15]. In addition to optimization, there are studies deploying simulation and geographic information systems (GIS) methodologies that give more emphasis to supply stability and optimal allocation of resources [16–18]. Decentralized energy systems have also been designed by means of multi-criteria and multi-objective methodologies [5,19–25].

Large availability of biomass resources in rural areas makes the efficient allocation of energy resources an important aspect of energy modeling in developing countries. The scope of the analytical procedure may vary from taking into account only the efficient distribution of energy resources to cover specific energy needs, to including land-use patterns, consumption rates of local agricultural and livestock-derived resources among others [26–31]. A more comprehensive review of model applications for designing rural energy systems is provided by Nakata et al. [32].

This paper describes an attempt to incorporate regional disparity into an optimization model describing a developing country's energy system.

3. Methodology

3.1. Decentralized energy system for rural electrification

In this study, an optimization model has been developed and applied for designing energy systems for decentralized electricity supply considering conversion technologies using biomass. The model incorporates regional disparity disaggregating the target area into urban, rural and remote areas. Urban areas correspond to large cities. Rural and remote areas are differentiated according to their location within or outside the areas where interconnection to the electricity grid is available. Both regions include small towns and dispersed population living in farms outside towns. A general representation of the energy system is illustrated in Fig. 3.

The performance of the energy system is evaluated according to three parameters: the net costs of the system, the net income generated in the target area, and CO_2 emissions. These parameters serve as approximate indicators for the effect that introducing the energy system may have on the electricity supply companies, the local community, and the environment, respectively.

The design of the energy system provides the most suitable combination of energy resources and conversion technologies to meet a certain quantity of electricity demand under a set of goals and constraints. Energy resources are divided into two groups: foreign resources, which comprehend electricity from the grid and fossil fuels such as diesel fuel; and local resources, which include agricultural wastes and wood biomass from forests. Energy conversion technologies included in the system are diesel generation with diesel fuel, and biomass conversion technologies based on direct combustion, and gasification. The demand-side of the energy system only considers the total amount of electricity demanded in the residential, industrial, and commercial sectors. In addition, the potential electricity demand in rural and remote areas without access to electricity is estimated.

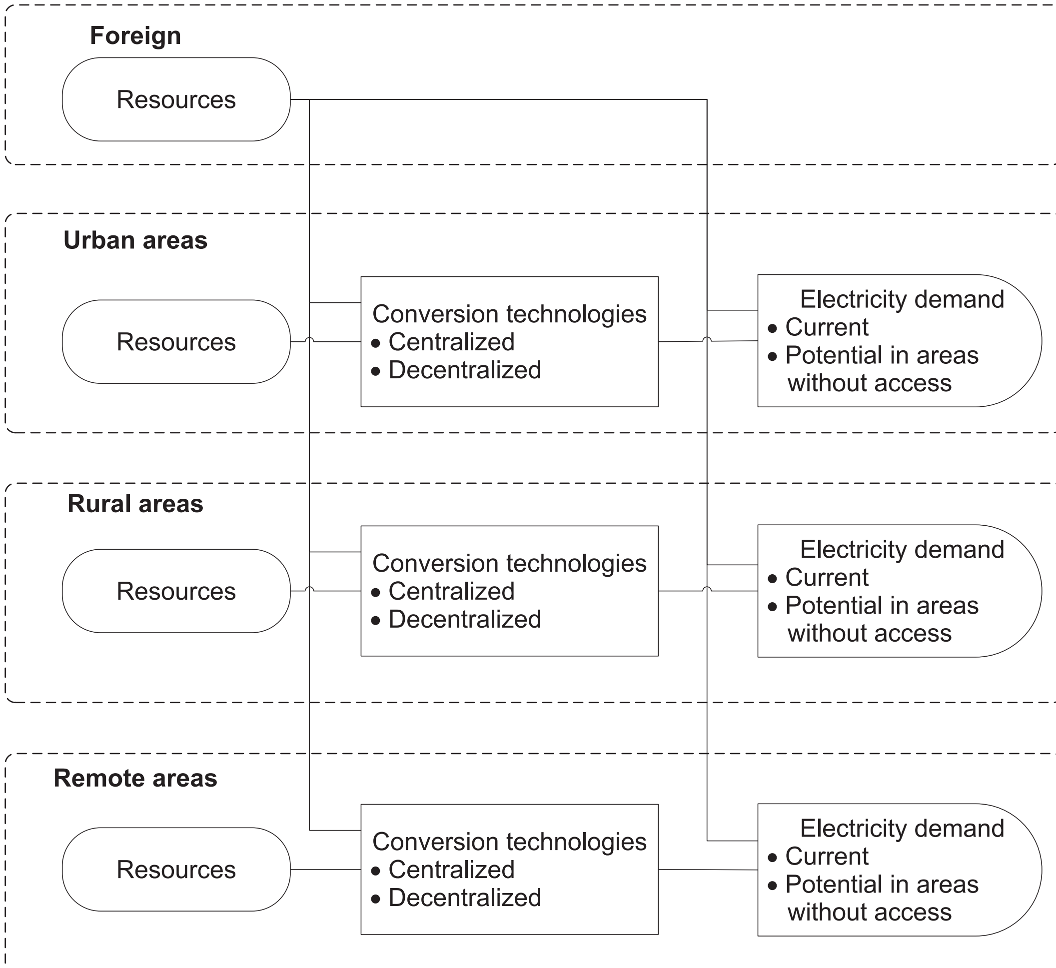

Fig. 3. Energy system for decentralized electrification considering regional disparity.

3.2. Formulation of the optimization model

An optimization model based on linear programming technique has been developed to design decentralized energy systems. It emphasizes the utilization of local biomass resources to promote rural development, and the reduction of disparity in energy access conditions between remote, rural and urban areas. The linear programming formulation, illustrated in Fig. 4, is explained below.

3.2.1. Objective function and constraints

Rural electrification programs in developing countries are likely to incur in total costs larger than the revenues collected from the consumption bills. Rural households have low levels of income and electricity consumption per capita, thus, electricity supply involve overrun costs. The local or central government in the form of subsidies generally compensates these costs. The energy system is designed looking forward the minimization of the resulting net costs, in order to provide electricity equitably to users in both the interconnected (urban and rural) and the non-interconnected (remote) areas. The following equations explain the objective function and the constraints of the linear programming formulation.

(a) Objective function – minimize total net costs.

$$Min\sum_k b_k = Min\sum_k\left(\sum_j\sum_i c_j\eta_j q_{ijk} - p_k d_k\right) \qquad (1)$$

(b) Meet total electricity demand.

$$\sum_j\sum_i \eta_j q_{ijk} = d_k \qquad (2)$$

(c) Maximum availability of resources.

$$\sum_k\sum_j\sum_i q_{ijk} \leqslant r_i \qquad (3)$$

(d) Utilization of agricultural waste for electricity generation.

$$\sum_k\sum_j q_{ijk} = \alpha_{Use,i} r_i \quad \text{for } i = \text{agricultural waste} \qquad (4)$$

b is the net costs (USD/yr), c the unit electricity generation cost (USD/MJ), d the electricity demand in each region (MJ/yr), p the unit price of electricity in each region (USD/MJ), q the resource allocated to conversion plant (MJ/yr), r the stock of energy resource (MJ/yr), η the electricity conversion efficiency, α_{Use} the resource use rate, i the energy resource, j the energy conversion technology, an k is the region (urban, rural, remote).

3.2.2. Aspects of system evaluation

(a) Net cost: equivalent to the difference between total costs and revenues from electricity bills.

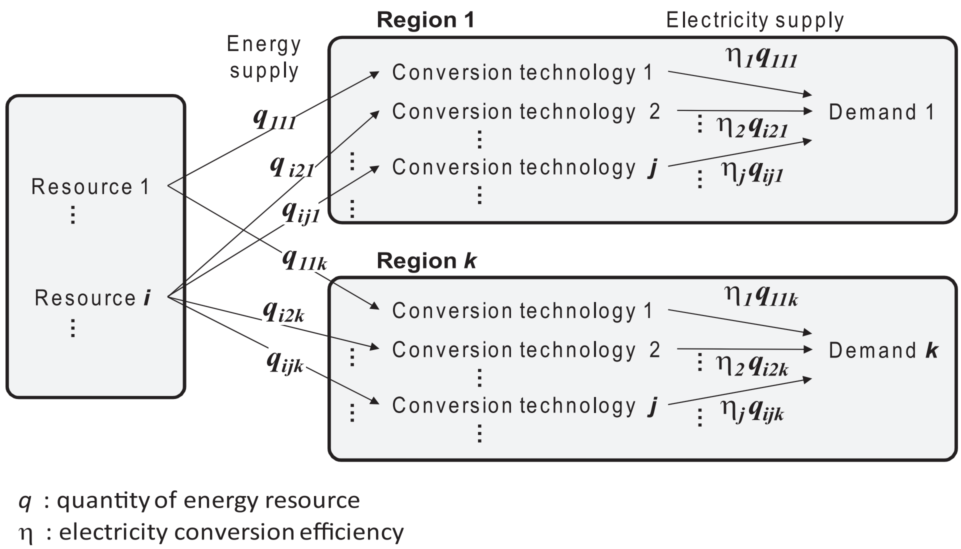

Fig. 4. Schematic representation of the optimization model for energy system design.

$$b_k = \sum_j \sum_i c_j \eta_j q_{ijk} - p_k d_k \quad (5)$$

(b) Net local income: equal to the difference between the income resulting from selling local biomass resources and the electricity bills paid by users in the region.

$$\sum_j \sum_i (c_{Fuel-Local} \eta_j q_{ijk} - p_k d_k) \quad \text{for } i = \text{local resource} \quad (6)$$

(c) CO_2 emissions: CO_2 emissions produced directly from electricity generation.

$$\sum_j \sum_i e_j \frac{q_{ijk}}{\eta_j} \quad (7)$$

$c_{Fuel-Local}$: unit cost of local resources (USD/MJ).
e: unit CO_2 emissions from electricity generation (kg-CO_2/MJ).

The model assumes that all agricultural waste is used for energy purposes as an alternative for waste disposal. This constraint is introduced to represent the environmental regulations proscribing the combustion of these materials in open fires.

3.3. Scenario setting

(a) Base scenario

This scenario represents the current structure of the energy system for electricity supply in the target area. Urban and rural areas within the interconnected area are served by the national electricity grid. Households in rural areas, which currently lack access to electricity, are served by decentralized diesel generators. Remote areas are served by decentralized diesel generators.

(b) Least-cost scenario

The energy system is designed in this scenario looking forward the minimization of net costs and considering the introduction of decentralized electrification with biomass; the constraint on promoting the use of agricultural waste for energy is not included in the formulation.

(c) Waste-use scenario

The system design in this scenario considers the promotion of agricultural waste for energy production; this scenario represents the introduction of environmental regulation regarding the prevention of waste disposal in open fires, a common practice in rural areas; the constraint on the use of agricultural waste for energy is included in the formulation.

(d) All-biomass scenario

In this scenario the design of the system considers the complete use of all biomass available in the target area in decentralized energy systems.

4. Case study for LP model application

4.1. Target area

The target area is a department in Colombia called Meta, corresponding to one of the 32 administrative divisions of the country. This region is a suitable case for analyzing the potential of decentralized electrification to narrow disparity between rural and urban areas in developing countries. Compared to other departments of Colombia, Meta has a considerable area outside the interconnected system in spite of its proximity to the capital city of the country, as showed in Fig. 5.

This region is partially served by the national electricity network, called national interconnected system (NIS). Over two thirds of the electricity supplied by the interconnected system is generated in large scale hydropower plants. The rest of the electricity is generated by coal and gas fired power plants [33]. Remote areas which are outside the interconnected area, referred to as non-interconnected zones (NIZ), depend on a low quality electricity service based on diesel generators using fossil fuels, with only eight hours of average daily operation. Dispersed distribution of population and poor road infrastructure limits the feasibility of electricity grid extension and the supply of fuels within remote areas. There are 170,577 people without access to electricity in the region [34]. Three regions are differentiated in the target area. Urban areas correspond to cities and large townships. Rural areas are medium size townships and farms within the area covered by

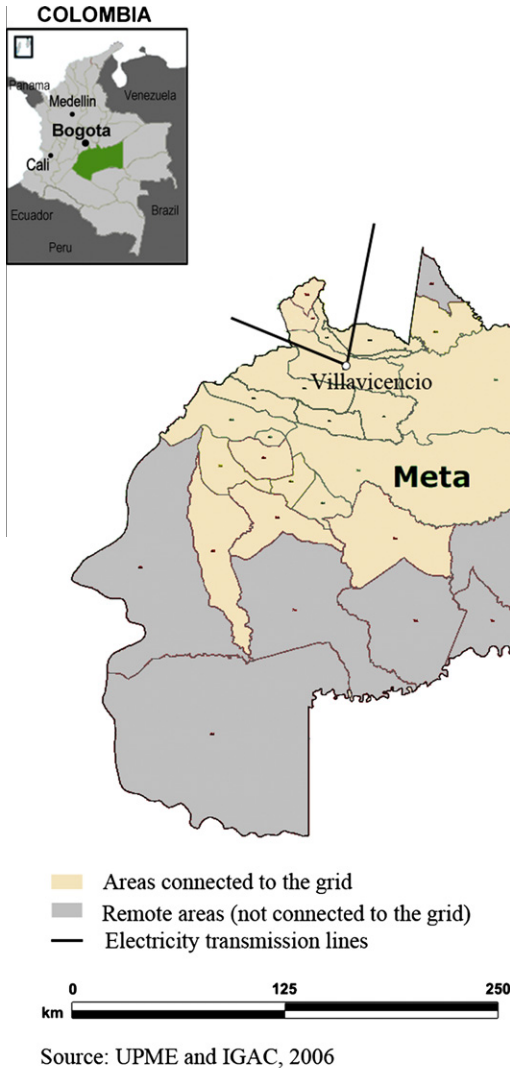

Fig. 5. Map of the target area (Meta Department, Colombia).

the electricity grid or NIS. Remote areas correspond to townships and farms outside area served by the grid. Agricultural activities in large plantations in the region generate considerable quantities of agricultural wastes, which offer an opportunity to produce electricity from local resources. The resources included in the model are rice husk, sugarcane plantations waste, bagasse, and forest wastes from planted and natural forests.[1] Although sugarcane agriculture and harvesting of forests occurs only at low scale in the region, soil and weather conditions offer good conditions for production. Technologies considered for decentralized electrification using biomass include boilers based on direct combustion of biomass in fixed bed furnaces (Boiler), and fixed-bed gasification units coupled with a gas engine (Gasification). Detailed diagram of the energy system considered for the application of the optimization model is presented in Fig. 6.

4.2. Data sources and assumptions

Electricity consumption and electricity prices for each location are listed in Table 2. Data on electricity demand and electrification rates for areas connected to the electricity grid has been collected from an online database from the supervising organ of the Ministry of Mining and Energy of Colombia (Superintendencia de Servicios Publicos). This database provides information on electricity demand for urban and rural areas of each municipality in Colombia. Data on electricity demand and electrification rates of areas not connected to the electricity grid (i.e. remote areas) has been collected from reports describing the energy situation in these areas in Colombia [34,41]. All data correspond to year 2003, which is the most recent information found for remote areas. It is assumed that households that currently lack electricity have a potential amount of electricity demand equivalent to the same levels of consumption than those observed in remote areas.

The data on availability and price of energy resources considered are presented in Table 3. Data of biomass energy resources has been collected from a report on the status and potential of agricultural waste and forest biomass as energy sources in different regions of Colombia [35]. Data on availability of biomass resources is not referenced with respect to their location other than the target area (Meta department). Thus, it has been assumed that 90% of the total amount available of each resource in the target area corresponds to rural areas, and that the other 10% is located in remote areas. The quantity of bagasse and wastes from sugarcane plantations correspond to 0.1% of the

[1] Rice husk is commonly used as fuel for drying or heating operations in agro-industrial activities, as structural material in construction and in beds for greenhouse grown plants, and as insulation material; sugarcane waste is mainly used as fodder for animals; bagasse principally serves as fuel for heating in sugar factories.

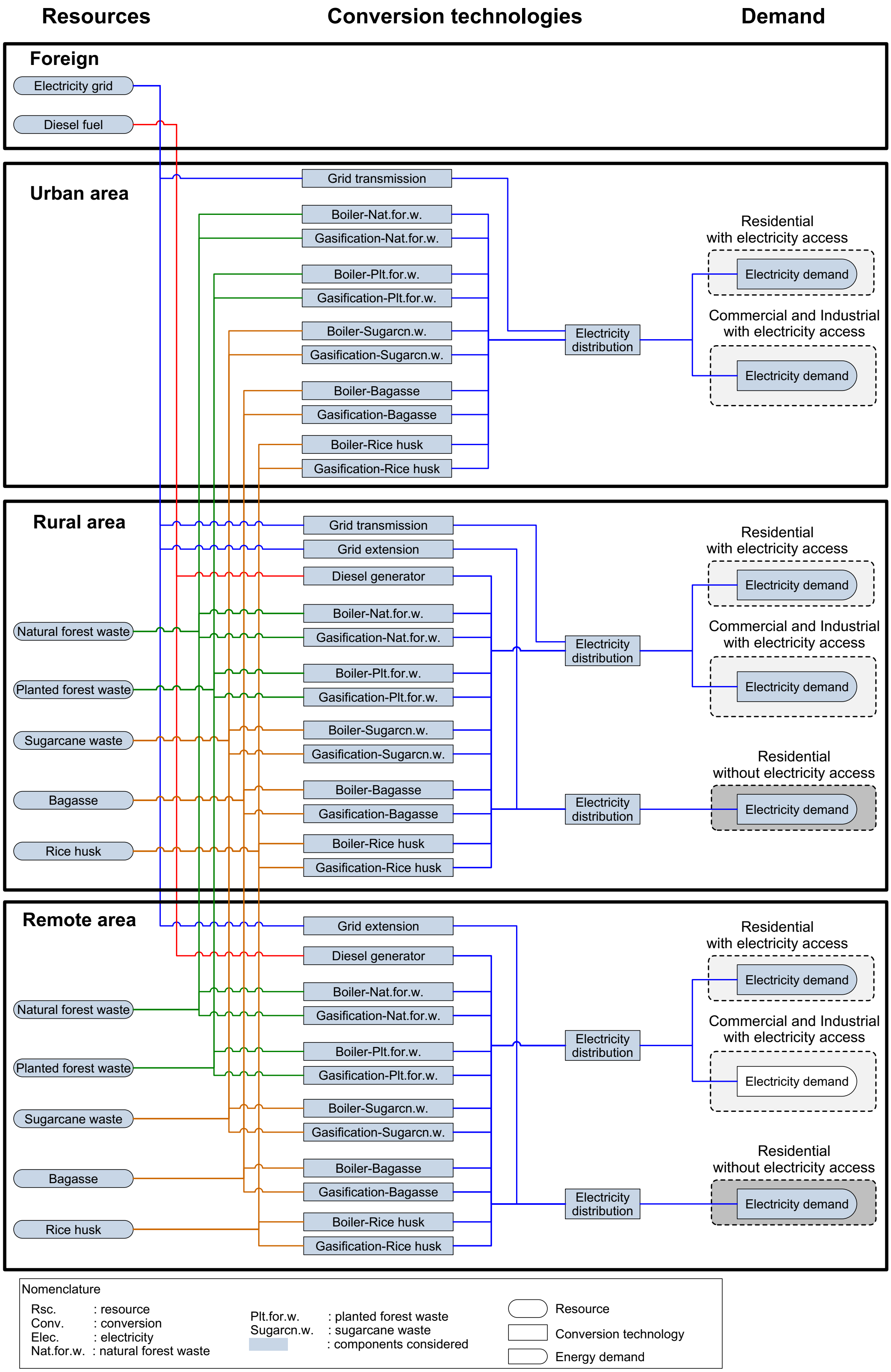

Fig. 6. Detailed energy system considered for decentralized electrification in the target area.

Table 2
Electricity demand and price in the target area.

Region	Users	Electricity demand	Electricity cost
		TJ/yr	USD/MJ
Urban			
Residential	106,870	709	0.019
Other sectors	3578	139	0.019
Rural with electricity access			
Residential	18,991	80	0.019
Other sectors	1035	27	0.019
Rural without electricity access	17,740	75	0.019
Remote with electricity access	3155	9	0.033
Remote without electricity access	3788	3	0.033
Total		1042	–

Calculated from data in [34] and SSP-SUI database.

Table 3
Input data of energy resources.

Resource	Energy content (MJ/kg)	Stock (mm kg/yr)	Fuel cost (USD/kg)	Transport cost[c] (USD/km/kg)
Electricity grid[a]	3.6	–	0.026	–
Diesel fuel[b]	38.5	–	0.246	0.0015[d]
Rice husk	13.9	43.84	0.079	0.0147
Bagasse	8.9	14.58	0.014	0.0074
Sugarcane waste	15.0	23.12	0.014	0.0049
Natural forest waste	16.8	198.16	0.026	0.0049
Planted forest waste	16.8	94.40[e]	0.032	0.0049

Based on data from [35] and [42].
[a] Values per kW h.
[b] Values in volumetric basis (per liter).
[c] Based on price difference for diesel in remote areas and bulk density for biomass resources.
[d] Assuming 100 km between foreign and remote areas.
[e] Does not include demand of firewood for cooking in traditional stoves.

potential amount produced assuming that all agricultural land in the target area is dedicated to sugarcane production.

Collection and storage of biomass resources are considered assuming two stages. In the first stage, biomass is collected directly from growing fields and forests, and stored in facilities owned by farmers. In the second stage, these resources are transported from farmer's storing facilities to electricity generation plants. Based on this, collection and storage costs of the first stage are assumed as part of the resource price. Collection and storage cost of the second stage are approximated to the transportation cost. These costs have been estimated based on the increase of diesel fuel cost commercialized in remote areas, the bulk density of the biomass resource and the distance between supply (farmers) centers and demand (conversion plants) centers.

Conversion technologies units are of 1 MW scale operating at 64% of the total capacity. For economic evaluation a discount rate of 10% and 20 years operating time have been assumed. Only CO_2 emissions embedded in electricity from the grid and from combustion of diesel fuel in diesel generators are considered.[2] CO_2 emissions factors of grid electricity and diesel generation are 0.439 kg/kW h and 0.882 kg/kW h respectively [36]. Capital and operation and maintenance costs of technologies, as well as distribution and transmission costs for electricity are included. Main features of technologies are presented in Table 4.

[2] Biomass is considered a carbon neutral source of emissions, therefore, CO_2 emissions from biomass combustion have been neglected.

Table 4
Input data of technologies.

Conversion technology	Efficiency (%)	Capital cost (USD/kW)	O&M costs (USD/kW h)
Grid transmission	80[a]	n.a.	0.017
Grid extension	80[a]	12,500[b]	0.017
Diesel generator	30	300	0.017
Boiler	14	4000	0.036
Gasification	17	2975	0.027

Data from [38] and [42].
[a] Equivalent to transmission and distribution losses.
[b] Cost in USD/km of transmission and distribution lines extended.

5. Outcomes of LP model application

5.1. Optimal energy system design

The application of the LP model provided the optimal design of the energy system for the scenarios considered. In the design for the Least-cost scenario, shown in Fig. 7, biomass is used only in remote areas, where conversion plants based on biomass gasification are used to supply electricity instead of diesel generators using diesel fuel. Sugarcane waste and planted forest waste contribute in this region to 40% and 60% of the resource supply, respectively. In rural areas that currently lack access to electricity diesel generators using diesel fuel are the most suitable alternative.

In the waste-use scenario the production of electricity as an alternative for the disposal of agricultural waste is introduced in the design of the system, presented in Fig. 8. Agricultural waste is allocated to remote and rural areas. Beside waste no other biomass resource is used for electricity supply. Different to the least-cost scenario, the conversion technology selected for remote areas shifts from gasification to direct combustion in boilers. This is due to the combined effect of a small electricity demand and the elevated cost of transporting agricultural waste from remote areas to other regions. The demand in remote areas is smaller than the minimum electricity output that can be generated using agricultural waste. Thus, a fraction of this resource, in this case sugarcane waste, has to be shipped to other regions in order to use it completely. Although electricity supplied by boilers using biomass is more expensive than gasification plants, the lower conversion efficiency of this technology results in a higher amount of waste used within the region, thus, reducing the need for resource transportation. In rural areas agricultural waste is used in gasification plants to cover all the demand in households that lacked access to electricity and to cover a portion of the demand in areas with access to the electricity grid. Biomass-based electricity supplies over 75% of total demand in this region.

The design of the energy system consuming all the biomass resources available in the target area for energy purposes is considered in the All-biomass scenario, shown in Fig. 9. The quantity of biomass is enough to cover nearly 70% of total electricity demand. The other 30% is supplied by electricity from the grid in urban areas. In remote areas electricity is generated in boilers using rice husk, bagasse and natural forest waste. Sugarcane waste produced in this region is used in rural areas. All electricity in rural areas is generated from biomass resources using boilers. Rice husk, bagasse and sugarcane waste contribute each to 34%, 7% and 21% of the resource supply in this region, respectively. The rest is supplied in equal proportions by natural and planted forest wastes. The importance of biomass transportation costs prevents the utilization of biomass resources in urban areas. Again, introducing boilers instead of gasification plants result in a lower system cost in the target area at the expense of a high cost within

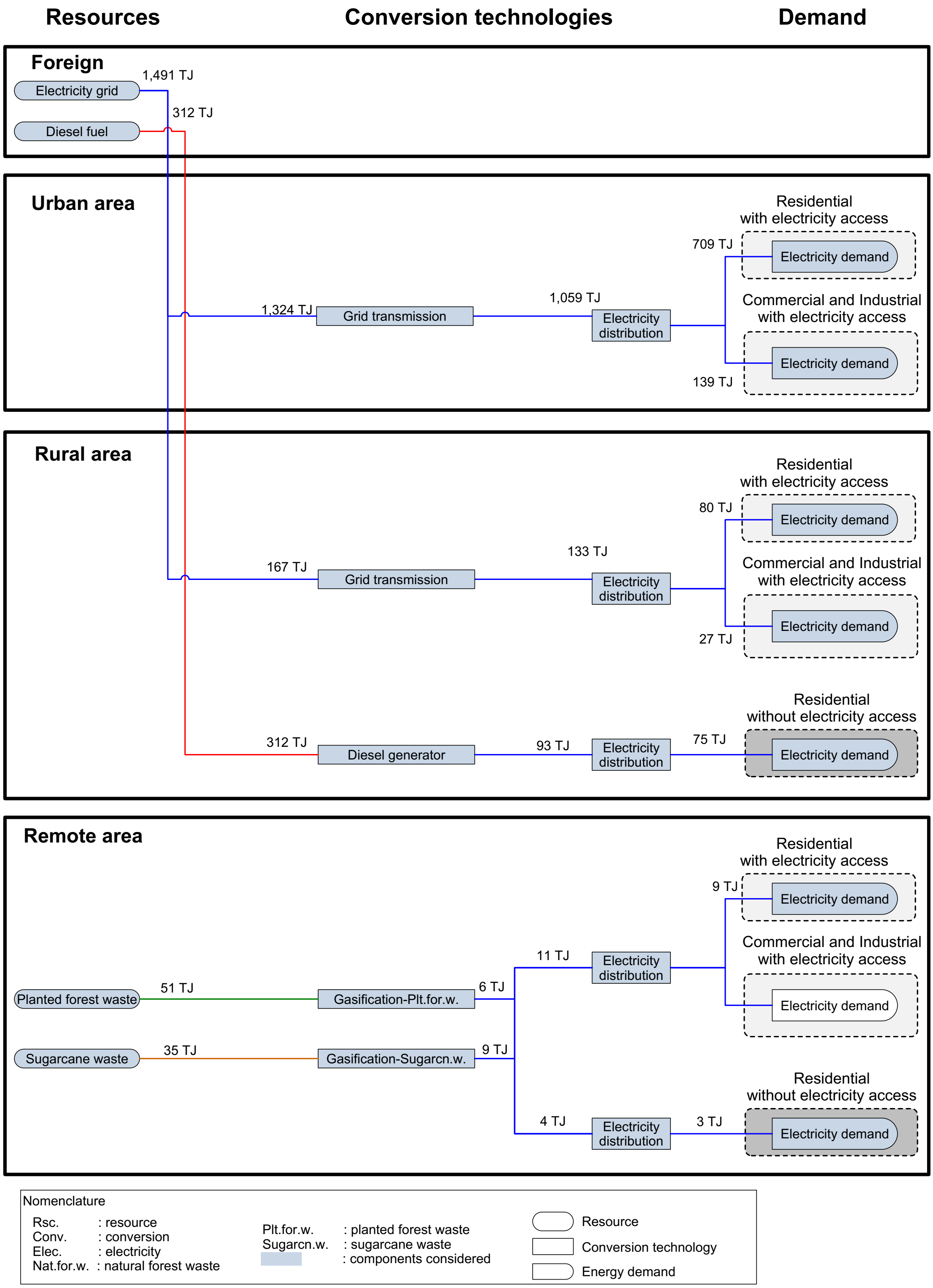

Fig. 7. Energy system design for Least-cost scenario.

one region. On the other hand, natural and planted forest wastes shipped to urban areas are used in gasification plants. The share of these resources in resource supply in urban areas is 62% and 25%, respectively.

Different to other scenarios, in the All-biomass scenario forest waste is introduced as part of the energy supply, mainly in rural and urban areas. These quantities are enough to displace conventional sources of electricity in rural areas, and most of them in urban areas (up to 70%). This result turns the reliability of the system highly dependent on stable supply of biomass resources. Thus, the biomass supply chain (harvesting, collection and storage on-site, collection to and storage in conversion plants) needs higher requirements in order to secure on-time deliveries and minimum average quality of biomass resources. Satisfying this feature in rural and remote areas may be a significant challenge.

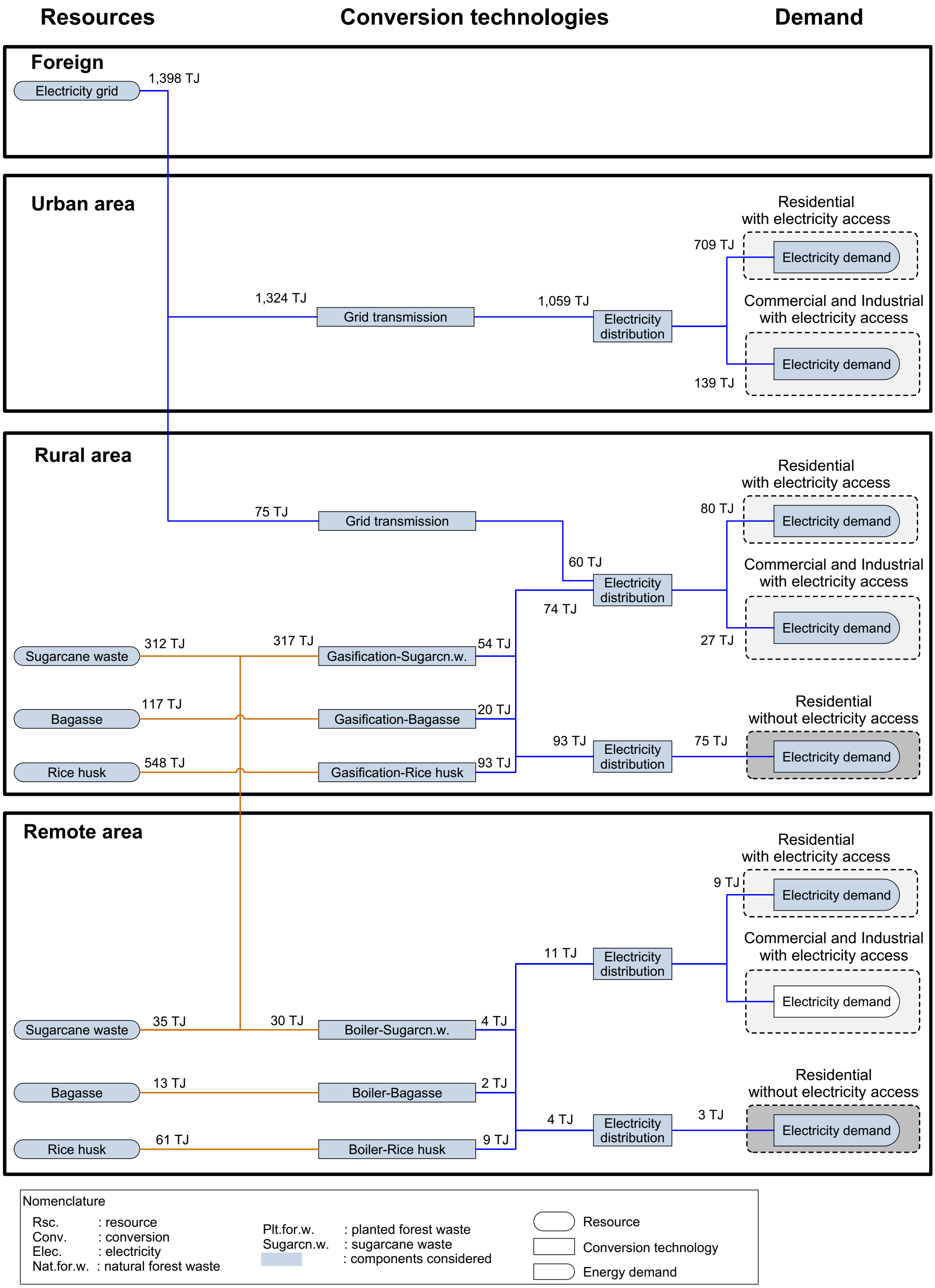

Fig. 8. Energy system design for Waste-use scenario.

5.2. Energy system performance

The performance of the energy system is evaluated in terms of the net cost, the net income generated from the use of local biomass for energy purposes, and the CO_2 emission from electricity generation. The outcomes on each of these aspects for the different scenarios and regions are presented in Figs. 10, 11, and 12. The performance of the entire energy system, aggregating urban, rural and remote areas is presented in Table 5.

The Base scenario is used as the reference for comparison. In this scenario electricity supply gives positive profits in urban areas, where unit net cost and unit total cost are −0.2 cents/MJ and 1.7 cents/MJ, respectively. On the other hand, nets costs in rural and remote areas are positive. In rural areas system net cost is

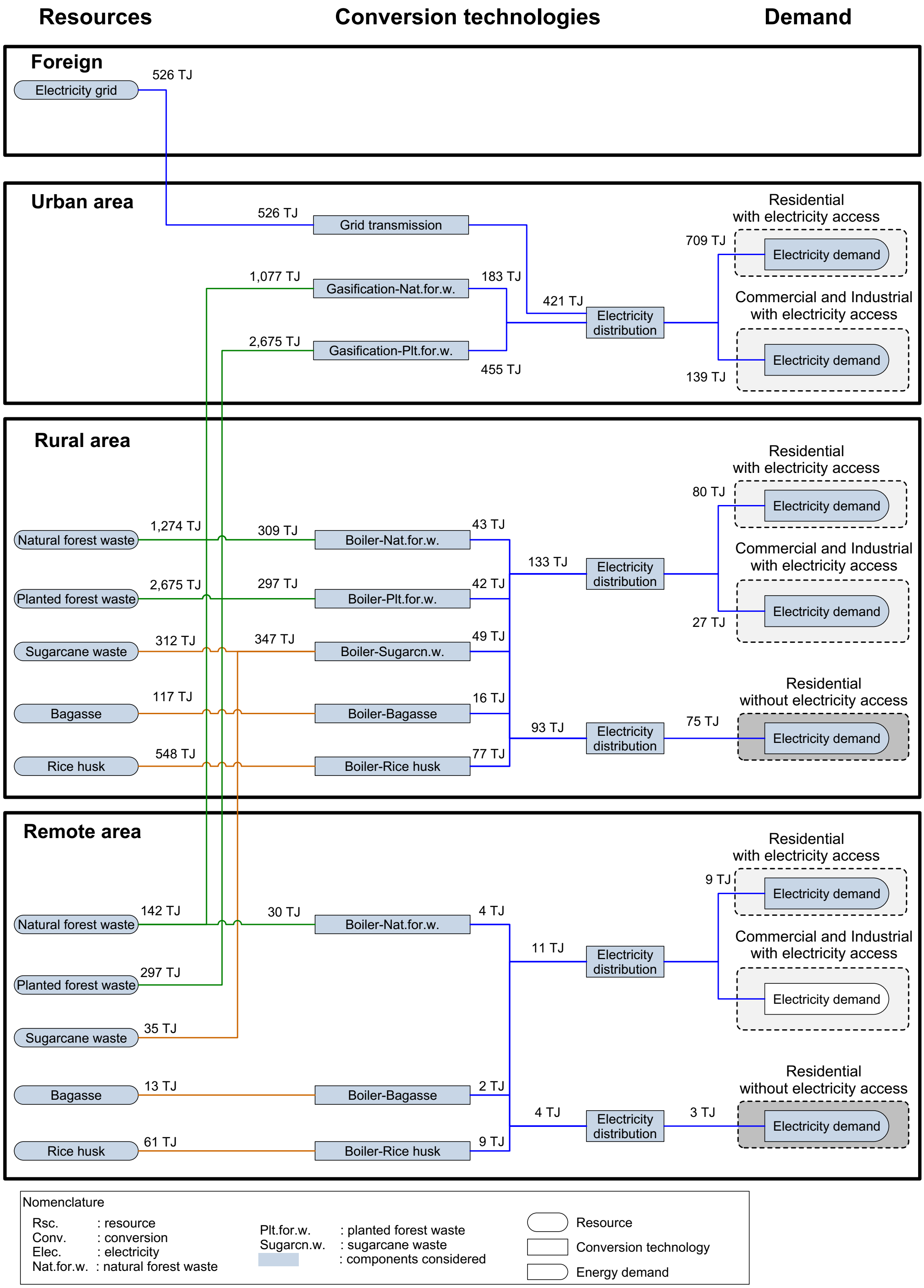

Fig. 9. Energy system design for All-biomass scenario.

0.9 cents/MJ, while system total cost is 2.8 cents/MJ. In remote areas system net cost is considerably higher, even when the electricity price charged to users is 70% higher than in other regions. Unit net cost and unit total cost is equal to 2.4 and 5.7 cents/MJ. Fuel cost contributes between 40% and 70% of total system costs. In remote areas, the transportation costs represent over 30% of total costs. There are also large differences among regions in terms of net local income. Higher electricity consumption and complete access to electricity in urban areas is linked to higher energy expenditures, equivalent to over 130 USD/house/yr. In rural and remote areas, energy expenditures are 95 and 82 USD/house/yr, respectively. In terms of CO_2 emissions, heavy dependence on diesel fuel for electricity generation results in higher emissions per electricity output in rural and remote areas, equivalent to 0.240 kg-CO_2/MJ

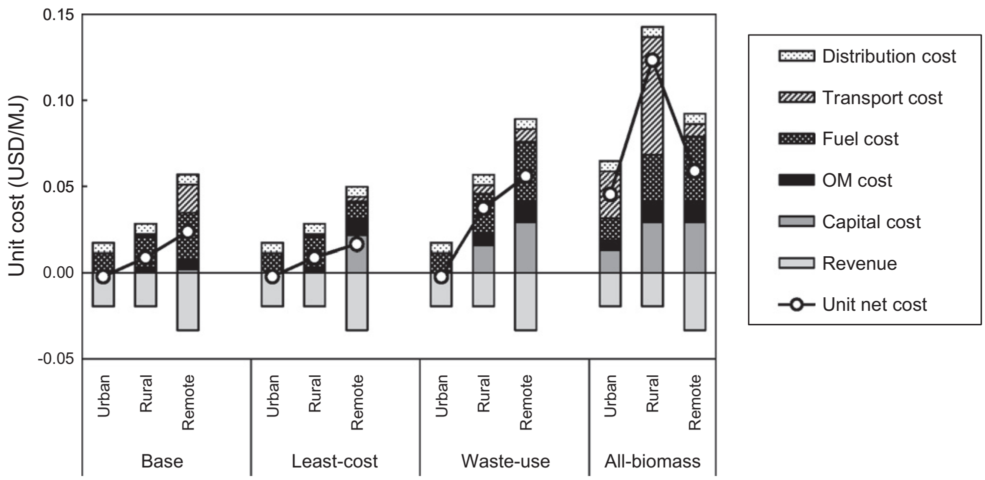

Fig. 10. Regional differences in unit electricity costs.

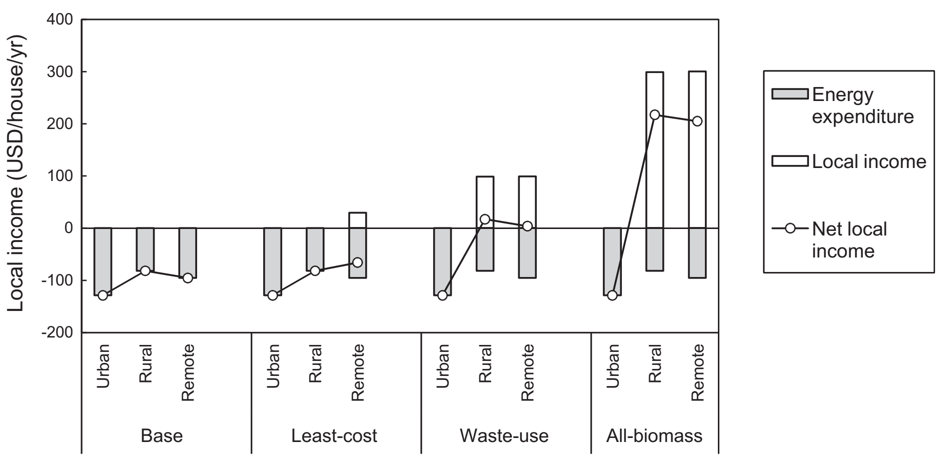

Fig. 11. Regional differences in local income and energy expenditure in households.

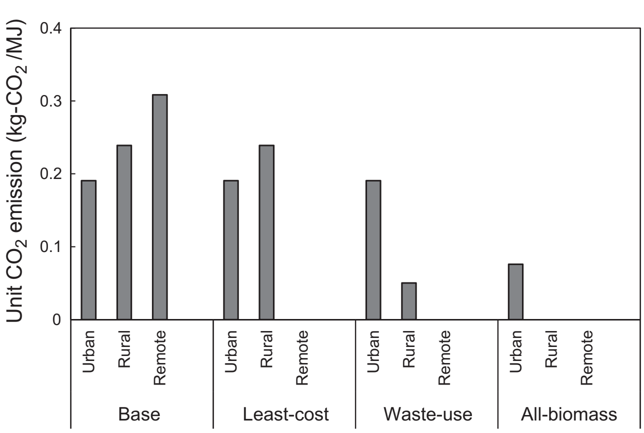

Fig. 12. Regional differences in CO_2 emissions from the energy system.

Table 5
Energy system performance outcomes by scenarios.

Resource	Base	Least-cost	Waste-use	All-biomass
Total net costs (10^3 USD/yr)	−14	−97	5545	61,467
Unit cost (USD/MJ)	0.020	0.020	0.025	0.079
Total local income (10^3 USD /yr)	0	120	4035	12,208
Net local income (USD/house/yr)	−116	−115	−89	−33
Total CO_2 emissions (t-CO_2/yr)	208,388	204,802	170,568	64,203
Unit CO_2 emissions (kg-CO_2/MJ)	0.200	0.197	0.164	0.062

for the former, and 0.308 kg-CO_2/MJ for the latter. In contrast, in urban areas, where electricity is supplied by the grid, emissions are 0.191 kg-CO_2/MJ. Emissions associated to grid electricity are lower due to the large share of hydropower in centralized electricity generation.

The shift from diesel-based to biomass-based electricity in remote areas obtained in the least-cost scenario brings along significant benefits to this region. The unit net cost decreases more than 30% compared to the Base scenario. The increase in capital costs is offset by the lower cost of biomass collected locally. Nevertheless, the value of net cost is still higher than that of rural areas. While disparity among regions from the perspective of electricity suppliers remains unchanged, households in remote areas achieve a 30% increase in net local income compared to the Base scenario, which results in a lower value than that of rural areas. This change enables a more equitable access to electricity based on the lower payment capacity of population in this region. CO_2 emissions reduction is less than 2% of the system's total emissions in the Base scenario.

The Waste-use scenario shows that promoting the use of agricultural waste for energy production escalates the system costs but provides large developmental and environmental benefits. Unit net costs in rural and remote areas rise by more than four and two times, respectively, compared to the Base scenario. Capital and fuel costs represent over 70% of total costs in both regions. In contrast, net local income grows sharply in these regions, achieving positive values. CO_2 emissions decrease by 80% in rural areas, resulting in the reduction of 15% of system emissions compared to the Base scenario.

The complete utilization of biomass resources for electricity generation leads to drastic changes in all aspects of energy system's performance. In the All-biomass scenario net costs rise sharply. For instance, net costs in urban areas turn positive and total costs increase by two to five times in all regions. Net costs are the highest in rural areas. The major component of system total costs is the transportation cost, which is over 50% in rural and urban areas. Net local income in rural and remote areas grows by over 200 USD/house/yr, while the situation in urban areas remains unchanged. The large share of biomass in electricity supply yields a 70% reduction in total CO_2 emissions.

5.3. Results of sensitivity analysis

Sensitivity analysis has been conducted in order to explore the changes in the performance of the energy system at different rates of biomass use. Outcomes on the net cost of the system, the net local income generated in households, and the CO_2 emissions in each region are presented in Fig. 13. Unit net cost and net local income increase sharply in remote and rural areas when up to 30% of all biomass available is used for electricity production. From the perspective of electricity producers, disparity increases between urban areas and other regions. Rates of biomass use above 30% affect only the net cost of electricity in urban areas and the net

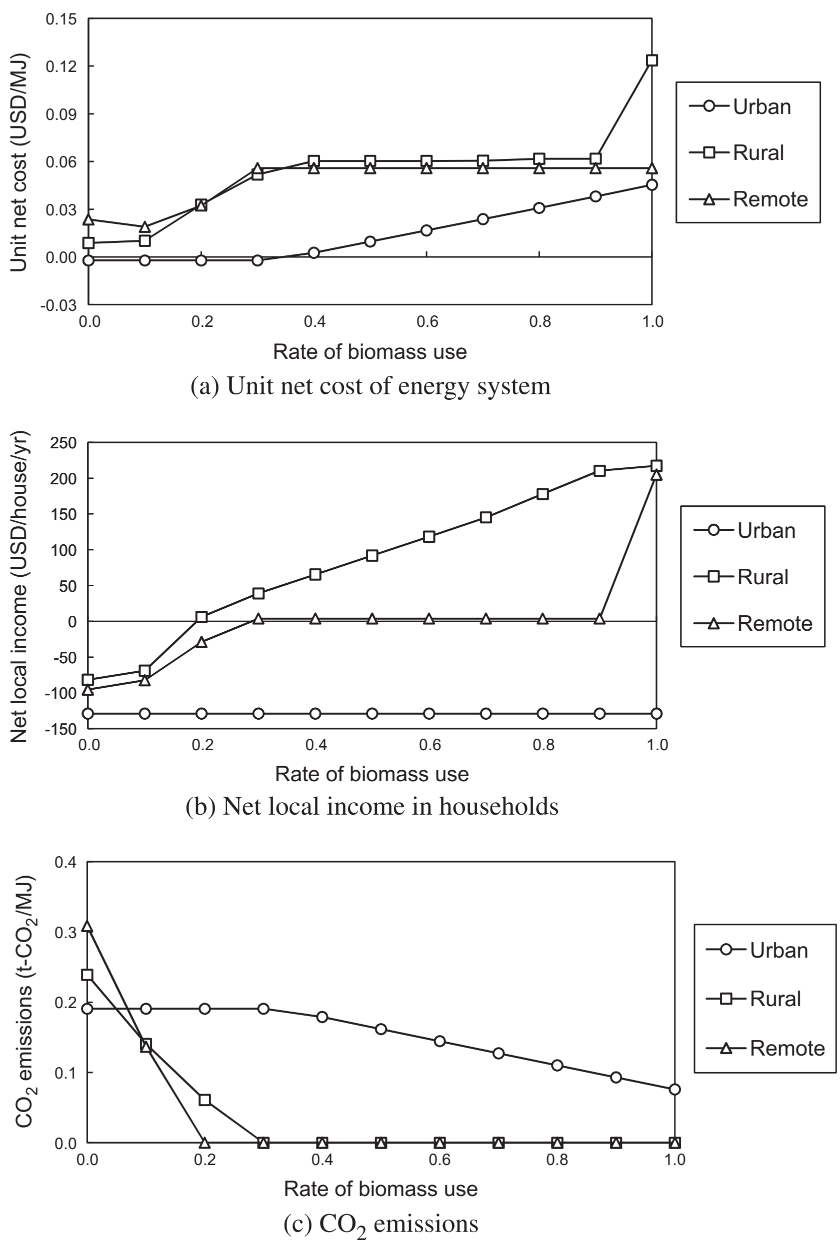

Fig. 13. Energy system performance at different rates of biomass use.

local income in rural areas. Both values increase steadily. This, in turn, narrows the difference in system net costs compared to urban areas. The rise in unit net cost in urban areas is a major obstacle to realizing the benefits from biomass use in terms of local income and CO_2 emissions reduction, due to the higher electricity consumption per capita and population in this region.

For instance, an increase of 0.1 cents/MJ in unit net cost in urban areas represents 848,000 USD/yr, which is equivalent to more than 4% of total system cost in the Base scenario. If the financial sustainability of the energy system requires that net costs in urban areas remain below zero, then less than 40% of the total biomass available in the region can be used. At a rate of biomass use equal to 30% significant benefits result in rural and remote areas at the expense of higher unit net costs. First, all agricultural waste is used for electricity generation. Second, average local income increases 121 USD/house/yr and 99 USD/house/yr compared to the Base scenario in rural and remote areas, respectively. This is equivalent to a net local income of 39 USD/house/yr in rural areas and 4 USD/house/yr in remote areas. Moreover, no CO_2 emissions are observed in both regions, resulting in 22% reduction of total system emissions compared to the Base scenario.

6. Discussion

The design of the energy system considering decentralized electrification with local biomass resources provides a more suitable alternative for electricity supply in remote areas based on the minimization of system net costs. Long distances prevent the deployment of diesel generators using diesel fuel and extension of the electricity grid. On the other hand, using local biomass resources reduces the dependence on foreign resources and the cost of electricity supply, thus, rising the reliability of the system in terms of resource supply. Moreover, the cost of biomass used for electricity supply represents a source of income for dwellers in remote areas, which decreases the net energy expenditure compared to rural and remote areas.

The waste-use scenario shows that promoting the disposal of agricultural waste in electricity conversion plants can avoid the dependence on foreign fuels for electricity supply. While the net cost of electricity increases considerably, the double environmental benefit obtained from the disposal of waste and the reduction of CO_2 emissions can offset such drawback. The internalization of these benefits in terms of opportunity costs and schemes like the Clean Development Mechanism (CDM) or the Global Environmental Facility (GEF), can support the financial sustainability of the system.

Nevertheless, these benefits are limited by the indirect negative impact on local agricultural activities. For example, several agricultural wastes currently have established applications, like nutrient sources for soils in growing fields, as structural material and as fuel for heat production in farms [37]. Regarding the use of agricultural waste as nutrients sources, diversion of the biomass demand towards the production of electricity may lead to additional inputs of fertilizers. In particular, increased use of nitrogen fertilizers, which need large inputs of fossil fuels for their production, can diminish the relevance of potential emissions reduction from biomass-based electricity.[3] Using other sources of agricultural waste or wood from planted forest for energy purposes may alleviate issues on competition for biomass resources. According to a report of the energy planning organ of the Ministry of Mining and Energy of Colombia, other options besides the five biomass energy resources considered in the present model include agricultural waste from oil palm, coffee, and cotton cultivation, and forest wood from several species [35].

Moreover, CO_2 emission reductions need to be assessed with a larger scope, including emissions from transportation and indirect emissions from possible increases in fertilizer use. Use of local resources reduces distances for fuel transportation and, thus, reduces emissions especially if fossil fuels used in conventional decentralized electrification are imported. Yet, the low energy density of biomass may result in a sharp increase of transportation needs and a net increase of emissions.[4]

Promoting the complete use of all available biomass within the region for electricity supply looking forward the generation of local income results in low conversion efficiency of the system, and, thus, in higher costs. Deployment of gasification plants instead of boilers can improve system efficiency and reduce costs. If an electricity output higher than current demand is considered it may be possible to balance the financial burden between electricity suppliers and the benefits for rural households. Therefore, it is essential to identify a market for the electricity surpluses produced from local biomass resources. One potential market is the substitution of other fuels used in households, especially traditional biomass used for cooking and fossil fuels for lighting. Another potential target for allocating electricity surpluses are the agricultural and industrial activities that rely on fossil fuels and machinery of low efficiency, such as water pumping and irrigation, food refrigeration, among others.

In order to reduce the cost of decentralized electrification using local biomass resources it is important to focus on transportation cost of fuels, and on capital cost and efficiency of biomass conversion technologies. Transportation cost of biomass is high due to the dispersed location of the resource and its low energy density. In the case of agricultural waste, such as rice husk, costs are elevated and energy applications are limited to locations where the resource is less dispersed. For example, rice husk can be used for energy production in large scale facilities for processing rice. Other option is to increase the energy density of biomass with processes for compacting materials in the form of briquettes or pellets. In the case of conversion technologies, advanced combustion and gasification plants, such as those including combined steam cycles, can raise efficiency to over 30% [38]. These technologies are expensive, thus, detailed financial analysis is needed to determine their feasibility.

The financial sustainability of the biomass-based electrification can be supported by subsidies to lower the capital costs of biomass conversion technologies and the prices paid by rural users. For instance, urban areas, which have higher income and capacity to pay higher electricity prices and consumption levels, can contribute to leverage the energy expenditures in rural and remote areas, which pay an amount of money comparatively higher for energy consumption relative to their income. Another mechanism worth considering is the trade of electricity among regions. If decentralized plants using biomass are connected to the national grid, for example in rural areas within the interconnected area, consumers in urban areas can balance the system costs since the costs for biomass resource transportation are avoided.

There are important uncertainties linked to the design of decentralized energy systems using biomass that have not been included in the LP model applied for this research. First, the detailed

[3] Rice husks provide little benefit as soil nutrient, only ashes from rice husk combustion are sometimes regarded as a potential source of silicon for soils; thus, using this material as energy source does not promote the dependence on nitrogen fertilizers. Bagasse is not regarded a significant source of nitrogen for soils, and it is widely used as fuel in sugar mills; sugarcane wastes (leaves, vines, etc.) can be used as soil nutrient, yet these materials are more often used as animal fodder or fuel.

[4] In the model studied, the contribution of CO_2 emissions from fuel transportation is not significant, since they represent less than 2% of system's baseline emissions and less than 3% of emissions reduction; however, it has to be noted that transportation emissions can vary considerably depending on the values assumed in the model for transportation distances.

characterization of the spatial distribution of biomass resources and demand centers has been simplified to three regions based on the availability of data, especially regarding the location of biomass resources. An average distance between and within regions has been assumed for application of the LP model. The distance needed for transportation of biomass and the cost of the resource depend on the geographic location. Accounting for this aspect of design is fundamental for studying the feasibility of biomass-based energy supply, given that collection and transportation costs are a major component of system costs. In addition, CO_2 emissions resulting from transporting fuels may eclipse emissions reductions granted by the introduction biomass-based electricity if the distance for collecting local biomass is too long.

Second, the effect of the scale of conversion plants has been omitted in the model. The size of decentralized electricity plants should be defined according to the size of the demand served. In the case of biomass conversion plants of small scales, i.e. below 5 MW, capital costs and conversion efficiencies are sensitive to the size of the plant. In one hand, direct combustion of biomass in boilers provides better performance at medium to large scales. On the other hand, biomass gasification plants can achieve lower unit costs at small scales without compromising conversion efficiency. Compared to boilers, gasification units have less physical components [38,39]. However, the applicability of these technologies is limited by high maintenance needs and fuel homogeneity requirements. In addition, there is a large range of efficiencies and costs in gasification technologies that vary according to the manufacturer. This brings along significant uncertainties in the definition of unit costs. Another aspect linked to the size of biomass conversion plants is the storage of biomass. The low energy density of biomass materials may lead to large storage requirements in facilities, which require special maintenance and short periods of residence in order to avoid humidification and degradation.

Third, an average population density of demand centers has been assumed to estimate the unit cost of extending transmission lines of the electricity grid. This factor affects not only the feasibility of grid extension, but also the scale of decentralized conversion plants. Fourth, the technical reliability of decentralized electrification has been evaluated only in terms of increased stability of fuel supply. The way in which systems are operated in a daily and monthly basis affects operational life and conversion efficiency. Regarding this aspects, conversion systems based on the gasification of biomass are considered as a technology with limited technical maturity. The generation of tar and the variability of the combustion gas resulting from biomass gasification are important factors that are difficult to control in commercial applications currently available for rural electrification in developing countries [8,39,40]. Gasification systems with standardized and reliable technological components are much more expensive, making their application limited to specific cases.

7. Conclusion

The introduction of regional disparity in the design of decentralized energy systems for rural electrification shows that transportation distances and conversion efficiencies of biomass technologies are essential factors for shifting from foreign fuels to local biomass to promote rural development. Biomass use for electrification reduces disparity in remote areas. Electricity costs reduce and net local income increase, resulting in improved access to electricity according to the lower income expected in remote areas. Promoting the use of agricultural waste increases the system costs, but provides significant benefits in terms of generation of local income, waste management, and CO_2 emissions reduction. Use of all biomass available within the region for decentralized electrification results in negative outcomes from the perspective of electricity suppliers, and large benefits for households and the environment. Several measures are necessary to enable the penetration of biomass-based decentralized systems in developing countries. In particular, it is important to balance the financial and technical barriers of these systems, with the benefits in terms of environmental protection and reduction of regional disparity through generation of local income. Production of electricity surpluses can help achieving this balance. Instead of supplying electricity to meet the current demand, allocating surpluses to new markets increases the system efficiency and profitability. Extended electricity generation capacity can be targeted at the replacement of traditional stoves, kerosene lamps and candles in households, and the introduction of electric machinery in agricultural and industrial activities in rural areas. Financial sustainability of energy system can be supported with more comprehensive evaluation procedures, financial mechanisms, and more efficient technologies. This support can be realized internalizing the benefits from CO_2 emissions reduction and local income generation, introducing subsidies across regions, and selling electricity from decentralized conversion plants to the electricity grid.

The application of an optimization model for the design of decentralized energy systems for electrification using biomass for Meta department in Colombia results in the following outcomes:

- The least-cost energy system design suggests the replacement of diesel generators using diesel fuel with gasification plants using sugarcane and planted forest waste in remote areas.
- Unit net costs in remote areas reduce by 30%. Net local income reaches the highest value among regions. Only 2% of total CO_2 emissions in the target area are reduced.
- Use of agricultural wastes for electricity production displaces all diesel fuel in rural and remote areas. Biomass supplies over 75% of demand in rural areas, and over 14% of the total demand in the target area.
- Wastes are used in the same region they are generated, with the exception of remote areas, where 13% of sugarcane waste is shipped to gasification plants in rural areas. Boilers are selected in remote areas and gasification plants are selected in rural areas.
- Unit net costs rise by a factor of 4 in rural areas and of 2.5 in remote areas. Positive net income values equal to 20 USD/house/yr and 4 USD/house/yr are obtained in these regions. CO_2 emissions reduce by 15%.
- Using all biomass available in the target area for electricity generation can supply close to 70% of total demand. Biomass is allocated to boilers in all regions.
- All agricultural wastes are used in rural areas, except rice husk and bagasse produced in remote areas. Biomass-based electricity supplies all the demand in rural areas, with wastes contributing 62% of resource supply. In urban areas, 60% of electricity is supplied by gasifiers using forest waste.
- Unit net costs rise sharply, and unit total costs reach 6.5 cents/MJ, 14.3 cents/MJ and 9.2 cents/MJ in urban, rural and remote areas, respectively. Net local income increases by 200 USD/house/yr in rural and remote areas. Over 144,000 t-CO_2 emissions reduction is obtained, equivalent to 70% of emissions in the Base scenario.
- If net costs are to be kept below zero, a maximum rate of biomass use equal to 30% can be achieved. This results in increased net cost of supply, net local income in households, and CO_2 emissions reduction in rural and remote areas.
- Biomass use rates higher than 30% result in increased net local income in rural areas and CO_2 emissions reduction in urban areas.

Further improvements of the model are needed in order to internalize benefits of decentralized electrification using local biomass in terms of increased local income and CO_2 emissions reduction. The model developed and applied in this research can be expanded beyond the analysis of electricity supply with the inclusion of other energy sources such as kerosene, coal, and other fuels. This will require a larger scope for the energy system in order to include end-use devices and useful energy demands. In addition, indirect impacts on local agriculture and from fuel transportation are worth incorporating into the model. Finally, more detailed description of spatial distribution of biomass supply and energy demand centers is necessary to gain deeper insight on the feasibility of decentralized energy systems.

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