INTEGRATED RURAL
ENERGY DECISION SUPPORT SYSTEM

by

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INTEGRATED RURAL

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Abstract

Rural areas in developing countries face severe energy problems. At some places, this problem is addressed by *ad-hoc* policies, which in many instances lack continuity. The lack of both energy data and the capability to analyse energy options for a given planning area have been the primary causes for misrepresentation of rural energy problems.

In this research, a systematic approach for analysing energy situations using a decision support system is proposed. The approach combines a geographical information system and a multiobjective programming method. A geographical information system helps in database management and multiobjective programming helps in the analysis of conflicting objectives such as cost, efficiency, environment, and equity.

The proposed system is applied to a rural region and two cases are studied. Ten energy options are discussed and resource allocations are shown for a few of these options. By knowing the resource allocation and evaluating their implementation possibility, the decision makers are expected to be in a position to

choose a better option for the planning area.

The results obtained for the study area indicate that the emphasis should be put on the distribution of efficient fuelwood stoves and exploitation of local energy resources. Any deficit in energy supply thereafter should be met with imported energy sources such as grid electricity and kerosene. The result also indicate that if the proposed energy allocation could be implemented, then it can provide rural employment and provides an opportunity to encourage interfuel substitution in the planning area.

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To

My daughter Selene

My inspiration for a steady work.

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Acronyms

DCs	=	Developing Countries
DSS	=	Decision Support System
EBS	=	Energy Balance Sheet
EFS	=	Efficient Fuelwood Stove
FAO	=	Food and Agricultural Organization
GIS	=	Geographical Information System
ha	=	Hectare
IEP	=	Integrated Energy Planning
KDCC	=	Kaski District Development Council
kg	=	Kilogram
kl	=	Kilo Litre
MOP	=	Multiobjective Programming
MOWR	=	Ministry of Water Resources, Nepal
mt	=	Metric Tons
NPC	=	National Planning Commission, Nepal
RES	=	Reference Energy System
Rs.	=	Nepalese Rupees (US $ 1.00 = Rs. 50.00)
SDSS	=	Spatial Decision Support System
UN	=	United Nations
UNDP	=	United Nations Development Program
VDC	=	Village Development Council
WECS	=	Water and Energy Commission Secretariat, Nepal

Energy Units

W	=	Watts
W_p	=	Peak watts
kW	=	kilowatt
kWh	=	kilowatt hours
MJ	=	Megajoules
MW	=	Megawatts
MWh	=	Megawatt hours
GJ	=	gigajoules(10^9 joules)
TJ	=	Terajoules (10^{12} joules)
PJ	=	Petajoules (10^{15} joules)

Chapter 1

INTRODUCTION

More than three quarters of the population of developing countries live in rural areas, where farming is the main economic activity and biomass is the main source to meet the energy demand for household chores. These people have fewer economic opportunities and live in a condition of lower infrastructure development with almost no supply of alternative resources, and have almost no role in decision making for their own area. These vulnerabilities have forced the rural people in developing countries into "a vicious cycle of poverty" (Chambers 1993). As a result, rural people are either forced to migrate to urban areas or to use already marginalized natural resources creating environmental degradation. Such a degradation, in the opinion of the World Commission on Environment and Development (WCED 1987), is a ".. new reality" to be increasingly faced by the world in the coming years. Therefore, the Commission suggests that "decisive political actions" should be taken to correct such a situation. Such actions should have an objective of sustainable development, that is, to meet the present and the future needs.

It is within the framework of sustainable development of rural areas in developing countries (DCs) that this thesis is developed. This work is expected to highlight the importance of energy awareness and rural energy development. As a part of this research, a decision support system has been proposed, which the decision makers (both at the local and the national levels) are expected to find useful to enhance their knowledge of the feasibility of rural energy policies.

1.1 Energy Planning Practice

The purpose of an energy planning exercise is to generate an energy policy. National level energy planning may be traced back to the industrial development of electricity generating equipment. Until the 1970s, energy planning was engineered with consumption driven supply planning. New generating facilities were added when the demand superseded the energy supply capability. The two "oil shocks" of 1973 and 1979 brought energy demand management considerations into the energy planning process. Then followed a series of energy plans or energy master plans with a key assumption of rising oil prices (Hills 1988). In the United states also, Project Independence was started by President Nixon to make the country independent of foreign oil imports by 1980 (Gass 1994). Nevertheless, the fate of this plan was sealed off due to the falling oil prices in the mid 1980s (Hills 1988). The failure, however, led to the idea of integrating energy plans with other economic activities, which we now call Integrated Energy Planning (IEP). It was realized that a better energy policy could be formulated if the energy programs were integrated with other development goals. By taking the case of forest denudation for fuel in Africa, Hosier et al. (1982) proposed that for an effective energy policy, energy plans and local developmental activities should be integrated. This was one of the first such propositions in the field of integrated energy planning.

The need to integrate national level energy planning with macroeconomic planning was consolidated by the "Integrated Energy Planning" manual published by the Asian and Pacific Development Centre (APDC 1985). The manual calls for using a *systems approach* to arrive at consistent energy policies at the *national level* over a long term. This manual seeks first to understand the linkage between the energy sector, macro-economic factors, and socioeconomic objectives so that a greater coordination could be achieved between energy demand and supply management. Although this type of planning process dilutes the effect of rural energy systems, there is a possibility of developing rural energy plans in the same fashion (Shah 1988).

A framework for designing rural energy plans based on the concept of integrated energy planning has been proposed in FAO (1990). The framework calls for micro-area based planning by assessing energy demand, energy supply, and potential energy technologies that could be implemented in the planning area.

Rural energy consumption is controlled by the consumers themselves and the interaction between the consumer and energy consumption is difficult to model (Ramani 1988). Nevertheless, it is important that rural energy planning should be highlighted alongside the urban oriented energy plan. If the rural energy situation does not improve, more people will have to spend more time collecting fuel (Hill et al. 1995) and less time in farming and other activities, thus further degrading rural life.

To augment the rural energy supply, some efforts have been made in the past by installing photovoltaic electricity generation, wind pump or wind mill operations, biogas plants, micro hydro plants, and by distributing efficient fuelwood stoves (EFS). However, these programs have lacked continuity in most of the participating countries (FAO 1990). In some DCs, like Nepal, India, and Thailand, supply planning and pricing of kerosene are major components of rural energy planning. The cross subsidization of kerosene is expected to replace fuelwood used for cooking. That could be true in the urban areas as shown by Pokharel (1992), but in rural areas the cross subsidization is likely to increase its use in lighting, but not in cooking (Romahn 1988). The cross subsidization alone is not enough to attract rural people to replace fuelwood consumption.

Except for some countries, energy planning for rural areas in DCs is either absent or controlled by central authorities (Tingsabadh 1988). The absence of local participation in rural development plans has led those plans to failure (Bartelmus

1986). This situation is aggravated by the number of uncoordinated and agency-specific similar programs in the same area (Shrestha 1988, Behari 1988).

The public participation can be brought into the design process in the form of grassroots level information, manpower training, and local employment. FAO (1990) suggests that if the community is made an integral part of energy programs, the chances of sustainability of such programs can be increased.

Energy related environmental problems in rural areas are immediate but conflicting at times. For example, the smoke from cooking/heating stoves causes health hazards (Pandey et al. 1990, FAO 1994), however, it preserves grains (Foley et al. 1984) and helps to abate the termite problem that destroys beams and pillars in the house. Collection of fuelwood from a nearby forest can reduce the working load of women (Shrestha 1985, Hills 1988), however, it might create the problems of soil erosion and land slides (Adhikary 1988) in or close to the farm land and affect the food supply chain further degrading rural life. Therefore, when implementing an energy plan, clear identification of such aspects is essential.

1.2 Energy Modelling

Modelling and optimization of models illuminates conflicts within a system and helps in generating a set of alternatives for further analysis (Liebman 1976). Therefore, an effective model is important to enhance rural energy planning.

The energy balance sheet (EBS) and the reference energy system (RES) have been used to model energy systems in many DCs. These tools help in identifying surpluses or deficits in supply and in designing an energy intervention program. RES has been used in energy planning in DCs including Sudan, Peru, Egypt, Indonesia, and Sri Lanka (Munasinghe and Meier 1993).

Economic tools like net present worth of investment, rate of return, and benefit-cost ratio are also used in energy planning. Christensen and Vidal (1990) and Pokharel et al. (1992) have used some of these economic tools for energy analysis. Statistical models may also be attached to such economic tools.

Linear single objective optimization has been used for energy analysis by Ramakumar et al. (1986), Joshi et al. (1991), Luhanga et al. (1993), Malik et al. (1994), Sinha and Kandpal (1991a, 1991b, 1991c, 1992), Srinivasan and Balachandra (1993), and Zhen (1993). By using goal programming, a type of multiobjective method, as a case study in energy planning, Chetty and Subramanian (1988), Ramanathan and Ganesh (1993 and 1994), Bose and Anandalingam (1996) have shown that the use of multiobjective programming methods could enhance the applicability of energy models.

The tools discussed above have been used to design generic energy models that are either supply or demand oriented. Supply oriented models generally focus on energy resources and their interaction with the economy, whereas demand oriented models focus on energy end-use and sectoral energy demands. Detailed reviews of these models can be found in Fuller and Ziemba (1980), Foat et al. (1981), UN (1982), UN (1989), and Munasinghe and Meier (1993). Basic information on some of the most widely used models, obtained from the reviewed literature, is given in Table 1.1.

Table 1.1 Basic information on some of energy models

Model	Main Data	Optimization of Objectives	Output
ENVEST	Energy flow, technology assessment	None	Rate of return for energy projects
RESGEN	Based on RES	None	Allocation of energy sources
ENERPLAN	Time series data on economics and energy	None	Econometric coefficients and demand projection
BESOM	Based on RES	Single, cost minimization for energy supply	Optimal mix of technologies
MARKAL	Based on RES	Single, multi-period	Optimal mix of technologies
PIES	Energy conversion, import, tariff, taxes, new supply.	Single, cost minimization	Optimal mix of technologies
MEEDE	Based on RES	None	Projection of energy requirements
TEESE	Cost, efficiencies, macroeconomic factors	Single	Optimal mix of technologies.

1.2.1 Supply oriented models

These models focus on energy resources and their interaction with the economy. The ENVEST model is perhaps the first energy supply model developed for any developing country. This model focuses on energy project analysis and evaluates a projects' internal rate of return. This model was followed by the development of a more flexible model, RESGEN, based on the reference energy system. This method requires a knowledgable user for implementation.

The Brookhaven Energy Systems Optimization Model (BESOM) is a static single objective linear optimization model, which focuses on a long range technology assessment and policy analysis. Conceptually similar is the Market Allocation model (MARKAL), a multi-period linear optimization model that calculates an optimal mix of technologies according to one of several possible criteria.

The Energy Planning model (ENERPLAN) is an econometric model based on time series data and is suitable for statistical analysis. This model has been applied to Thailand and Costa Rica as part of a demonstration.

The Long term Energy Analysis Package (LEAP) is a large scale energy-economy model, which simulates market processes through supply and demand interaction and provides recommendation for policy options.

1.2.2 Demand oriented models

These type of models focus on energy end-use or sectoral energy demands and may use econometric tools. The Project Independence Evaluation System (PIES) model is an energy demand model for large scale energy systems. This model was developed in the early seventies to chalk out a plan for foreign oil independence of the United States by 1980 (Gass 1994). This model incorporates economic and linear programming sub-models for bringing about an economic equilibrium in energy supply and demand.

The MEEDE model disaggregates the total energy demand into homogenous end-use categories and determines the long term energy demand evolution within a specified time horizon. The Waterloo Energy Modelling System (WATEMS) is a linear or nonlinear single objective optimization model used for cost minimization of energy technology mix in RES framework (Fuller and Luthra 1990). The Tata Energy Economy Simulation and Evaluation model (TEESE) uses pricing and single objective linear optimization as guiding tools for energy analysis.

Both the supply and demand oriented models described above are designed for a market-based situation and therefore, they may not be suitable for application in rural energy analysis. However, the tools like EBS, RES, and optimization used in the above models could also be used to represent the rural energy situation.

1.3 Rural Areas and Energy

More than 75% of the population in developing countries live in rural areas. In some of the developing countries, as much as 90% of the population lives in rural areas (FAO 1994). People living in rural areas depend heavily on local resources for their livelihood. The energy supply is dominated by biomass fuels and most of the energy resources are used to meet household energy demands (Best 1992, Hills et al.1995) as shown in Table 1.2. A further level of disaggregation as to the availability of biomass resources in selected DCs is given in FAO (1994).

Table 1.2 Energy consumption in PJ in selected developing countries[1]

Country	Total energy consumed (a)	Biomass energy consumed (b)	Total consumption in households (c) [(c)/(a)]%	Household Biomass consumption (d) [(d)/(b)]%
Bangladesh	377	268	294 (78%)	249 (93%)
Colombia	714	172	194 (27%)	122 (71%)
Bolivia	61	16	23 (38%)	12 (75%)
Costa Rica	72	32	31 (43%)	25 (78%)
Gabon	60	24	28 (47%)	23 (96%)
India	7249	2602	2913 (40%)	2345 (90%)
Indonesia	2375	1286	1450 (61%)	1231 (96%)
Kenya	332	248	269 (81%)	237 (96%)
Nepal	255	241	242 (95%)	238 (98%)
Nicaragua	58	32	29 (50%)	26 (81%)
Niger	44	38	39 (89%)	38 (100%)
Nigeria	1385	948	1011 (73%)	947 (≈100%)
Pakistan	891	267	339 (38%)	220 (82%)
Philippines	697	345	384 (55%)	310 (90%)
Sri Lanka	125	72	59 (47%)	50 (69%)
Zambia	171	116	117 (97%)	113 (97%)

[1] Source: FAO (1994)

To analyse a rural energy system, an understanding of the energy flows in and around the rural areas is necessary (Habito 1988). A very broad energy flow diagram with the sun as the main energy source and cooking and lighting as main energy end-uses is shown in Fig. 1.1. The energy flow path from solar energy to forests, for example, is not considered in this thesis as it represents indirect solar energy conversion and large gestation period for energy conversion. This thesis considers only direct solar energy conversion as with solar to PV and to electricity.

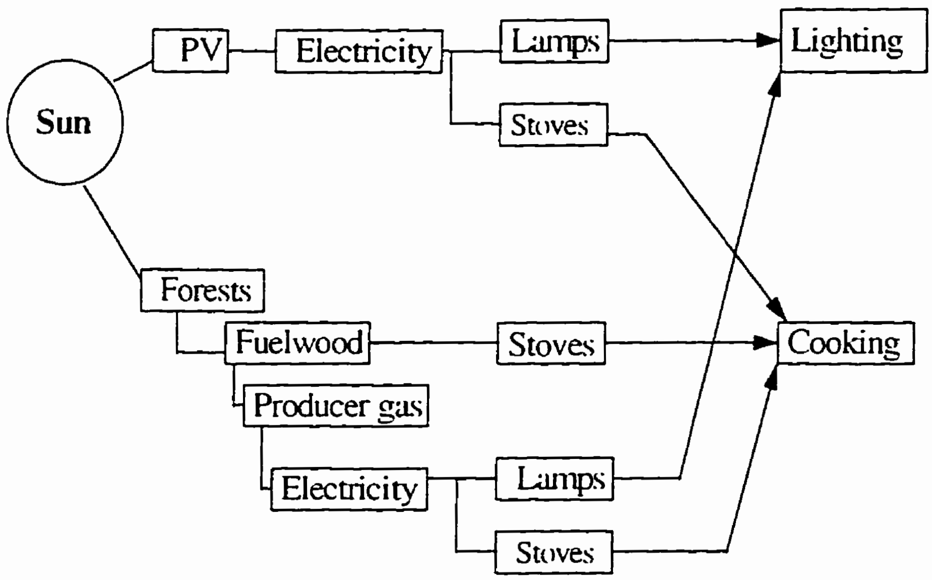

Figure 1.1 A general energy flow diagram

A detailed and exploded view of major energy flow path used in this thesis is shown in Figure 1.2. This figure shows the specific end-uses that could be derived from a particular fuel source. The boundary of the energy system, as indicated by dashed lines, shows that sources such as forests, cultivated land, and livestock are the input parameters to the system and end-uses such as cooking, lighting, and space heating are the output parameters of the energy system.

Figure 1.2 shows that there are various stages of transformation (extraction, conversion, distribution, and utilization stages) in energy flow from source to the end-uses. The energy utilization efficiency of various end-use devices has also been shown in the figure (in parenthesis), which shows that efficiency of biomass stoves generally ranges between 10% and 20%.

Figure 1.2 shows some reverse arrows for some resources to indicate not all of the resources available in the rural areas could be used for energy purposes. As

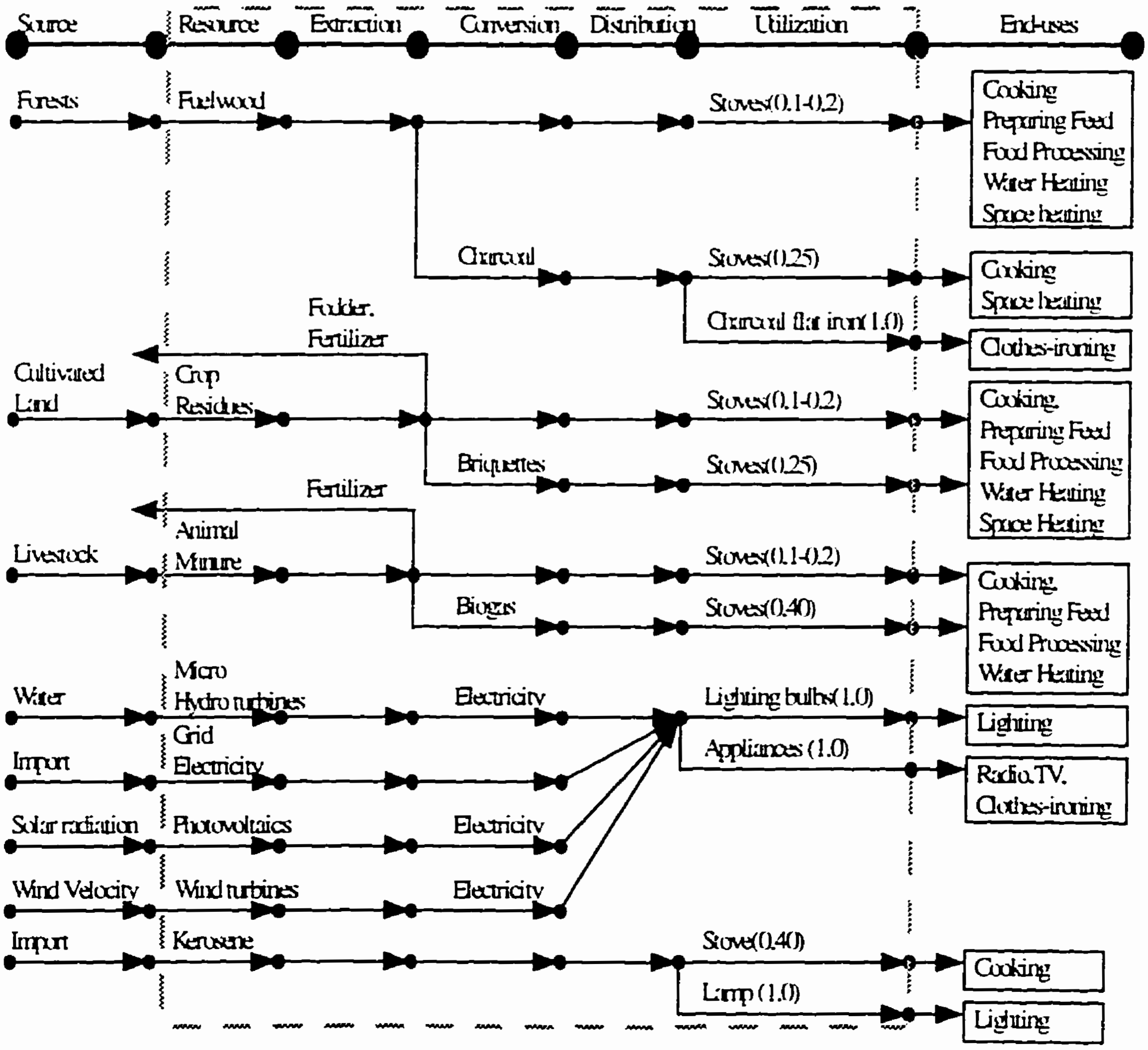

Figure 1.2 Typical energy flow in rural households

shown by back arrows in the figure, crop residues and animal manure have other significant competing uses. Crop residues are used as mulch and fodder in many rural areas. Similarly, animal manure is often the only fertilizer used in crops. Therefore, such competing uses of resources should be carefully examined while designing a rural energy system.

Figure 1.2 is drawn from the resource point of view, that is, to identify major end-uses that could be derived from a particular fuel. In Figure 1.3 and 1.4, energy flow diagrams for two major end-uses are shown. These figures show what fuel sources can be used for a particular end-use. Figure 1.3 shows that at least five energy sources and four end-use devices can be used for cooking in rural areas.

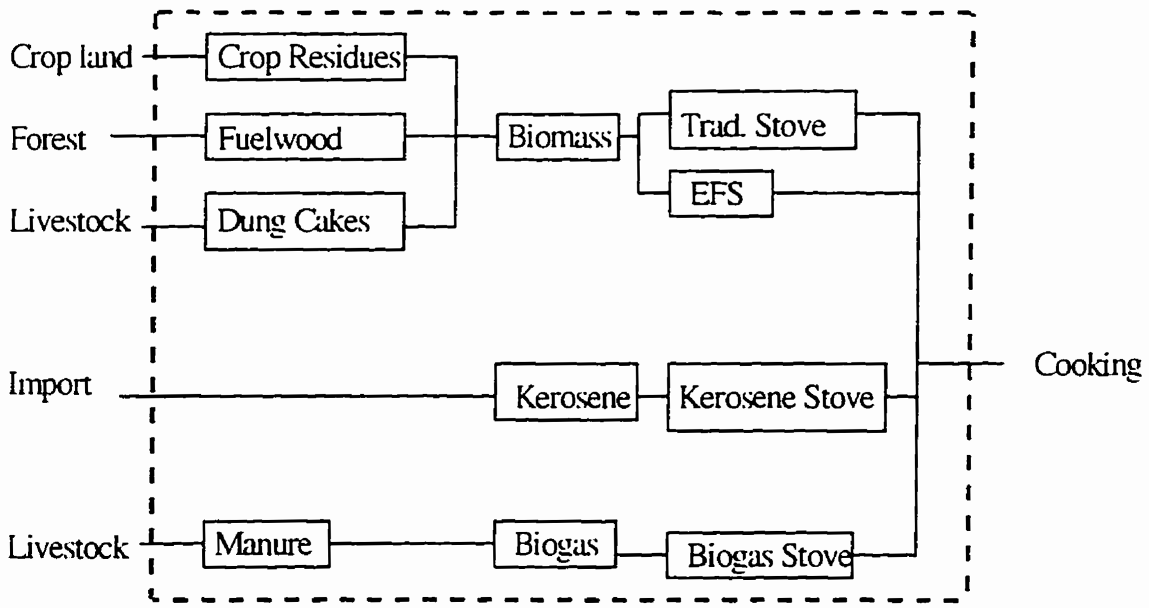

Figure 1.3 Energy flow diagram for cooking

Similarly, as shown in Figure 1.4, at least six energy sources and six end-use devices can be used for lighting in rural areas. These type of figures can be drawn for all

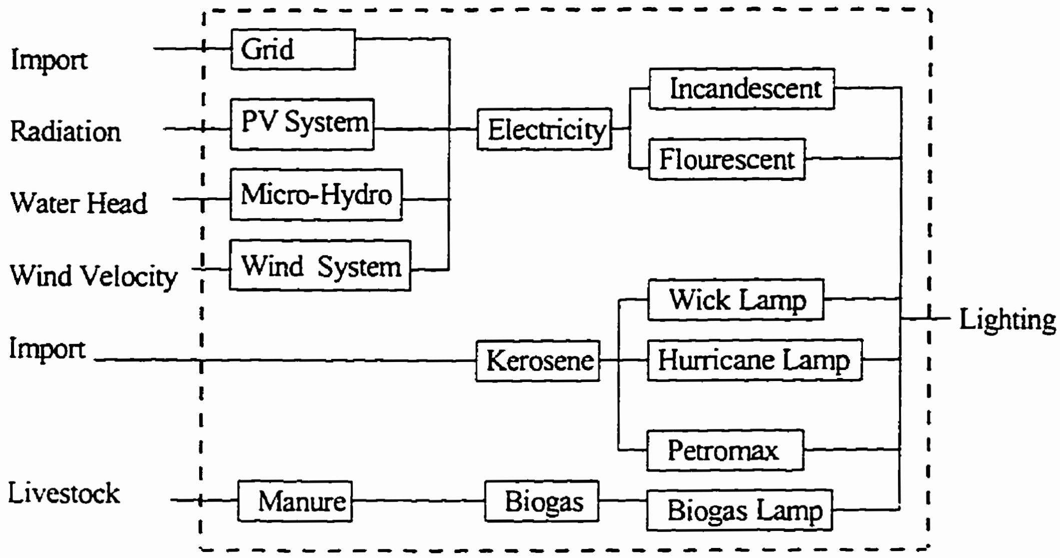

Figure 1.4 Energy flow diagram for lighting

energy end-uses shown in Figure 1.2. A detailed discussion on energy resources and energy end-uses is given in the following subsections.

1.4 Energy Resources

In rural households, fuelwood, crop residues, animal manure, kerosene, electricity and biogas are main energy sources. However, the use of each energy resource depends upon its availability, accessibility, and affordability.

1.4.1 Fuelwood

Fuelwood is one of the dense biomass energy sources. The density of fuelwood varies between 400kg/m^3 and 1100kg/m^3 (UN 1987). The energy content of air dried fuelwood varies between 16 GJ[1] (UN 1987) and 20 GJ (Bhatt and Todaria 1990) per metric ton (mt). The energy value of fuelwood depends mostly upon its moisture content (UN 1987). The moisture content of green fuelwood varies between 50-150% (Bogach 1985) and in air-dried fuelwood the moisture could be as high as 30% (Earl 1975).

Fuelwood production on a sustained basis from a forest depends upon the tree species, forest (or crown) density, and geographical conditions. The higher the crown density, the higher the fuelwood availability. Similarly, the lower the altitude the higher the fuelwood yield. The annual gross sustainable fuelwood and timber supply from Nepal's natural forests given in MOFSC (1987:Table 19) shows that the yield in the mountains is almost half the yield in the Tarai (plain region in the lower altitude). The sustainable yield and growing stock of forests in some African states are given in Milington et al. (1994) and the fuelwood characteristics of some mountain trees are given in Bhatt and Todaria (1990). These types of information are helpful in understanding the variations in fuelwood production in different regions.

1.4.2 Charcoal

Charcoal is obtained from carbonisation of fuelwood or crop residues in kilns. Typical earthen kilns have an energy conversion efficiency of about 17-29% (Hall

[1] GJ = gigajoules

et al. 1982). However for volumetric conversion, the efficiency is as low as 10% (Hills et al. 1995). The calorific value of charcoal is about 29 GJ/mt (WECS 1994a).

Charcoal can be used for cooking, space heating, and in appliances such as press iron or in cottage industries like black-smithy and gold-smithy (Cecelski 1979, Chirarattananon 1984, Energy Research Group 1986, Moss and Morgan 1981). The efficiency of a charcoal stove could be as high as 65% (Moss and Morgan 1981).

1.4.3 Crop residues

Crop residues are comparable to fuelwood in energy value and use. Dense crop residues, like jute sticks and maize cobs, burn well and make better fuels. The crops yield in metric tons per hectare (mt/ha) and residues to crop ratio are given in Table 1.3.

Table 1.3 Residue to crop ratio and calorific values[1]

Crops type	Crops yield mt/ha	Types of residue	Residue:crop ratio	Energy Content in GJ/mt
Paddy	0.3 - 8.0	Husk Straw	0.3 1.1 - 2.9	15.3 - 16.8 15.0 - 15.2
Maize	0.2 - 11.0	Cob Stalk	0.2 - 0.5 1.0 - 2.5	17.4 - 18.9 16.7 - 18.2
Wheat	0.3 - 4.9	Straw	0.7 - 1.8	17.2 - 18.9
Sugarcanes	10.0 - 113.0	Bagasse	0.1 - 0.3	16.0

[1] Source: (B&K 1985, WECS 1994a)

The yield of a crop and its residue depends upon factors such as farming system and agro-climatic conditions. Crop residues are also recycled to reduce soil erosion from farm land (Hall et al. 1982). They are also used as fodder (Shacklady 1983). However, not all of the crop residues are good for recycling (B&K 1985) nor for animal fodder. Crop residues like rice straw, green maize stalks, and wheat stalks are common animal fodder. Therefore, the availability of crop residues for fuel may be limited in some rural areas.

1.4.4 Animal manure

Animal rearing is an integral part of rural households in many areas. However, the availability of animal manure depends upon the type and species of livestock as shown in Table 1.4. Livestock manure is an invaluable fertilizer in the rural areas, therefore, its availability for fuel may be limited.

Table 1.4 Animal manure production per year[1]

Livestock	Air-dried manure/livestock in mt
Cattle	0.5 - 1.7
Buffalo	0.7 - 2.0
Sheep/Goats	0.1 - 0.2

[1] Source: B&K 1985

Animal manure could be used as fuel either directly as dried dung cakes or dried dung sticks or indirectly as biogas. Usually, only cattle and buffalo manure is used for energy purposes. The energy content of air-dry animal manure is about 11 GJ/mt (WECS 1994a).

1.4.5 Hydropower

Hydropower is exploited in rural areas either through a traditional water wheel for grain processing or with modern steel turbines for grain processing and electricity generation. In countries like Nepal, China, Bhutan, Myanmar, India, Thailand, Pakistan, Sri Lanka, and Papua New Guinea, there is a large potential for generating smaller scale hydropower. Such power could be a way of providing affordable energy to rural areas (Inversin 1986).

Hydropower could replace kerosene (used for lighting) and diesel (used for agro processing). An ordinary kerosene lamp consumes an average of about 20 ml/hour (researchers' survey). If the lamp is used for about four hours a day, the average annual kerosene consumption would be about 30 litres per kerosene lamp. A 10-kW hydropower turbine can deliver 5-6 kW of electricity for lighting. This would translate into a saving of about 4 kilo litres of kerosene per year. Similarly, a grain mill consumes about 3-5 litres of diesel fuel per hour. If a mill runs for about six hours a day and for about 200 days in a year, about five kilo litres of diesel are required, which could be replaced by hydropower-based grain processing units. Such a saving at different places can become significant on a national scale. The installation of turbines in rural areas also provides employment opportunities in these rural areas (Pokharel 1990).

1.4.6 Solar energy

The solar energy absorbed by the earth's surface is as high as 8 kWh/m^2-day (Dayal 1993) in sunny, arid regions. The availability of solar energy depends upon the local weather conditions and the geographical location. Solar energy is a potential source for water pumping, crop drying, electricity generation, and cooking (Bassey 1992, Hegazi 1992, GTZ 1992, Sinha 1994).

1.4.7 Wind energy

The availability of wind energy is site and time specific. About 4 m/s of wind speed is required to operate a wind mill (Stout et al. 1979), but about 7 m/s is desirable for electricity generation (Grubb 1992). Methods for calculating wind energy potential in a particular area are given in Heng (1985) and Stout et al. (1979).

Wind energy is used for water pumping, grain processing, and electricity generation (Sinha 1994). However, long term wind velocity data of an area are required to plan for wind energy extraction.

1.4.8 Biogas

Biogas is produced by anaerobic digestion of animal manure. Its production is dependent on the type of animal manure and site temperature. Higher digester temperatures, not exceeding 35°C, will promote faster generation of biogas (UN 1984).

There are two main types of biogas digesters, which come in various capacities. Pokharel (1992) has given a method for calculating the capacities of biogas digesters for different energy demand levels. The methods for calculating gas generating potential of biogas plants and the economic benefits due to methane production are given in Jiapao and Cheng-xian (1985), and in Pokharel and Yadav (1991).

Biogas contains 50% - 60% methane, with a calorific value of between 20 and 28 GJ/m^3. Biogas could be used for cooking, lighting (0.14 m^3/hr of biogas is required to produce lumens[1] equivalent to that of a 60-W incandescent bulb), and in grain processing (in combination with diesel, 50%-60% of diesel replacement). About 70% of the input dung is available as spent dung (called slurry, extracted after biogas formation), which can be used as field manure. Biogas installations use local resources and provide an opportunity for local employment.

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[1] Lumens per square meter is called lux. Gleny and Procter (1992) have suggested that about 500 lux is recommended for office work. The requirement in household could be slightly lower.

1.4.9 Petroleum products

In general, two petroleum products --kerosene and diesel -- are used in rural areas, if available. In some rural areas, kerosene is also used for cooking. Kerosene could be an energy option to meet lighting and cooking energy demands. Diesel is generally used to run irrigation pumps (Chambers et al. 1989), grain processing units, tractors, and for electricity generation.

1.5 Energy Consumption Pattern

As shown in Figure 1.1, the main end-uses of energy sources in rural households are cooking, preparing feed for livestock, lighting, space heating, food processing, water heating, and using appliances. However, some end-uses like space heating and water heating depend upon the geographical location of the rural areas (Bhatia 1988, Best 1992). In the following sections, major end-uses in a typical rural area are discussed.

1.5.1 Cooking

Both human food cooking and livestock feed cooking are important in rural households. Cooking requires about 50% to 90% of the total household energy and is the major end-use activity[1]. The main types of cooking stoves used in rural areas

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[1] Zhu et al. (1983), Chirarattananon (1984), Munasinghe (1985), Sathaye and Meyers (1985), Leach (1988), Sathaye and Tyler (1991), Best (1992), Mwandosya

are stone stoves, tripods, traditional mud stoves, iron sheet stoves, and efficient fuelwood stoves (Foley et al. 1984). The end-use device efficiencies of different types of cooking stoves have been given in Pokharel (1992).

1.5.2 Lighting

Lighting is the second major energy end-use in terms of necessity. Fuelwood in an open stove (Foley et al. 1984), kerosene, biogas, and electricity are the main lighting source in rural areas. An ordinary kerosene lamp produces about 20 lumens (derived from Sharma 1984). As a comparison, an incandescent lamp and fluorescent lamp produce about 12 lumens/watt and 75 lumens per watt (Gleny and Procter 1992), respectively.

1.5.3 Space heating

Space heating is important in areas where the temperature drops considerably in winter or during the night (Foley et al. 1984). The demand for space heating changes with the season and is dependent upon the floor area to be heated (Goldemberg et al. 1987). However, distinguishing between the energy required for heating and cooking might be difficult in some areas, as the stove used for cooking also heats the surrounding area.

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and Luhanga (1994).

1.5.4 Food processing

Making alcohol, beating rice, processing milk, drying of fruits, and making sweetmeats are some of the main food processing activities in rural households. Estimates of fuelwood requirements per unit weight of processed food are given in Table 1.5.

1.5.5 Other household uses

Clothes ironing, water heating, and the use of appliances fall under this end-use category. In rural areas of DCs like Indonesia (Soesastro 1984) and Thailand (Chirarattananon 1984), clothes ironing using charcoal-based press-iron is one of the common activities.

Radios and television (where electricity is available and TV transmission is received) are also used in rural areas. In areas where electricity is not available, dry cell batteries are used in the radios.

Table 1.5 Fuelwood requirements for food processing[1].

Processed product	Fuelwood kg/kg product	Energy MJ/kg product
Beaten rice	1.5 - 3	25-50
Milk products	1.0 - 6	17-100
Sugarcanes Juice products	0.5 - 1	9-17
Sweetmeats	0.5 - 1	9-17
Alcohol	2.0 - 4	33-66
Parboiling rice‡	1.0 - 2	17-33
Juice concentration‡	3.0 - 5	50-84
Fruit drying	5.0 - 8	90-128
Tobacco curing	5.0 - 6	90-100

‡estimate

1.6 Multiobjective Decision Making

Real world problems are multiobjective (Steuer 1986, Janssen 1992) and often conflicting. Decision-making is a process of analysing conflicting objectives and choosing a solution for possible implementation. Therefore, in this process, the decision makers try to influence, bargain or negotiate with each other to arrive at a decision (Blair 1979).

The decision makers are increasingly relying on analytical techniques in decision making (Densham 1991). Multiobjective programming (MOP) methods are

[1] Source: Suwal (1992)

an example of such analytical techniques, which are being increasingly used as components of decision support systems in public and private sectors (Cohon 1978, Eom and Lee 1990, Hwang and Masud 1979, Korhonen et al. 1991).

Applications of MOP in water resources planning are given in Duckstein and Opricovic (1980), Haimes and Allee (1982), and Magnouni and Triechel (1994). A review of the application of MOP methods in facility location is given in Current et al. (1990). Barber (1976) has applied a MOP method to analyse environmental impacts, land use incompatibilities, facility access and energy consumption. Werczberger (1976) has applied a MOP method to evaluate industrial locations in the context of air pollution and economic achievement. Njiti and Sharpe (1994) have used goal programming, a MOP method, to analyse the competing use of land for forest and agriculture in Cameroon.

Siskos et al. (1994) have used a compromise programming approach to model regional agricultural planning in Tunisia by incorporating five objectives-- to maximize gross margin, employment, seasonal labour, and forage production, and to reduce the use of tractors. Their analysis helped to arrive at a suitable development policy specific to the given socioeconomic condition. Bowerman et al. (1994) have applied a MOP method to analyse a school bus routing problem by considering five conflicting objectives -- student miles travelled, number of routes, total bus route length, load balancing, and length balancing. The authors recommend that this type of multiobjective analysis helps in arriving at an economically efficient and politically acceptable solution. Kopsidas (1995) has analysed objectives to minimize the total investment and annual production cost per ton of prepared green olive in an olive factory by using a l_p-metric technique. The author argues that his model reflects the actual practice in green olive producing factories in some European countries.

The use of MOP methods to energy planning would enhance the decision making process (Cohon 1978, Munasinghe and Meier 1993). The objectives to evaluate in such a problem could be cost minimization, reduction in environmental impacts, and an increment in labour and energy supply. A MOP provides an opportunity to assist in energy planning for regulatory and investment purposes. Blair (1979) has used the concept of goal programming for energy facility location in the USA. He has analysed seven different objectives to reflect the views of the decision makers from the government, electric utility, environmental groups, and consumers. Janssen (1992) has applied a MOP method for selecting alternative electricity generation options in the Netherlands. He has analysed seven different fuel options against 15 different environmental criteria.

Multiobjective methods are being increasingly used for policy planning because they avoid a situation where the decision makers have to select a single optimal solution. Also, MOP methods can be used to analyse several non commensurable objectives without having to combine them into a single unit like cost minimization or environmental improvement and this capability has increased the applicability of MOP in real world problems (Cohon 1978).

Janssen (1992) has shown that a decision system using MOP should satisfy three main objectives-- generation of information, generation of alternative solutions, and provision of understanding the structure and the content of the decision problem. The information generation in such a support system could be handled by an information system or by a geographical information system in the spatial context.

The use of multiobjective methods enhances the conflicting views of the decision makers and promotes the selection of an educated solution. With the use of an interactive multiobjective programming method, the decision makers are able to analyse the changes in the solution with a change in their preference to different objective functions.

1.7 Thesis Organization

In this chapter, it was shown that rural energy planning is under-emphasized in many developing countries. Some considerations have been given to falling energy supply capability in the rural areas, but those programs have been *ad-hoc* and the long term implications of such programs have hardly been realized. It was established that by including local participation and by integrating energy programs with other rural development activities, a better rural energy policy could be formed.

In a rural energy system, the household is the major energy consuming sector. Therefore, a slight improvement in the household energy demand situation can make a considerable impact on the total energy supply situation in rural areas.

The recent trend in policy planning encourages the use of hybrid tools like a database program or an information system and multiobjective programming methods to analyse decision problems. Energy planning could also be analysed in the same fashion by integrating costs, environmental concerns, and local concerns. Establishment of such an analysis procedure would promote energy awareness and promote a systematic energy decision making process.

In Chapter 2, the objectives of this dissertation is discussed. The scope of this dissertation and the contributions made by the researcher are also discussed in this chapter.

In Chapter 3, various multiobjective programming methods are reviewed in brief. A particular multiobjective programming method suitable for rural energy analysis is discussed in detail. The applicability of the principles of a geographical information system for the development of a decision support system to analyse rural energy system is also discussed in this chapter.

In Chapter 4, a methodology to obtain energy information from a geographical information system is discussed. The nexus between energy information and MOP for the application is also shown in this chapter.

In Chapter 5, data required for the proposed decision support system are discussed. A case area for the implementation of the support system is presented and the spatial information related to that area is discussed.

Spatial analysis and results are presented in Chapter 6. Energy resource availability, energy consumption patterns and energy balance sheets are also given in this chapter. The resource and energy consumptions are combined to arrive at an energy balance for the study area.

In Chapter 7, the results obtained in Chapter 6 are moulded into a multiobjective model and two different cases are studied. It is shown that the decision makers can explore various solutions and understand the impact of their preferences for one or another objective functions on resource allocation. This is expected to promote more educated energy decision making in the future.

Conclusions and recommendations are presented in Chapter 8. The future research work in this regard is also discussed.

The survey form used during the rapid rural appraisal of the watershed is given in Appendix A. The cost coefficients used in energy variables are discussed in Appendix B and the employment coefficients are discussed in Appendix C. The formulations of objectives and constraints are given in Appendix D.

Chapter 2

OBJECTIVES AND CONTRIBUTIONS

Energy is a necessity for basic human activities. In rural areas, energy requirements are fulfilled mainly by biomass whereas in urban areas nonbiomass energy sources are primarily used. Scarcity of one biomass fuel in the rural areas leads to substitution by other biomass fuels. For example, a scarcity of fuelwood leads to an increased use of crop residues and dung for fuel. These substitutions are possible because biomass sources are collected almost for free and the availability and affordability of other fuels (nonbiomass) is low. If efficient and clean fuels are available and affordable, the scarcity of one fuel leads to its replacement by a higher cost, more efficient, and cleaner fuel (Smith et al. 1994).

Due to varied energy collection and energy consumption patterns, the energy planning process should be different in urban and rural economies. In rural areas, energy planning should focus on the decentralized management of resources, whereas in urban areas, it should involve demand and supply management tools such as energy pricing and the marketing of improved technologies (Pokharel 1992).

The traditional farming system dominates the economic activity in rural areas (Dixon 1990). When the population grows, the crop availability per capita from the rural production declines. The crop availability can be increased by either adopting modern farming system such as using high yield variety seeds and irrigation or land expansion. When the first option is not accessible and not affordable, rural people resort to land expansion by encroaching forests and marginal lands. Such a land expansion for cropping brings about ecological imbalances including a decreased sustainable yield of forests (Sharma 1988) This cycle continues until the environment is severely damaged to cause food and energy crisis in rural areas. This will further degrade the quality of rural life.

2.1 Purpose and Scope

To address a degrading rural energy situation, it is important that the energy planners be equipped with a proper information tool so that energy decisions become more representative of rural areas. In the decision-making process, if the decision makers could be presented with an initial solution to the rural energy problem then reactions could be attracted . If the impact of their reaction could be illustrated, then this would help in the search for a better area specific solution to the rural energy problem.

In this thesis, an effort has been made to propose a methodology to analyse rural energy situations and to reach at a better energy planning decision through an **Integrated Rural Energy Decision Support System (IREDSS).** It is expected that the adoption of the proposed methodology would help the decision makers to visualize the planning area in terms of its energy supply and demand characteristics and to interact and dialogue with one another so that a more informed decision could be reached.

The proposed decision support system (DSS) framework in relation to the national planning process is shown in Figure 2.1. The technical and economic data, for example, system efficiency and costs, are external to the proposed system.

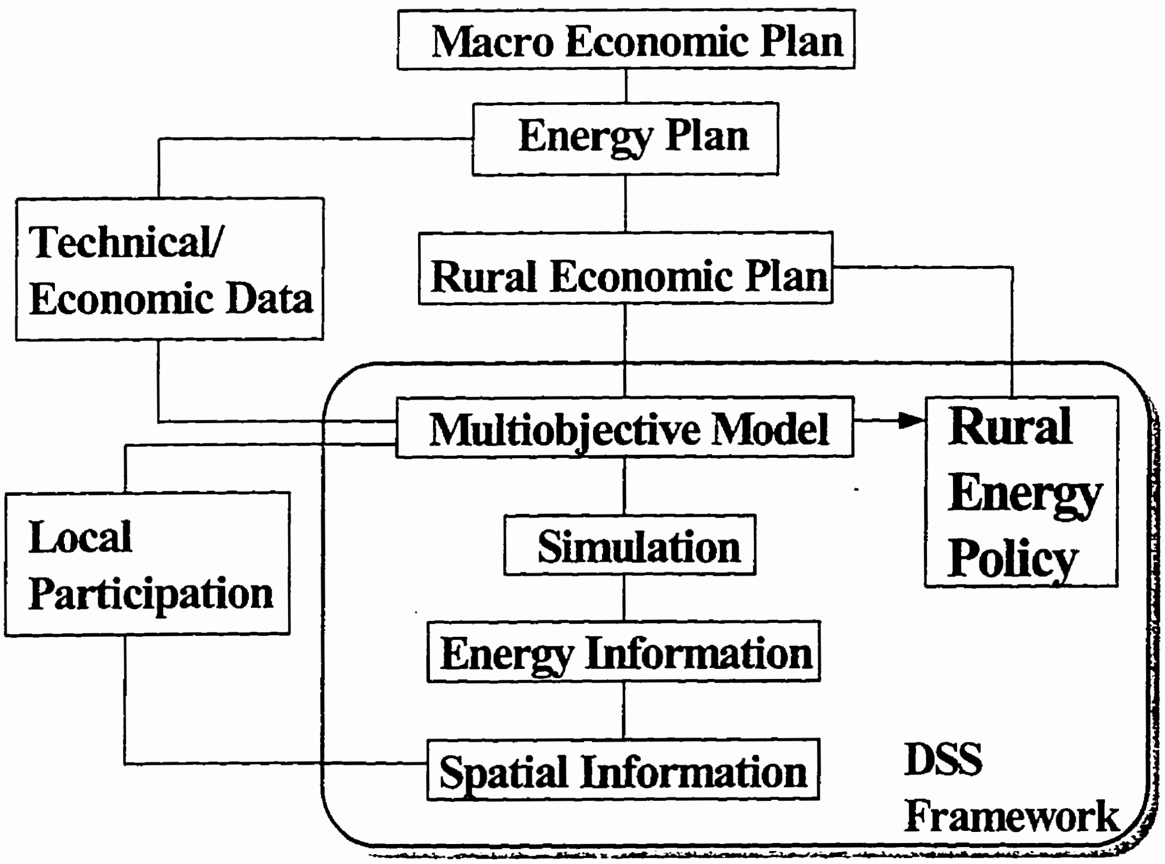

Figure 2.1 Energy planning and decision support framework

Since households consume about 90% of the energy in rural areas and energy use in the households is not efficient (Macualey et al. 1989), this thesis focuses on household energy consumption only.

2.2 Objectives

The objective of this research is to propose an **Integrated Rural Energy Decision Support System** to model rural energy systems. The system exhibits integration in two ways: first, between the objectives of energy planning and the second, between the tools -- namely geographical information systems and multiobjective programming. The specific objectives of the research are given below.

i. Develop a rural energy database model in a suitable geographical information system package;

ii. Integrate the output from the GIS database with a multiobjective programming module for policy analysis;

iii. Implement this system for a study area and study the applicability of the model; and

iv. Recommend possible policy options for the study area.

2.3 Contributions

The researcher has made three contributions in this thesis towards the understanding and analysis for rural energy planning. The first is the use of an iterative multiobjective method. The second contribution is the use of a GIS to calculate energy resources, energy demand, and energy balances for the study area and the third is the development of a decision support system by combining the above tools, which is represented as the shaded area in the triad in Figure 2.2.

Goal programming and preemptive, weight-based multiobjective programming methods have been used in test cases for energy analysis, site selection, and the selection of electricity generation facilities. Predetermination of goals and weights may be difficult in a planning exercise. In this research, it is shown that a suitable iterative MOP technique, that does not require prior specification of goals or weights and allows progressive articulation and

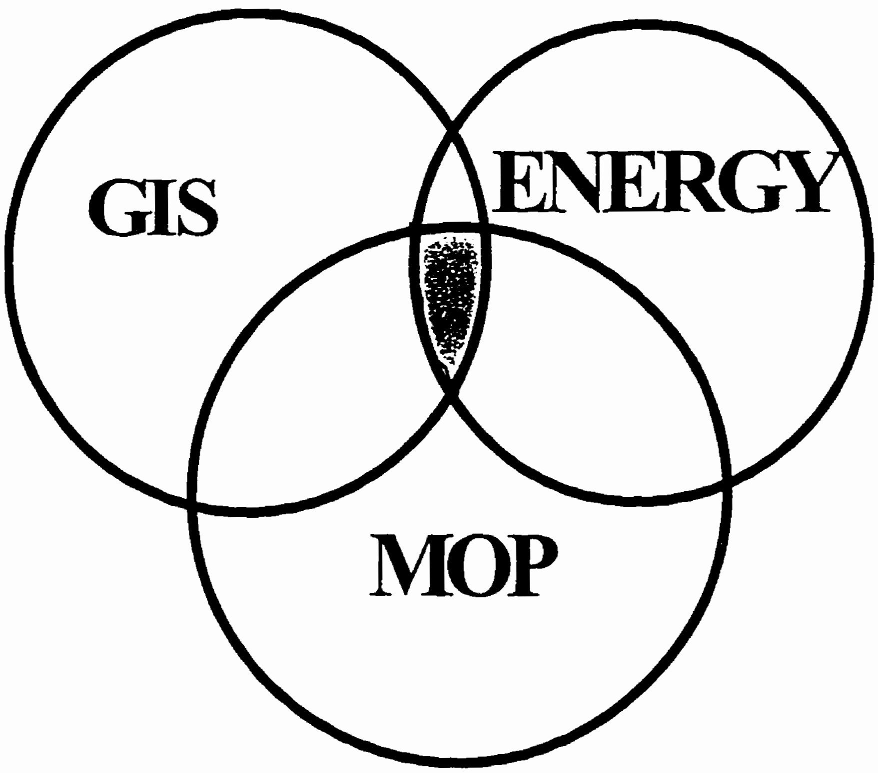

Figure 2.2 Contribution in the thesis

exploration of solutions is the best method for rural energy planning.

It is also shown that the principles of GIS could be applied for energy data storage and analysis. Such an analysis is helpful for assessing the energy balance either for the whole region or for smaller blocks within the study area.

The DSS developed by exchanging inputs and outputs between GIS and MOP is expected to help the decision makers to explore different feasible options or to test whether a particular option is technically feasible. As it will be seen later, this combination allows the development of a better energy related policy.

Chapter 3

TOOLS FOR DECISION SUPPORT

In the proposed decision support system, a geographical information system (GIS) is used for data capture, storage and analysis and a multiobjective programming (MOP) method is used for policy analysis.

In this chapter, various MOP methods are reviewed in brief. A particular MOP method suitable for rural energy planning is identified and reviewed in detail. The chosen MOP method is an iterative method, which combines both features of a decision support system: calculation and decision making.

The applicability of the principles of a geographical information system for the development of the proposed DSS are discussed in this chapter. The literature on the integration between GIS and MOP are also reviewed. The possibility of such an integration for rural energy planning is discussed at the end of the chapter.

3.1 Multiobjective Programming

In general, a multiobjective maximization problem with q objective functions is defined as,

$$Max\,[\,f_i(x)\,],\quad i = 1, \ldots, q$$

$$s.t.\quad x \in X \subset \mathbb{R}^n$$

$$where\ X = \{\, x \mid g_j(x) \le 0,\ j = 1, \ldots, n;\ x_j \ge 0\} \tag{3.1}$$

Various multiobjective methods to solve problem (3.1) are reviewed in Cohon (1978), Zeleny (1982), Steuer (1986), Nijkamp et al. (1990), and Shin and Ravindran (1991). These methods produce solutions that are given specific names depending upon their location and decisions made by the decision makers.

A feasible solution $x^* \in X$ to problem (3.1) is called a *non-inferior* or an *efficient solution*. The corresponding value of the objective f_i is called an *efficient outcome* if there exists no other feasible solution $y \in X$ that satisfies (Cohon and Marks 1975),

$$f_k(x^*) < f_k(y)\ for\ some\ k \subseteq q\ \ and$$

$$f_r(x^*) \le f_r(y)\ for\ r \in \mathbb{R}^n,\ r = 1,2,\ldots k\text{-}1, k\text{+}1, \ldots q. \tag{3.2}$$

In other words, a feasible solution x^* is non-inferior, if there exist no other feasible solutions that will improve the value of one objective function without degrading the value of the other objective functions.

When problem (3.1) is solved using the k^{th} objective only, then an optimum value f_k^0 is obtained. The vector which defines the optimum values for all of the objective functions is called an *ideal solution* or an *utopia point* (Yu 1973). The decision makers would like to be as "close" to the ideal solution as possible, since it would maximize each of their objectives. Different MOP methods provide approaches to arrive at such a "close" solution. A feasible solution that is accepted by the decision makers is called the *satisficing solution* (after Simon 1957).

The concept of the multiobjective programming method is illustrated for a two objective (f_1 and f_2) maximization problem in Figure 3.1. The shaded area in the figure represents the feasible *objective space*. Therefore, any solution that lies within or on the boundary of the objective space is called the *feasible solution*. For example, solutions that are represented by points *a, b, c, d,* d_1 and *e* are the feasible solutions in the given objective space.

The solution which lies outside the feasible objective space, for example the solution represented by point *u*, is an *infeasible solution*. If the solution at point *u* defines the optimum values for both of the objectives, then it is called the ideal solution.

The values of both objective functions at point *d* can be increased simultaneously to point d_1 as seen in Figure 3.1. It is also possible to improve the value of one of the objective functions without decreasing the value of the other, that is, the value of objective function f_1 can be increased from *d* to *c* without decreasing the value of objective function f_2. Similarly, the value of objective function f_2 can be increased from *d* to *e* without decreasing the value of objective function f_1. Solutions represented by *d* and d_1, which lie inside the feasible objective space and provide the opportunity to improve the value of at least one of the objective functions without degrading the values of the other objective functions are called *inferior solutions* or *inefficient solutions*. However, if the decision makers are happy with one of these inferior solutions then it would still be called the satisficing solution (Yu 1985).

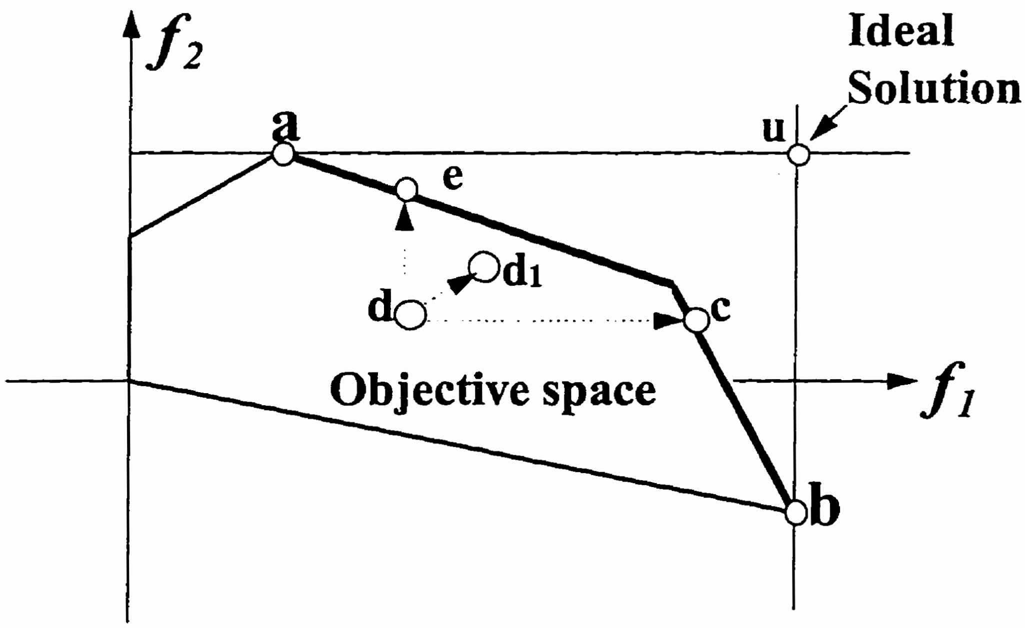

Figure 3.1 Various solutions of a MOP problem

Now let us consider the solutions represented by points *a*, *b*, *c*, and *e*. At these points, an attempt to improve the value of one objective function decreases the value of the other objective function. While moving from *a* to *e*, for example, the value of objective function f_1 increases but the value of objective function f_2 decreases. Similarly, while moving from point *c* to *e*, the value of f_2 increases but the value of f_1 decreases. Therefore, as defined in equation (3.2), the solutions represented by points *a*, *b*, *c*, and *e* are called non-inferior solutions or non-dominated solutions or efficient solutions. The solution set representing the non-inferior solutions is called the *non-inferior set* or the *efficient frontier*. The line segment *ab* in Figure 3.1 is the efficient frontier.

A non-inferior solution can also be a satisficing solution. However, the reverse is not necessarily true. For example, in the goal programming method, goals for each of the objectives are set before the problem is solved. Such goals may be represented by any feasible solution. However, in many cases, the goals may lie within the objective space, for example at point d_1, which is a feasible but inferior solution leaving room for improvement in the objective function values. However, if the decision makers are happy with the solution represented by point d_1, then it is the *satisficing solution* for the given goal programming problem.

The approach in this thesis is to locate a non-inferior solution, which promotes the understanding of *tradeoffs* among the objective functions being analysed. The non-inferior solution generated by a multiobjective method is called the *compromise solution*. Different multiobjective methods may lead to different sets of compromise solutions. If the decision makers choose a particular compromise solution for implementation, for example the solution represented by point *c*, then it is referred to as the *best compromise solution*.

3.2 MOP Solution Techniques

Multiobjective programming techniques can be broadly classified as generating technique and preference-based techniques (Cohon 1978) and are discussed in the following sections. The focus of multiobjective methods using generating techniques is on the generation of many compromise solutions so that the decision makers can choose one of these solutions as the best compromise solution. Conversely, in preference based techniques, the decision makers are required to articulate their preferences for different objective functions. Such articulation could be done once during the formulation of the MOP problem or progressively during the process of solution generation.

3.2.1 Generating techniques

The two common multiobjective methods that use generating techniques are the simple additive weighing (SAW) method and the constraint method. In the simple additive weighing method, strictly positive weights are attached to the objective functions. Then all the objectives are added together. This reduces the MOP problem into a single objective programming (SOP) problem, which is solved with a suitable SOP method to generate a *non-inferior solution*. The non-inferior solution set is generated by repeatedly solving the problem with other weights on the objective functions. These solutions are presented to the decision makers for the selection of the best compromise solution.

In the constraint method, the optimum value of one of the objectives is searched for by treating the other objective functions as constraints. However, all of the objectives treated as constraints should be binding at the optimal solution to the constrained problem (Cohon 1978). The set of solutions thus generated is presented to the decision makers for the selection of the best compromise solution.

The set of non-inferior solutions generated from these methods provides a basis for selecting the best compromise solution. However, as the number of objective functions and decision variables increases, the number of compromise solutions also increases (Cohon and Marks 1975), which might make decision making intractable.

3.2.2 Preference-based techniques

The multiobjective programming methods using preference-based techniques are either non-iterative or iterative. These methods are less computationally intensive than methods using generating techniques because the specification of preferences allows the bulk of non-inferior solutions to be ignored (Cohon 1978). In the non-iterative, preference-based methods such as the goal programming method, the lexicographic method, and the utility function method, preemptive preferences on the objective functions are required before solving the MOP problem.

In the iterative methods, however, preferences on the MOP problem are progressively articulated by the decision makers. Therefore, these methods can promote negotiation and dialogue among the decision makers and lead to the generation of a better solution for the given decision-making environment. Examples of some preference-based iterative techniques include: interactive goal programming (Lee 1972), local approximation of utility functions (Geoffrion et al. 1972), sequential MOP (Monarchi et al. 1973), and the STEP-method (Benayoun et al. 1971).

The interactive goal programming (IGP) method proposed by Lee (1972) starts with finding a solution based on predefined criteria. If this solution is not satisfactory to the decision makers, then the tradeoff information associated with achieved goals is used to modify the original problem. This tradeoff information is obtained from the final tableau of the goal programming simplex method. The modified problem is solved using the goal programming method. This procedure is repeated until a solution that satisfies the decision makers is found. Like the goal programming method, IGP may also produce an inferior solution.

The interactive method presented by Geoffrion et al. (1972) requires local approximation of a utility function. This method uses the Frank-Wolfe algorithm for steepest ascent (or descent) from the initial feasible solution (to be specified by the decision makers) to obtain a compromise solution. To find the steepest direction of movement, the algorithm uses the marginal rate of substitutions among the objectives. The marginal rate of substitutions provide information to find a direction that will improve the utility function. The information obtained for the direction is then used to obtain the step size for the movement and the problem is reformulated and solved to get the utility function. The decision makers can choose a solution with an improved utility function obtained in subsequent calculations. The algorithm is stopped when there is no change in the direction and the step size. That is, when the utility function does not change from the previous one. The interaction with the decision makers makes this method better than the utility function methods, however, this method assumes that the decision makers can articulate the preferences exactly. In many cases, the approximation of a utility function is either difficult or impossible (Dyer 1972).

The sequential MOP (SEMOPS) technique presented by Monarchi et al. (1973) is a nonlinear iterative method and relies on the minimization of deviations from goals. In this method, goals are specified as intervals rather than fixed points. In each iteration, some of the objectives are bounded by goals and are treated as constraints. The MOP problem is then solved to generate a non-inferior solution. This procedure is repeated until the decision makers are satisfied with a solution. However, as mentioned before, the specification of some goal intervals in this method might yield an inferior solution.

The STEP-method proposed by Benayoun et al. (1971) is suitable for analysing linear objectives and constraints. In this method, optimum values are obtained first through the individual optimization of objectives subject to the constraints, thus defining the *ideal point*. In the STEP-method, this information on optimum values is used to calculate weights to be assigned to each of the objectives. The problem then is to minimize the "distance" between the *ideal solution* and a solution in the *non-inferior solution set*. The solution so obtained is forwarded to the decision makers, who may adopt the solution as their best compromise solution. Otherwise, the values of one or more objective functions are changed and the problem is solved to explore other possible solutions. Such a solution exploration process allows the decision makers to understand the impact of their preferences on the objectives (Johnson and Loucks 1980, Janssen 1992) and promotes the formulation of a better policy.

None of the MOP methods are suitable for all applications. Therefore, selection of a particular MOP tool for a particular application is a difficult task (Duckstein 1982, Janssen 1992, Antunes et al. 1994). The choice of a particular method depends upon the type of available information, the decision making environment, and the expected output.

Methods to compare different multiobjective methods for an application are given in Duckstein (1982), and Steuer (1986). Steuer (1986) suggests that 16 questions should be answered and analysed before choosing a method. The questions range from computer sophistication to CPU time required to process the algorithm.

Duckstein (1982) has given 28 criteria divided in the following groups to rank 17 preference-based methods of which six are iterative.

i. Mathematical programming versus decision analysis;

ii. Quantitative versus qualitative criteria;

iii. Timing of reference determination (prior, post, progressive); and

iv. methods of comparing alternatives.

However, not all the criteria can be applied to all applications. The comparison of six iterative methods indicated that only the STEP-method allows a direct comparison between the alternate solutions. Such a direct comparison of solutions produced with different preference levels would help to make the decision makers aware of the impact a particular preference for an objective function has on the compromise solution. For these reasons, the STEP-method reflects the public decision making process better. Moreover, the STEP-method is simpler to understand and to implement, and it requires fewer iterations in obtaining the required solution (Cohon and Marks 1975). However, Steuer (1986) suggests that the STEP-Method may not be able to locate a solution. This situation could be avoided by relaxing more than one objective at a time and iteratively going through the original problem. The algorithm can be implemented in single objective linear programming packages such as GAMS®(General Algebraic Modelling System) and LINDO® (Linear Discrete Optimization). Therefore, this method is used for rural energy planning in this thesis.

3.3 The STEP-Method

As shown in Figure 3.2, the first step in the STEP-method is to formulate conflicting objectives and constraints. Then at iteration $t=0$ (where $t = 0, 1, 2, \ldots, q$), each of the objectives is individually optimized. This would generate an ideal solution (that is, the vector of all individually optimized solutions) for the formulated problem.

Let the optimized solution of the i^{th} objective be called x_i^o and the optimum value of the objective function be called f_i^o. These optimum solutions are used to generate a pay-off matrix. The payoff matrix for the maximization of the MOP

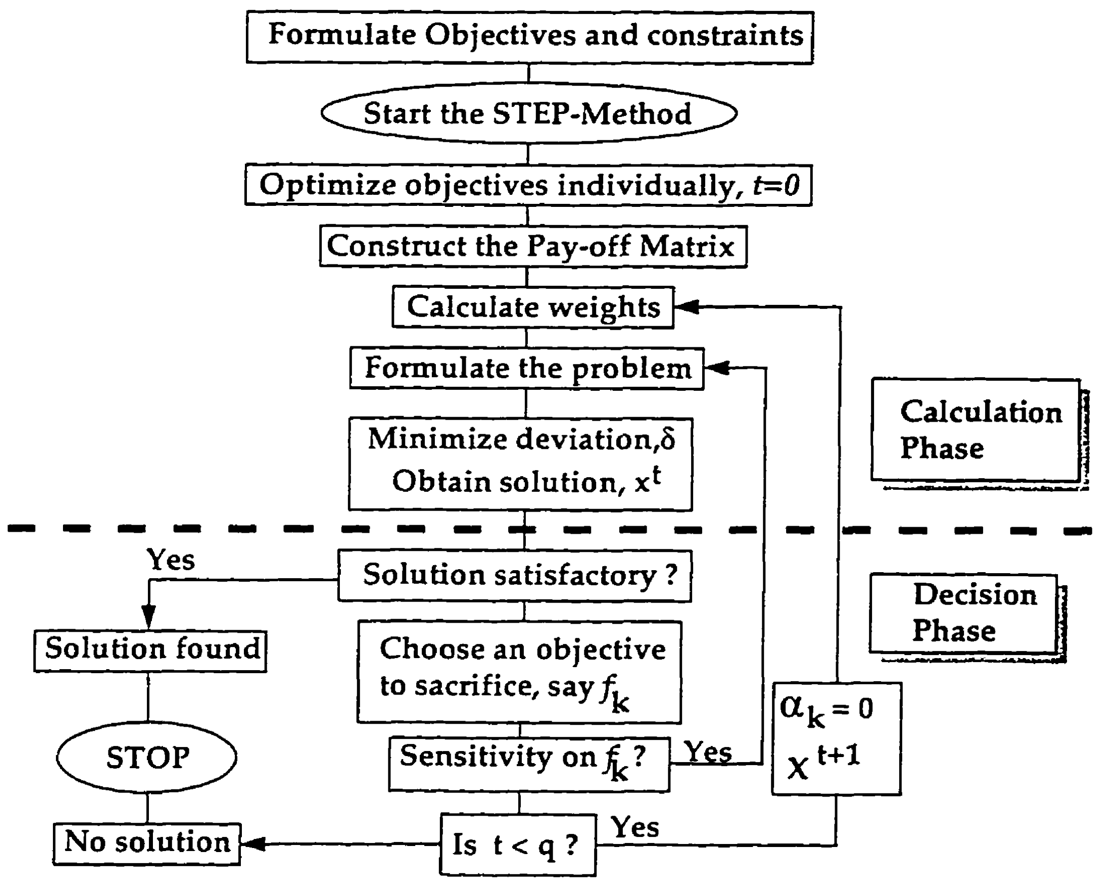

Figure 3.2 Flow chart for the STEP-method

problem (3.1) is shown in Table 3.1. The i^{th} row in the payoff matrix is obtained by substituting the solution x_i^o into each of the objective functions. For a maximization problem, the first element in the first objective column f_1 is the maximum value of f_1 (that is, $f_1^o = f_1^{max}$). Let f_1^{min} represent the minimum value in the same column.

Table 3.1 Construction of the Payoff Matrix

Solution that optimizes *ith* objective.	Value of *ith* objective f_1	..	f_k	..	f_q
x_1^o	$f_1^o(x_1^o)$	..	$f_k(x_1^o)$	..	$f_q(x_1^o)$
x_2^o	$f_1(x_2^o)$	..	$f_k(x_2^o)$	..	$f_q(x_2^o)$
.	..	..	..	..	..
x_k^o	$f_1(x_k^o)$	..	$f_k^o(x_k^o)$	..	$f_q(x_k^o)$
.	..	..	..	..	..
x_q^o	$f_1(x_q^o)$	..	$f_k(x_q^o)$	..	$f_q^o(x_q^o)$

The maximum and minimum values obtained from an objective column are first substituted into (3.3) to obtain values for 'scoping variables' α_i ($i= 1,2,....., q$). Then values for each scoping variable is used in equation (3.4) to calculate corresponding weights π_i ($i = 1,2,....., q$) for each of the objective functions being analysed. The weights π_is obtained in the STEP-method are effective only in one iteration.

$$\alpha_i = \begin{cases} \left[\dfrac{f_i^{max} - f_i^{min}}{f_i^{max}}\right] * (\Sigma_j a_{ij}^2)^{-1/2}, \text{ when } f_i^{max} > 0 \\ \left[\dfrac{f_i^{min} - f_i^{max}}{f_i^{min}}\right] * (\Sigma_j a_{ij}^2)^{-1/2}, \text{ otherwise.} \end{cases} \quad \forall i \qquad (3.3)$$

and $$\pi_i = \alpha_i / \Sigma_i \alpha_i, \quad \forall i \qquad (3.4)$$

In equation (3.3), a_{ij} refers to the coefficient of the j^{th} decision variable in the i^{th} objective. Benayoun et al. (1971) suggest that the term with the objective coefficients a_{ij} in equation (3.3) normalizes the values taken by the objective function.

When the difference between the maximum and minimum value for an objective is small, the weight to be assigned to that objective also becomes small. This means that there is not much room to manoeuvre on the value of the particular objective and it is not a good objective to sacrifice in order to obtain changes in the other objectives (Benayoun et al. 1971).

The weights calculated using equation (3.4) are associated with their corresponding objectives to obtain the non inferior solution closest to the ideal solution. The equation shown below is developed for problem (3.1).

$$\begin{aligned} &\textit{Minimize } \delta \\ &\textit{subject to } \; x \in X^t \\ &\delta \geq \pi_i * [f_i^o - f_i] \qquad \forall i \end{aligned} \tag{3.5}$$

In the above equation, δ is the deviation between the *ideal solution* and the *non-inferior solution* in each iteration *t*. In the first iteration, $X^1 = X$. Let the solution obtained in iteration t be called x^t and the values of the objective functions corresponding to this solution be called f_i^t.

The values of the objective functions and the solution x^t obtained by solving equation (3.5) are presented to the decision makers, who, if satisfied with it, accept it as *the best compromise solution* and stop the STEP-method algorithm. Otherwise, the decision makers choose the value of an objective $f_k^t \in f_i^t$ to sacrifice. The value of f_k^t is altered by a value Δf_k chosen by the decision makers. If Δf_k is reduced from the current solution f_k^t, then the new decision space X^{t+1} in iteration $t = t+1$ is formulated as shown in equation (3.6).

$$X^{t+1} = \begin{cases} X^t & \\ f_k \geq f_k^t - \Delta f_k & \\ f_r \geq f_r^t & \forall r = 1,2,..,k-1,k+1,..,q \end{cases} \tag{3.6}$$

For this new problem α_k is taken as zero, therefore, $\pi_k = 0$. That is, the solution for the k^{th} objective is fixed in this iteration. However, the values of other scoping variables remains the same as in the first iteration. Then the weights π_rs for the remaining objectives are computed using the equation (3.4). The modified problem incorporating (3.6) is then solved to obtain a new compromise solution. If the decision makers are not satisfied with the new solution, then this procedure is repeated until the number of iterations equals the number of objectives. Sensitivity analysis could be done either by setting a target for f_k or by setting different values of Δf_k and then solving the modified problem repeatedly. This type of sensitivity analysis is called the *standard sensitivity analysis* (Benayoun et al. 1971, Hwang and Masud 1979).

If the best compromise solution for the MOP problem is not found in $t \leq q$ iterations, it is concluded that the best compromise solution does not exist (Cohon and Marks 1975), and the STEP-method algorithm is terminated. This situation can arise when the decision makers do not want to alter their position. Then obviously, there would be no solution. However, such a situation could be avoided by doing standard sensitivity analysis or by choosing to relax more than one objective in one iteration.

The STEP-method has been applied to analyse capacity planning and resource allocation in a department of the University of Saabruecken, Germany, by Dinkelbach and Isermann (1980). It has also been applied for water resources planning by Loucks (1977) and Johnson and Loucks (1980). The authors argue that the STEP-method is suitable for public decision making. In the water resources application, Johnson and Loucks (1980) used computer graphics to illustrate solutions at each iteration of the STEP-method. The authors suggest that the use of computer graphics enhances the understanding of alternate solutions and promotes a closer interaction among the decision makers.

Antunes et al. (1992) have developed a software package to evaluate multiobjective programming problem. The package, developed in Apple Macintosh®, implements the STEP-method as one of its modules. The most recent version of the software can analyse three objectives, 64 constraints, and 116 variables.

Korhonnen (1992) and Zionts (1992) argue that future development in MOP should be on its applicability in a decision support system (DSS) framework. If computer graphics are included in a DSS then the understanding of the alternatives would be improved (Dikson et al. 1986, Tufte 1990, Korhonnen 1992, and Zoints 1992). Eom and Lee (1990) found that current decision support systems use multiobjective-based models and computer graphics more than the simulation models.

3.4 Geographical Information System

A geographical information system (GIS), in its simplest form, can be described as location specific information. In a GIS, geographical data in maps, slides, and photographs provide references to the non geographical data (called attributes).

Geographical data are represented as points, lines, and polygons. A point represents a location. A line feature is a combination of arcs and nodes and represents features like roads and streams. A polygon represents an area enclosed by lines.

Geographical data are stored either in vector format or raster format. Remote sensing data or scanned data are, for example, available in raster format, in which the attribute and position of a line, point, or area are represented by a grid cell(s), their size depending upon the available resolution of the data or the required accuracy. Normally, the smaller the grid cell the better the accuracy. In vector format, the positions of points, lines, and polygon can be more precisely located because the coordinates are assumed to be continuous. These formats can be interchanged with a suitable software.

Geographical information for an area may include its geographical boundary, stream networks, paths, trails, roads, and other features of interest to the analyst. The disaggregated level of information for a rural area is shown in Figure 3.3. The relevant information on rural areas can be disaggregated to various *information layers* such as population, land use, solar and wind regimes, temperature, stream networks, and in some cases political preferences.

In a GIS, importance is laid on the geographical element and its attributes and this is the key feature that distinguishes a GIS from other information systems

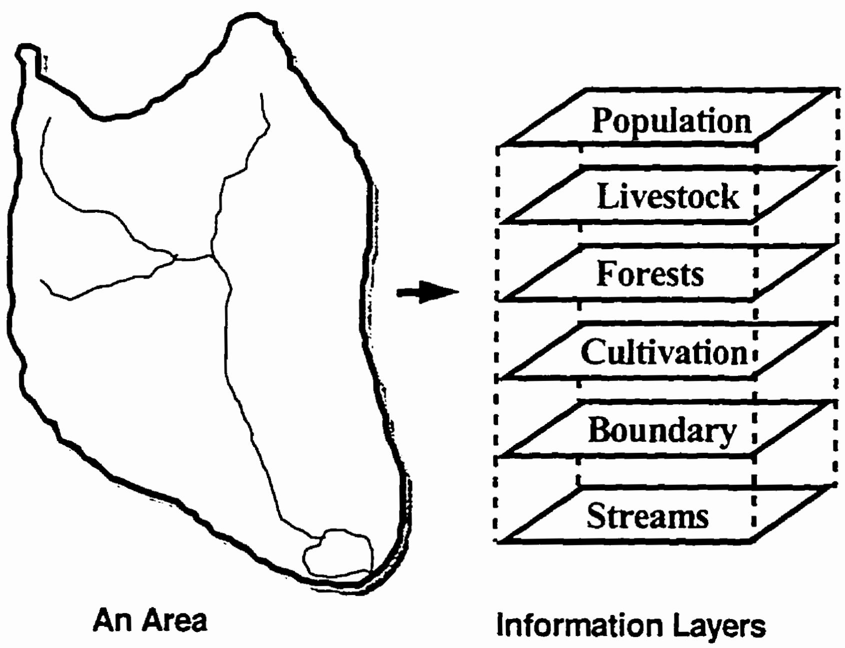

Figure 3.3 Spatial information on an area

(Maguire, Goodchild and Rhind 1991) such as computer cartography, remote sensing, computer aided design, and database management system.

A GIS integrates different geo-referenced data into a common reference system and allows spatial query of complex, spatial and non spatial data sets, to provide both qualitative and quantitative information required by the user. This concept of a GIS has been implemented to develop many generic software packages, some of which are discussed in Castle (1993) and Peuquet and Marble (1990).

In a GIS application, the information layers concerning one specific location are processed or overlaid. Such an application should provide answers to basic questions with regard to mapping, management, suitability, and simulation (Berry 1994a). The answers to these questions help to investigate the interrelationship among various data. Lanfear (1989) suggests that the use of a GIS contributes to a new level of understanding of the issues. This significance is reflected by the increasing use of GIS in fields like water resource management, watershed management, forestry management, health care planning, tourism planning, transportation planning, landslide hazard management, and environmental impact analysis. Many of such applications can be seen in Schoolmaster and Marr (1992), SMRS (1994), Adamus and Begman (1995), Thapa and Weber (1995), Rowbotham (1995), ICIMOD (1992 and 1995), Tiwari (1995), and UNU/IIST (1996). A list of GIS applications in developing countries has been given by Yeh (1991). However, GIS applications in developing countries have limited access and the information generated by the applications are not widely disseminated (Yeh 1996). Many of these GIS applications are limited to database management and simple structural queries.

3.5 GIS and Decision Support System

The decision process transforms the inputs as individuals and information through a model (or method) so that a decision can be obtained. Therefore, the quality of a decision depends upon the inputs and the methods adopted for analysis (Janssen 1992).

If the result obtained from a spatial model could be processed by using an external model, as shown in Figure 3.4, then the combination of spatial and external models acts as a spatial decision support system, SDSS (Densham 1991) or a decision support system (DSS) for a particular application (Fedra and Reitsma 1990, Burrough 1992, Engel et al. 1992, Johnson 1990, Kontoes et al. 1993, Rhind 1992, van der Meulen 1992). Such an integration also helps the decision makers to solve problems in less time mainly for three reasons -- provision of interactive colour

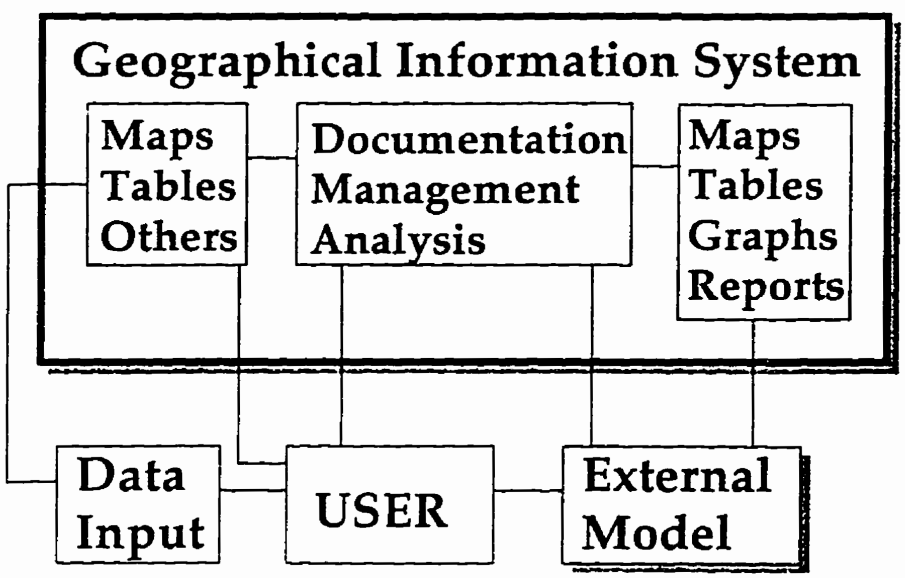

Figure 3.4 Spatial decision support system

displays, the efficiency in displaying maps, and a better grasp of problems because of a better display with a GIS (Crossland et al. 1995). The decision makers may resort to a judgemental decision too, avoiding the solution provided by the system, however, the type of integration and interaction provided by a DSS would be of great value in preparing such decisions (Kreglewski et al. 1991).

Decision making involves the analysis of conflicting objectives, therefore, the effectiveness of such a DSS could be increased by analysing the GIS output with a MOP model (Wierzbicki 1983). Such a DSS should be easy to learn and should provide meaningful information (Loucks 1995). A DSS allows iterative use of the framework. Repeated inputs from the decision makers can alleviate the practice of forcing the problem into a solvable form (Vertinsky et al. 1994). The inputs may suggest that some choices of the decision makers may not be feasible under the given decision making circumstances.

A DSS allows the decision makers to pose different queries to solve unstructured problems (Bracken and Webster 1989). Since MOP is only a mathematical tool, with no database management system attached to it and a GIS is a database management system, the integration of the two could result in an interactive decision support system for an application like energy planning.

The recent work into integrating a MOP method with a GIS to develop a DSS can be seen in Carver (1991), Janssen and Herwijen (1991), Diamond and Wright

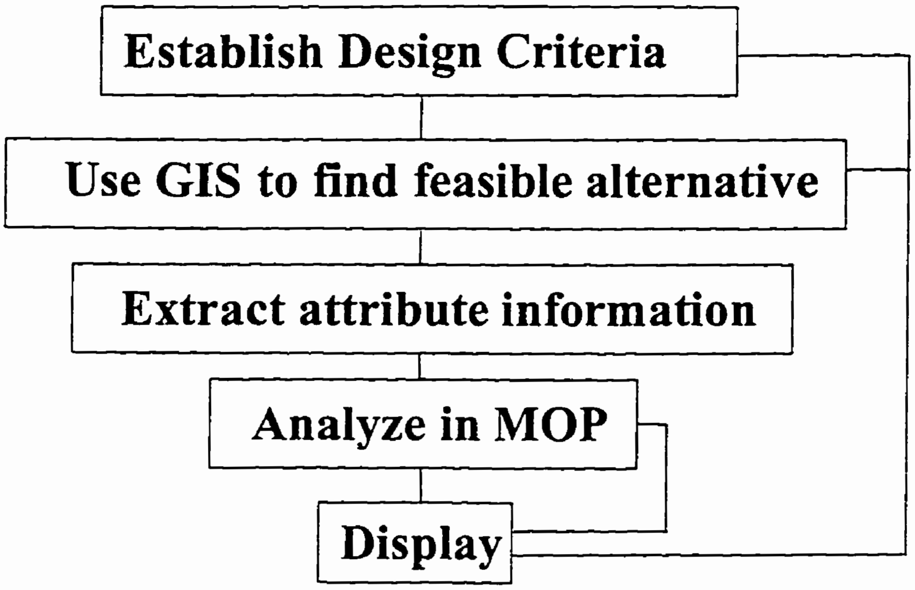

Figure 3.5 A typical MOP-GIS linkage

(1988), Jankowski and Richard (1994), and Stansbury et al. (1991). The type of GIS-MOP integration currently being implemented is shown in Figure 3.5.

Stansbury et al. (1991) have integrated a water model, a GIS, and a MOP method to evaluate alternatives for water supply. The water model determines the hydrological impacts of the alternatives and the GIS provides an estimate of the impacts of alternatives as for economic, social, and ecological factors. These impacts are assigned scores and fed to the MOP module, which presents the best alternative.

In Diamond and Wright (1988), a GIS is integrated with a rule-based system (RBS) and a MOP method for land resources planning and management. The RBS selects weights for different factors and identifies an appropriate functional form for combining the maps. The MOP problem with objectives for cost, area, shape, suitability, and tradeoff between solutions is used to select the best alternate solution in this application.

Carver (1991) has integrated a GIS with a MOP method for disposal of radioactive waste in the United Kingdom. In his application, alternative sites produced by a GIS overlay were weighed based on their perceived level of importance to identify a smaller number of compromise alternatives. The author has recommended further research on such an integration for other applications but warns that the technique bias and preference bias could lead to a completely different set of results.

A GIS-based land suitability analysis and MOP are integrated by Jankowski and Richard (1994) to select water supply routes. The authors view that their approach produces a better decision, as the spatial analysis involves an entire set of criteria rather than a set of only pressing criteria.

3.6 Energy Policy Formulation

Blair (1979) indicates that an energy policy should be judged by assessing scientific, technological, economic, environmental, and societal feasibility. The inclusion of scientific, technological, and economic factors in energy planning were mentioned in Chapter 1. Environmental and societal factors are being considered only recently. Environmental factors deal with the impact of technology on the quality of the environment. Societal factors, for example, willingness to accept a policy, generally deal with human perception, which could be improved by involving the local beneficiaries into the decision-making process. However, it has been observed that when the benefits from a program are tangible, visible, and immediate, then the program is embraced by the local beneficiaries (DSCWM 1990). The success of a program due to local participation is also highlighted in Periera (1983).

There are two aspects of energy planning. When the decision makers are not aware of the local situations as to the resource use pattern, then there is a very high chance of culminating conflicts in energy decision making and implementation. Therefore, it is important that the energy decision support system should be simple for communication and it should clearly present the energy situation. The second aspect is the objectivity of energy planning. For example, energy problems may not be the (first) priority of the people. They might be more interested in resolving other issues like employment and environment. For example, in a study conducted by DSCWM (1990), the list for improvement included trails, water source protection, canal improvement, conservation plantation, and gully control. Therefore, energy programs should show that the identified issues are being addressed to the extent possible.

Energy analysis is spatial in nature as energy consumption and resources are linked to a specific location. The information on forests, cultivated land, solar radiation, water availability, stream networks, elevation, temperature, rainfall pattern, and population could be used to study the energy resources potential. Similarly, the information on population and energy consumption attributes could be used to study the energy demand in a planning area. The energy balance sheet for the area can be prepared by overlaying the information on energy resources and energy demand. The energy balance sheet indicates the energy surplus or deficit blocks in an area. Identification of such pockets can help the decision makers to choose the best energy alternative or energy intervention programs, through MOP analysis, targeted either to those pockets or to the whole planning area.

One of the earliest recommendations to establish an "indicative" energy system domain came from Morse et al. (1984). Such an analysis could be performed in an ecological area rather than an administrative area because a rural energy system is also a manifestation of the ecosystem. DSCWM (1990) views that the use of thematic maps on a particular area leads to the development of a better management plan. Ramani (1988) views that planning at the village level may ignore the structure of the local government from where a part of resources may have to be extracted. Therefore, as suggested by Conway (1987) and Sinha et al. (1994), analysing the energy system on a cluster of villages (or on a watershed level) would be more effective. Watson and Wadsworth (1996) have also used a river catchment (watershed) for their research on the development of a rural policy formulation system. The result so obtained can provide location specific guidelines for different parts of administrative areas (Morse et al. 1984).

The integration of a GIS and a MOP method enhances the understanding of a rural energy situation, promotes an interactive decision-making process, and helps in formulating energy policies. In such a system, a GIS would be helpful in managing data and the MOP method would be helpful in analysing the policy alternatives.

When a problem is forwarded for analysis in different conditions, for example, short term planning *versus* and long term planning, a different set of decision makers, or decision making at different times, the decision makers will undoubtedly assign different values to the objectives, variables, and the constraints (Densham 1991). Therefore, the decision support system should be flexible enough to incorporate the variations in decision-making environment.

Chapter 4

ANALYSIS METHODOLOGY

The management and planning of energy resources requires an organized decision-making method. Such an approach can help the decision makers to tackle different situations during decision making. Checkland and Scholes (1990) suggest that in such a situation, a soft systems methodology, based on the systems approach, which promotes a clear problem definition, is very useful. Odum and Odum (1976) have shown that such an approach could be applied to various fields including energy analysis. The systems approach includes an iterative process of systems analysis and decision making. The systems analysis part includes identification of the problem, evaluation of information, alternate solution generation, and solution evaluation. This process could be largely handled by the geographical information system. The decision making process includes the selection of a solution, and its implementation and evaluation. This process could largely be handled by the multiobjective programming methodology. Such an approach, therefore, directs the decision makers to interactively seek a workable solution in the given decision-making environment.

As shown in two models below-- spatial and multiobjective-- this research follows a systems approach in the analysis and selection of a particular energy policy within the physical boundary of a planning area and the conceptual boundary defined by energy related resources -- human and livestock population, land use pattern, hydrology consideration, solar radiation and wind velocity, and technological choice.

4.1 The Spatial Model

To develop the spatial model, the information on spatial distribution, such as land use and resources, should be collected first. This information might be available in thematic maps or in digitized form. If the information is available in thematic maps, then the maps need to be digitized into information layers. However, if the digitized information is available, then the information might have to be edited to process data into different information layers. Recent aerial photographs, if available, can aid in updating the land use information. If such information is not available, then a base map or an administrative map should be digitized first and a rural appraisal should be conducted to consult the local people for approximating the availability of different resources and demands. The local people are best informed as to the availability of resources and "outsiders," as termed by Chambers

(1993) for researchers, should learn from them.

When the basic information is ready, attribute information like forest types and crown cover densities, should be added to obtain information layers (or *coverages*) in the spatial database. These coverages are either reclassified or added with entities to arrive at energy coverages. The collection of these coverages, with their capability for query and other analysis has been termed the *Energy Information System* (EIS) in this thesis. The spatial model that considers local energy sources for the proposed DSS is shown in Figure 4.1 and an expected data dictionary is given in Table 4.1.

Six local energy resources coverages are considered here. Information in these coverages can be processed to arrive at biomass and nonbiomass resource modules. A biomass module consists of information on fuelwood, crop residues, and manure (and biogas) and a nonbiomass module consists information on solar, micro hydro, and wind energy potential in the area. Kerosene and grid electricity are also used in the watershed, but they have to be imported into the area. As shown later, two additional energy consumption layers are created to show electricity and kerosene consumption in the watershed.

The energy demand coverage is created by overlaying the boundary and population coverages and then adding energy consumption attributes. These attributes are either processed as a proxy value obtained from nearby similar

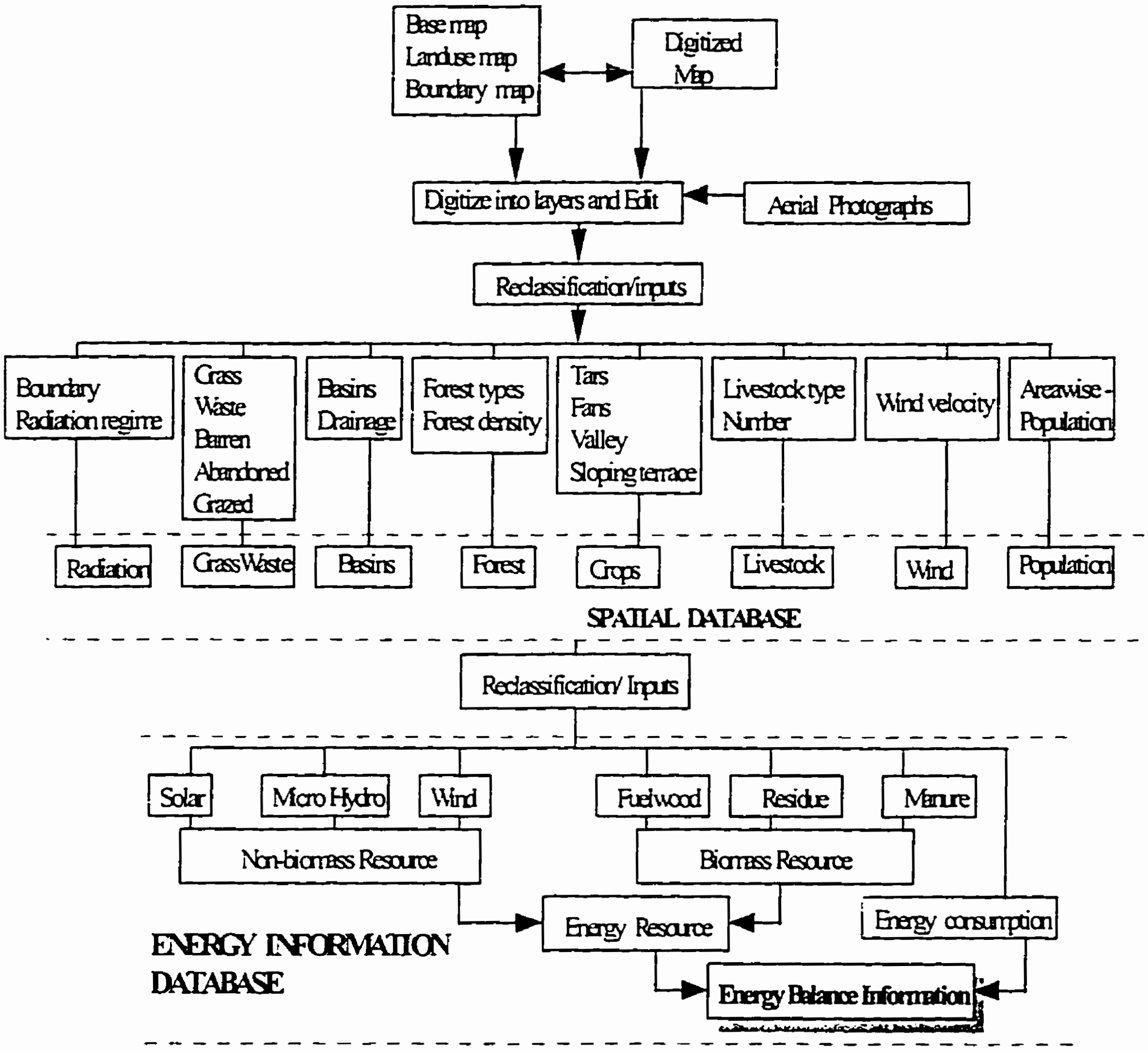

Figure 4.1 Energy information system model

geographical locations or collected by rapid appraisal (RA). The area of interest for the energy balance information should be provided by the decision makers. It could be either village development councils, blocks, or districts or a sub watershed within the planning area. A typical configuration of these areas is given in Figure 4.2.

Table 4.1 Data dictionary for the spatial model

Coverage Name	Feature	Item	Item Category
Energy Resource	Polygon	Energy resource	Fuelwood Crop residues Livestock dung Biogas potential Hydropower potential Solar energy potential Wind energy potential
Energy Demand	Polygon	Energy demand	Human population Energy demand by end-use Energy demand by fuel End-use devices Total energy demand
Energy Balance	Polygon	Energy balance	Total energy balance Energy balance by fuel type Energy balance by end-use Energy balance in VDCs

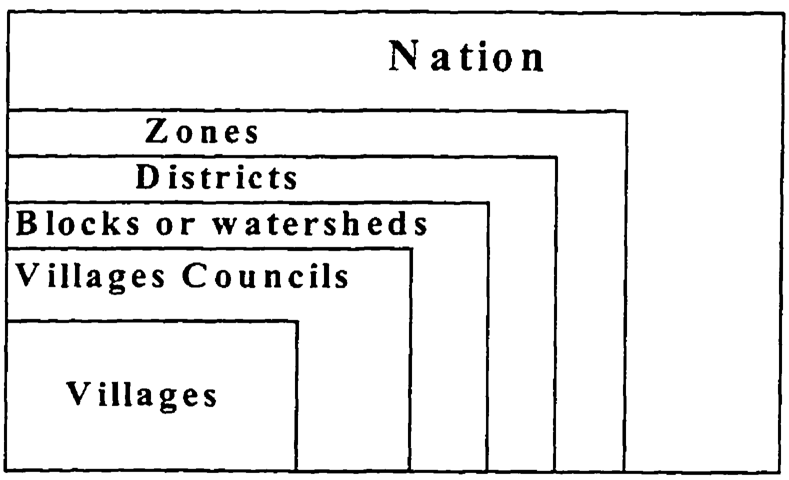

Figure 4.2 Typical disaggregation of boundaries

4.2 The Multiobjective Model

The set of objectives that can be considered for planning in different disciplines such as production, forestry, and staff allocation is given in Steuer (1986). The author suggests that maximization of sustainable yields of forest, visitor days of dispersed recreation, wildlife habitat and months of grazing, and minimization of budget allocation could be the conflicting objectives for forestry management.

Chetty and Subramanian (1988) give three energy planning objectives as minimization of energy costs and use of non-local energy resources, and maximization of system efficiency. In addition, Ramanathan and Ganesh (1993 and 1994) also consider maximization of employment generation, use of local energy resources, and minimization of pollutant emission. However, minimization of non-local resources and maximization of local energy resources may not be conflicting objectives.

General objectives considered in an energy planning exercise are discussed below. The parameters used to define the multiobjective model are assumed to be linear and it is also assumed that the chosen policy could be implemented. There are two approaches to ensure the implementation of the proposed policy: *top-down* and *bottom-up*. In the top-down (or forward) approach, it is assumed that considerable thought has been given to the formulation of objectives. In the bottom-up (backward) approach, it is assumed that only those solutions which are implementable should be chosen. The backward approach is useful if the consequences of a planning policy could be foreseen or could be compared with similar projects near the planning area.

To formulate the multiobjective model for energy planning, let the subscript of planning variables used in Chapter 3 be ***redefined*** here. Let x_{ijkp} be the variable to be used for energy analysis. This variable represents the secondary energy (for example, the gigajoule value of one metric ton of fuelwood) to be met by fuel i used in end-use device j for end-use k in area p. If the study area is not disaggregated to sub areas, then the fourth suffix p is omitted. Table 4.2 shows the combination of ijk used in the analysis.

The list presented in Table 4.2 is not exhaustive but represents major fuels, end-use devices, and end-uses in the rural areas. As shown in Table 4.2, not all of the fuels can be used in all of the listed devices. For example, fuelwood can be burnt in tripod stoves, traditional stoves, or efficient fuelwood stoves for cooking, feed preparation, space heating, food processing, and water heating. As another example, biogas cannot be fed into a fuelwood stove. In these cases, the coefficient of the energy variables is set to zero.

The units of measurement for secondary energy is taken as gigajoules for all energy sources so that energy produced by a fuel could be combined to develop the energy balances. This unit is also adopted by many international agencies to convert the primary units of fuel (such as tons, litre, and kilowatt hours) to a common unit (UN 1987). Other units of measurement could be ton of coal equivalent or ton of oil equivalent. The average conversion factors for these units are given in UN (1987).

Table 4.2 Some possible combinations of *i*, *j*, and *k*.

Fuel, *i*	End-use devices, *j*	End-use, *k*
1 = Fuelwood 2 = Crop residue	1 = Tripod stove 2 = Traditional stove 3 = Efficient fuelwood stove	1 = Cooking 2 = Feed preparation 4 = Space heating 5 = Food processing 6 = Water heating
3 = Dung cakes	1 = Tripod stove 2 = Traditional stove 3 = Efficient fuelwood stove	1 = Cooking 2 = Feed preparation 5 = Food processing 6 = Water heating
4 = Charcoal	4 = Charcoal stove	1 = Cooking 4 = Space heating
	0 = Appliances	7 = Appliances
5 = Kerosene	5 = Kerosene stove	1 = Cooking 2 = Feed preparation 5 = Food processing
	8 = Kerosene lamp	3 = Lighting
6=Hydro, 8 = Solar PV	9 = Electric bulb/Fluorescent	3 = Lighting
9 = Grid electricity	0 = Appliances	7 = Appliances
7 = Biogas	6 = Biogas stove	1 = Cooking 2 = Feed preparation 5 = Food processing 6 = Water heating
	7 = Biogas lamp	3 = Lighting

When energy resources need to be collected and delivered to the users, then the notion of external efficiency becomes important. The external efficiency β_i can be defined as the efficiency of collection and possibly conversion of an energy source to a useable form. The other efficiency factor, which becomes important in energy analysis is the end-use device efficiency, η_{ij}. This efficiency defines the ratio of energy that is delivered by a proper end-use device to perform an energy service to the energy fed to the end-use device.

The external efficiency, β_i, and the end-use efficiency of different devices are given in Table 4.3. The external efficiency for fuelwood, crop residues and animal manure denotes collection efficiency. The external efficiency of animal manure is the ratio of collectable manure to total manure produced by the livestock. When the animals are grazed for a longer period, the dung collection efficiency reduces considerably.

The external efficiency for grid electricity is the efficiency of distribution. The higher losses of electricity are due to technical losses in distribution and at the sub-station (for stepping down the voltage). In the case of local electricity generated by micro hydro units, the efficiency is lower because of converter efficiency and distribution losses.

The external efficiency for charcoal includes charcoal conversion (from fuelwood) and collection efficiency. The external efficiency for solar photovoltaic indicates an 11% of conversion efficiency, about 60% of battery and inverter efficiency, and about 75% of distribution efficiency. The system efficiency is the product of end-use device efficiency and the external efficiency.

Table 4.3 External and end-use device efficiency.[1]

Fuel, i	External efficiency, β_i	End-use device, j	Efficiency, η_{ij}
Fuelwood	95%	Tripod stove	3%
Crop residues	95%	Traditional stove	10%
Animal dung	55%	Efficient fuelwood stove	20%
Charcoal	18%	Charcoal stove	25%
Kerosene	90%	Kerosene stove	45%
Local electricity	65%	Kerosene lamp	100%
Grid electricity	75%	Biogas stove	40%
Biogas	90%	Heating stove	100%
Solar photovoltaic	5%	Electric bulb	100%

The efficiency of a kerosene lamp, an electric bulb and a heating stove is very high. A 100% efficiency of a device refers to the efficiency of energy utilization. For example, if kerosene lamp is the only device used for lighting then the amount of kerosene consumed does not generally depend upon the intensity of light but depends upon the number of kerosene lamp and the kerosene consumption per lamp-hour. Similarly, if kerosene lamps are to be replaced by electric bulbs, then the replacement in the rural areas are based on the number of bulbs to be installed and not on the intensity of light they produce. Therefore, it is assumed that energy resources used for lighting are fully utilized. However, if there is an option to replace existing kerosene lamp with an efficient one (such as replacement of wick

[1] Sources: UN (1987), Masera and Dutt (1991) and Pokharel (1992).

lamp by hurricane lamp) or replacement of incandescent bulb with a fluorescent bulb, then the intensity of light (or lumens) produced by these devices should also be taken into account.

4.2.1 Energy planning objectives

The goal of any representative government is to maximize the social welfare of its people. Economic efficiency, equity, and environmental quality are the main ideals of social welfare (Cohon 1978). However, such qualitative ideas should be quantified for planning purposes (Changkong and Haimes 1983). Table 4.4 highlights objectives and constraints that could be examined for energy planning. Some of these objectives have been analysed in this thesis.

Table 4.4 List of possible objectives and constraints

Objectives	Constraints
1. Economic Objectives - Reduced cost; - Increased efficiency; - Reduced energy input; 2. Equity Objectives - Increased employment; - Use of local resources; 3. Environmental Objectives - Reduced pollution	1. Limit on sustainable energy supply; 2. Meet all energy demand; 3. Limit on technology; 4. Limit on external energy supply;

a) *Economic objectives*

In general, increasing economic efficiency means the maximization of the net income to the country, which also means a high benefit to cost ratio -- that is, minimized cost for a particular program or minimized energy use for energy services.

Energy programs that arise in policy evaluations may be technically viable but costly. Therefore, the best approach would be to minimize the costs of introducing new energy technologies, the maintenance of existing energy resources, and the generation of new resources in the planning area. Cost minimization is one of the popular tools that has been traditionally adopted for energy planning purposes (Blair 1979).

Let C_{ij} refer to the energy cost per gigajoules for fuel *i* used in device *j*. Various methods to calculate energy costs are also given in Pokharel et al. (1992) and Anandalingam (1984).

For national economic planning, energy cost means the economic cost of producing or purchasing, transporting, and distributing an energy resource. Whereas for the financial analysis, the energy cost is the energy purchase cost for a user. For example, if fuelwood is collected freely from a forest, then there is no financial cost to the user, however, the economic cost is the cost to supply an equivalent quantity of fuelwood from a source on a sustainable basis -- that is the cost of land, plantation, maintenance, harvest, transportation, and distribution. This cost might vary from region to region.

When the energy programs are to be implemented, national and local governments would have to allocate funds immediately. In such cases, the immediate cost of the programs would be important. Therefore, the energy cost coefficients to be used in energy planning analysis depend upon the scope of analysis: long term, short term, or immediate.

The objective of economic efficiency for energy planning could be written for the minimization of program cost as,

$$\text{Minimize} \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{p=1}^{P} C_{ij} * x_{ijkp} \tag{4.1}$$

and the minimization of energy input for different end-uses as,

$$\text{Minimize} \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{p=1}^{P} x_{ijkp} \tag{4.2}$$

b) *Equity objective*

Equity refers to the distribution of benefits to a region, population class, or a gender. Certain types of energy resources may promote equity in implementation. If women are trained to install and use efficient fuelwood stoves then it would generate an income for them and reduce respiratory problems for the cook. If an energy source is promoted locally, then it might reduce fuel collection time and labour required to fetch the fuel. Cohon (1978) indicates that the equity objectives are politically motivated and are therefore difficult to identify. The author suggests that minimization of the difference between the range of benefits of different regions could be a way to promote equity.

For rural energy planning, two objectives could fulfil equity considerations. First is the provision of employment for the region and second is the promotion of the use of local resources.

Equity objectives could also be achieved by distributing efficient end-use devices to the poor households. However, this is more an implementation objective than a planning objective.

Let θ_{ij} refer to the equity related parameter, which could be the person-years that could be employed if an energy program is implemented. For example, forest management could help in systematizing fuelwood collection based on a sustainable fuelwood supply. Nevertheless, to maintain forests at the local level, forest guards and technicians might have to be employed and equipment might have to be supplied. The objective for the maximization of employment to be generated by introducing a particular type of energy technology or management process could be written as,

$$Maximize \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{p=1}^{P} \theta_{ij} * x_{ijkp} \tag{4.3}$$

However, not all the combinations of θ_{ij} are possible. Therefore, when such combinations are not possible, the parameters are assigned a zero value.

The objective to fulfil the energy demand by I_L ($I_L \subseteq I$) types of local energy sources to the extent possible could be formulated as,

$$\text{Maximize} \sum_{i=1}^{I_L} \sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{p=1}^{P} X_{ijkp} \qquad (4.4)$$

c) *Environmental objective*

Maintaining or augmenting environmental quality is currently being given much attention in various planning circles. The objectives that would satisfy the environmental considerations could mean a decrease in soil erosion, a decrease in the emission of pollutants, a decrease in the inundated land, or a decrease in the known negative environmental impacts. However, environmental objectives are problem specific and are difficult to quantify (Cohon 1978). Jannssen (1992) indicates that environmental problems have long term impacts which may not appear instantaneously. Therefore, it is imperative to look at these factors to the extent possible.

Let ξ_{ij} refer to the parameter having negative impacts (for example, pollutants) generated by a fuel defined by x_{ijkp}. Then the objective to minimize negative environmental impact could be formulated as,

$$Minimize \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{p=1}^{P} \xi_{ij} * x_{ijkp} \tag{4.5}$$

4.2.2 The Constraints

Four main constraints that could impose restrictions on the realization of energy planning objectives are discussed below.

a) *Sustainable supply of energy resources*

There is a limit on the sustainable supply of energy resources in a particular area. For example, there is a limit on fuelwood yield from the forest, residues yield from the cultivated land, and the production of animal dung. Let U_{ip} refer to the limit for the supply of local energy resources, I_L, in an area p, then the constraint could be written as,

$$\sum_{j=I}^{J} \sum_{k=1}^{K} x_{ijkp} \leq \beta_i * U_{ip} \quad \forall p,\ i=1,2,\ldots,I_L \tag{4.6}$$

b) *Energy demand*

Whichever policy is chosen, the present energy demand should at least be met. There could be a shift in the fuel for different end-uses or a shift from one type of end-use device to the next because of changed resource allocation. Such substitutions are discussed in detail by Pokharel (1992). Let D_{kp} represent the energy demand for an end-use k, in an area p, then the constraint could be formulated as given in equation (4.7).

$$\sum_{i=1}^{I}\sum_{j=1}^{J} \eta_{ij} * x_{ijkp} \geq D_{kp} \quad \forall k,\ p \tag{4.7}$$

c) *Limit on technology*

Not all of the available energy sources could be converted to desired secondary energy. For example, the use of animal dung for fuel may be limited because of energy conversion constraints. Similarly, distribution of EFSs to all households may not be feasible and desirable in the specified planning period. The generation of biogas may not be possible at higher altitudes.

Let the upper limit on the potential of generating or supplying additional energy by using a feasible technology be defined by L_{ijp}, then the constraint could be formulated as,

$$\sum_{k=1}^{K} x_{ijkp} \leq L_{ijp} \quad \forall i,\ j,\ p \tag{4.8}$$

d) *Limit on external energy supply*

The limit on the local sustainable energy supply and the minimization of cost and the maximization of environmental quality may create a shortage of fuel in the planning area. In such cases, the option is to import energy from outside the planning boundary. The import of kerosene, charcoal, and electricity, for example, can supplement the local energy supply. However, the decision makers may want to impose restrictions on the use of such fuels in a particular area. Let that restriction be referred to as Φ_{ip}. Then the constraint for this case can be formulated as follows.

$$\sum_{j=1}^{J} \sum_{k=1}^{K} x_{ijkp} \leq \beta_i * \Phi_{ip} \quad \forall p,\ i > I_L \tag{4.9}$$

4.3 Sensitivity Analysis

The multiobjective model used in this thesis requires input parameters such as cost coefficients, energy resources, energy demands, employment coefficients, and end-use device efficiencies. However, these input parameters change with technological change and macro economic impact such as changes in economic policy and inflation. The estimates of the input data also depend upon the data collection methodology (Sinha et al 1994). Owing to these uncertainties, the input data and parameters might change, leading to a change in the ideal solution and the compromise solution. Consequently, the choice of the best compromise solution might also change.

In this research, small changes in the output (that is, the ideal solution to the problem) due to small changes in the input data and parameters are being considered. This type of sensitivity analysis using a single parameter for testing is also called *first-order sensitivity analysis.* Many linear programming software packages, such as the linear programming module of GAMS® used in the thesis, provide some information to carry out the first-order sensitivity analysis.

In a multiobjective situation, another type of sensitivity analysis, called the *standard sensitivity analysis,* can also be carried out by changing the values of one or more of the objective functions (Benayuon et al. 1971 and Hwang and Masud 1979). When the MOP problem is solved with such a change, it would alter the value of the other objective functions. This might also change the allocation of energy resources.

The opportunity to carry out the first-order sensitivity analysis on the ideal solution is provided by *dual prices* (also called *marginal costs*). Dual prices define the slope of change in the value of the objective function due to a small change in an input parameter. For example, if changes in the values of the objective functions f_i are to be tested against a small change in the demand D_{kp} for an end-use k, in an area p, the marginal cost (MC) is defined by equation (4.10). In equation (4.10), f_i^o refers to the optimum value of objective f_i.

$$MC_{D_{kp}}^{f_i^o} = \frac{\partial f_i^o}{\partial D_{kp}}, \qquad \forall i \tag{4.10}$$

The higher the marginal cost, the higher is the sensitivity of the particular input parameter being tested. Therefore, care should be given while estimating such input parameters. On the other hand, when marginal costs are equal or nearly equal to zero, then the resources associated with these values (for constraints or variables) are referred to as non-scarce resources. Changes in the values of such constraints or variables do not have much impact on changes in the optimality of the solution.

In order to rank the sensitivity of objective functions to the input data and parameters, the marginal values need to be normalized. A normalized value (S) shows the percentage change in a function for one percent change in the input parameter. Equation (4.11) gives the relation to calculate normalized value for D_{kp}.

$$S_{D_{kp}}^{f_i^o} = \frac{\partial f_i^o}{\partial D_{kp}} \frac{D_{kp}}{f_i^o}, \qquad \forall i \tag{4.11}$$

As mentioned before, the STEP-method requires that the objective functions be optimized separately first (at iteration $t=0$). Therefore, the sensitivity of the objective functions with respect to input parameters can be studied from the marginal costs obtained in iteration $t=0$. These changes would indicate the movement in the ideal solution and consequently the changes in the compromise solutions in the following iterations.

In this research, the decision support system is implemented to study the energy resource allocation in two cases. In the first case, the watershed is treated as one region (aggregated case) and in the second case the watershed has been divided into six sub regions (disaggregated case). The first order sensitivity analysis is carried out for both of these cases and is presented in section 7.6. The ranking of the sensitivity analysis has been studied for the aggregated case and is presented in section 7.6.4.

As an illustration of the standard sensitivity analysis in this research, the value of one of the objective functions is changed and its impact on the other objective functions is analysed. This type of sensitivity analysis is illustrated for the disaggregated case in section 7.5.

4.4 The Decision Support System Model

The decision support system model for rural energy planning is illustrated in Figure 4.3. In the proposed model, data are first analysed in a GIS and then

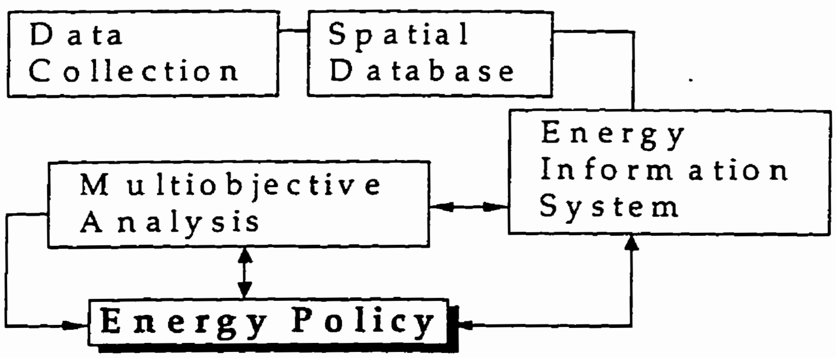

Figure 4.3 The energy decision support model

converted to an *Energy Information System* (EIS). The output of the EIS is energy balance information. This information along with other parameters is analysed with the STEP-Method to obtain the best compromise solution for implementation. Such a solution is expected to provide a direction on the formulation of an energy policy for the planning area.

Chapter 5

DATA COLLECTION

The purpose of the case study investigated in this thesis is to examine the possibility of implementing the integrated rural energy decision support system, developed in this thesis, for energy policy planning. As such the selection of a case study site was motivated by the availability of a geographical information base upon which the application of IREDSS could be shown, as opposed to selecting a site with potential for actual implementation.

Nepal (Figure 5.1) is chosen for the research because of a perceived need for resource management, data availability, data accessibility, and the researcher's familiarity with the location. Two candidate sites--Kulekhani and Phewa*tal* (*lake* in Nepali) watersheds in Nepal were screened in the first phase as they are prioritized as sites for watershed management by the Department of Soil Conservation and Watershed Management (DWSCM).

Kulekhani watershed is located to the southwest of Kathmandu. The watershed covers about 123 square kilometres. Indrawati lake at the south-eastern end of the watershed is of national importance as it provides water to operate hydroelectric plants at two sites that generate a total of 92 MW of hydroelectricity. Soil erosion in the watershed has led to increased siltation of the lake. Consequently, hydroelectric plants have been shut down for months many times in the past.

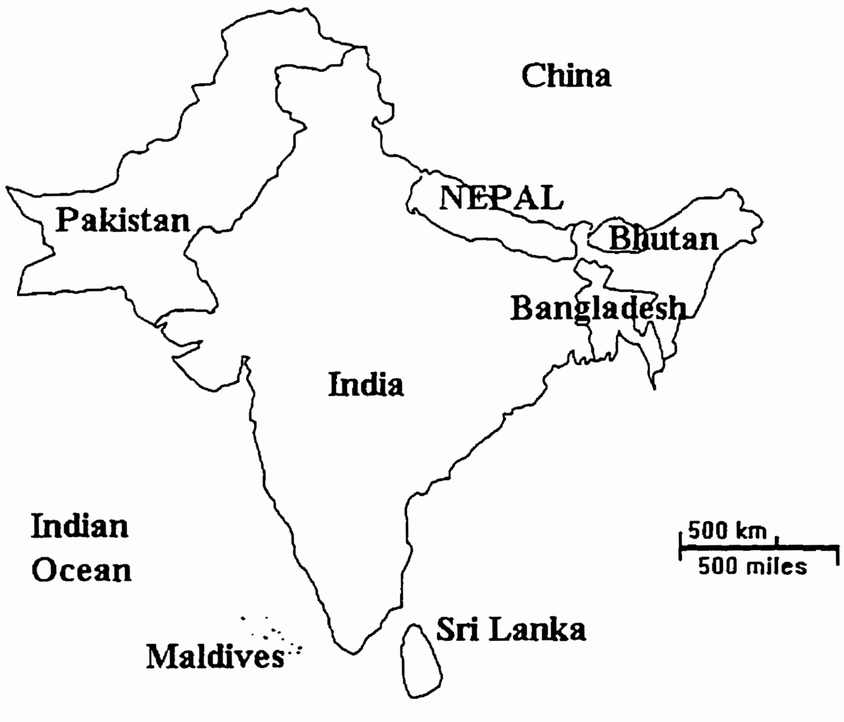

Figure 5.1 Location map of Nepal

Phewatal watershed is located about 200 km west of Kathmandu, near Pokhara and covers an area of about 122 square kilometres. There is a lake (called Phewa *tal*) at the eastern end of the watershed. This lake provides water for irrigation and power generation and is a popular tourist destination in Nepal. Therefore, its siltation will have a significant economic effect in and around the watershed.

A preliminary screening found that only an ammonia printed base map was available for Kulekhani watershed. For Phewatal watershed, however, reports on socioeconomic studies, a base map, a land use map, and a soils map were available both in the printed form and in digitized form. Since more information for Phewatal watershed was readily available, this watershed was chosen for the implementation of the decision support system. The availability of digitized data reduced the physical work (to digitize the maps) considerably.

In the Phewatal watershed, continuous population pressure on resources, mainly forests for fuel, has resulted in increased soil erosion and crippling land slides (Rowbotham 1995), and increased flash flood occurrence affecting the livelihood of the rural population. If the current rate of soil erosion continues then the sediment load in the lake would be about 39 tons/ha-year. With this rate, the lake would be filled up with silt in about 70 years compared with a life span of over 450 years on a manageable sediment load of 10 tons/ha-year (Impat 1981). Balla (1988) estimates that soil loss from non-degraded forested land is only about 3 tons/ha-year, whereas from grazing land it is about 67 tons/ha-year. Fuelwood extraction is one of the major causes of forest denudation (ARDEC 1984) in the watershed leading to such a high siltation rate. Therefore, this watershed needs immediate attention for resource management.

Digitized information on land use, contours, path, and trail of Phewatal watershed is available in Rowbotham (1995). This information was imported, edited in conjunction with aerial photographs, and reclassified for the database development.

There are six village development councils in the watershed. A village development council may contain more than one village. Thematic maps obtained from the conservation project and Kaski District Development Council (KDDC) during the field visit were digitized to establish internal administrative boundaries of the village development councils.

As shown in Figure 4.1, the available information was first compiled to form a GIS database, which was reclassified to obtain energy resource data. The information on energy consumption was not available. Therefore, energy demand data from other areas, in and outside of Nepal were referred to in the initial stage of database development. In this regard, the findings of the Tata Energy Research Institute (TERI) for UW's Indo-Shastri Project on rural energy in Dhanawas and district energy profiles prepared by the Water and Energy Commission Secretariat (WECS), Nepal were helpful.

A rapid appraisal (RA) was conducted at the site and in Kathmandu during Dec. 1995-Jan. 1996 and June-July 1996. The objectives of RA were to:

- validate the information obtained through IREDSS analysis on land use and minimum flow in the streams;
- assess the main energy consuming activities;

- assess the average amount and type of energy consumed;
- identify the changes in villages boundaries;
- understand the forest management practice; and
- understand the public awareness on community participation.

During the RA, 52 households were surveyed to assess the energy consumption patterns in the watershed. This information was recorded in tables and in maps.

The rapid appraisal was also helpful for understanding the planning concerns of the local population. This was important for multiobjective analysis. The observation illustrated that the community concerns are restricted to employment and roads or trail construction.

Agencies related to energy policy formulation in Nepal were also visited with the objective of assessing the viability of the proposed decision support system. This idea was presented to the multidisciplinary teams at the Tata Energy Research Institute, New Delhi, India in December 1995, and the Water and Energy Commission Secretariat and the Ministry of Population and Environment, Nepal in January 1996 and was well received. It was felt that such a model would help the organizations in the design of a better energy policy.

The International Centre for Mountain Research and Development (ICIMOD), the Department of Soil Conservation and Watershed Management (DSCWM), the Finnish International Development Agency (FINNIDA), and the Land Resource Mapping Project (LRMP) were some of the other agencies visited for the collection of the site specific secondary data. ICIMOD has an ongoing GIS activity for the Hindu-Kush regions and is developing a Mountain Environment and Natural Resources Information System (MENRIS) on an ongoing basis. The MENRIS database could be modified to develop an integrated rural energy decision support system. When MENRIS and IREDSS are combined, a better decision support system for rural development could be created. As both MENRIS and IREDSS are developed in ARC/INFO® software, such a creation should be straight forward.

The DSCWM has developed a long term watershed management plan for the research area. The objectives of the watershed management project as obtained from the DSCWM 1989 leaflet are:

- to sustain long-term, on-site soil productivity and reduce downstream damage;
- to advocate better use of resources; and
- to motivate and involve community participation.

The soil conservation and watershed management in the watershed was initiated in 1974 (IWMP 1992). During 1980-1986, the project was assisted by a UNDP/FAO program. From 1987 to 1994, FINNIDA assisted the project. From April 1994, the Japan International Cooperation Agency (JICA) and the Japan Overseas Cooperation Volunteers (JOCV) have been involved in planning future work for watershed management. Until January 1996, however not a great deal of planning was done. One of the site managers, Ms. Mikiko Nagai (at Bamdi), told the researcher that in the current project the micro level watershed management aspect is being considered. This requires public participation and an understanding of geographical features of the area, where the information provided by this thesis could be very helpful.

The DSCWM has produced a base map, a land use map, a soils map, and a village boundary map at a 1:25,000 resolution based on 1989/1990 aerial photographs. An ammonia printed 1:25,000 map with 20 m contour intervals interpreted from 1978 aerial photographs is also available. However, this map could not be used because of its poor quality. A list of maps obtained for the study are shown in Table 5.1.

Table 5.1 Maps obtained for Phewatal watershed

Information	Maps
Topographic Information	Base Map
Geological Information	Soils Map
Land use Information	Land use Map
Village Development Council Boundaries	VDC Map

The contours on the base map are at 100 metres interval. The base map also contains information on the location of villages, however during RA it was found this information is incomplete. The land use map contains information on the type and crown density of forests and cultivated land. The soils map has not been used at present but it could be a potential source to locate afforestation areas in conjunction with the slope map, which could be extracted from the base map.

5.1 Spatial Information

The location of the Phewatal watershed in Nepal is shown in Figure 5.2. The watershed extends from 28°11'37" to 28°17'26" N latitudes and from 83°48'2" to 83°59'18" E longitudes in the Middle Mountains of Nepal.

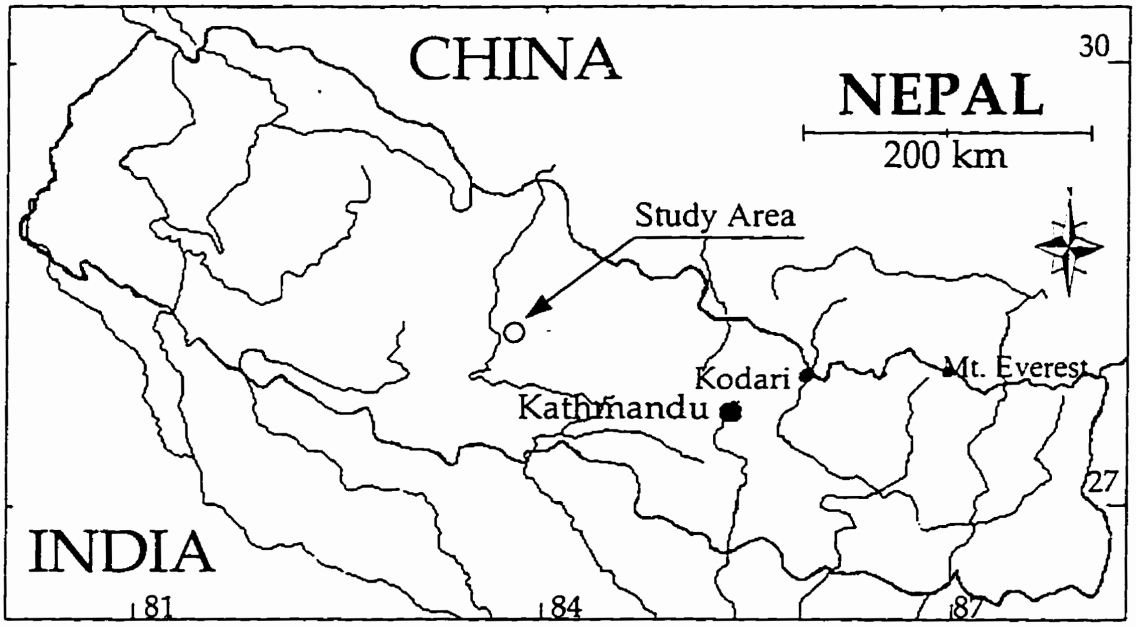

Figure 5.2 Location map of the study area

The elevation of the watershed ranges from 793 m at Phewa lake to 2508 m at Panchase *dada* (*mountain* in Nepali) at the west. The average slope of the watershed is about 40% (Manandhar 1987). However, the slope of the valley is between 3% and 5%. The lake has an average depth of nine metres and can hold up to 39 million cubic metres of water at its full capacity (Leminen 1991). The town of Pokhara is located at the eastern end of the watershed and covers about six square kilometres.

The administrative boundaries and the lake in the study area are shown in Figure 5.3. As stated earlier, there are six village development councils in the watershed, three of which lie in the northern part and the rest in the southern part of the watershed.

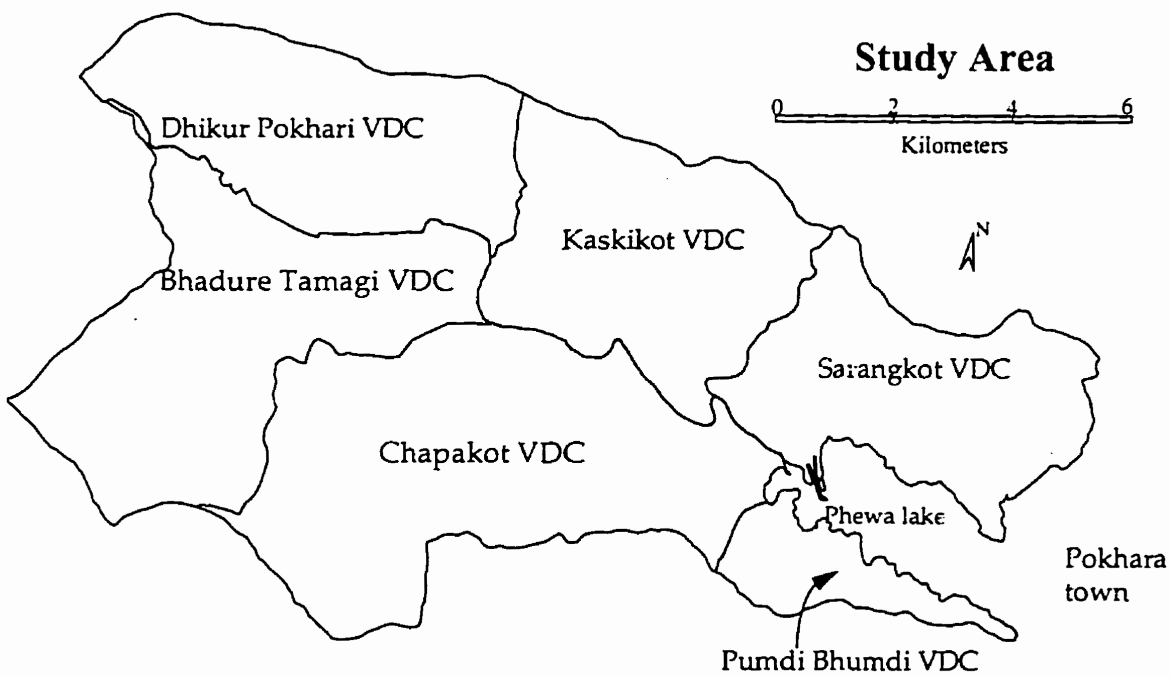

Figure 5.3 Site map of the Phewatal watershed

5.1.1 Climate

The climate in the watershed is humid subtropical (to about 1000 metres elevation) to cool temperate (IWMP 1992). The average annual temperature ranges from about 19° Celsius in the valleys to about 10°-15° Celsius in the mountain.

The Monsoon occurs between June and September and contributes almost

85% of the total rainfall (Ramsay 1987). The average annual rainfall recorded for two years at Banpale (1425m), Toripani (1500m), Tamagi (1650m),and Panchase (2508m) are 4385 mm, 4919 mm, 3843 mm, and 7500mm (IWMP 1980), respectively. Times series rainfall data collected for 15 years at Pokhara airport (854 m) and Lumle (1662 m, about 5 km northwest of watershed) show that the annual average rainfall in those areas is 3856 mm and 5200 mm (period 1971-86), respectively. Based on these data and data on six other sites around the watershed, a correlation is developed by Ramsay (1987) as,

$$Precipitation(mm.) = 2176 + elevation\ (metres) * 1.64, \qquad r=0.847 \qquad (5.1)$$

About 57% of the rainfall is assumed to be the runoff in the watershed (DSCWM 1980). The high rainfall intensity is an indication towards the increased annual water availability. However, before such a conclusion may be drawn, more reliable data on seepage, evapotranspiration, and runoff coefficients are necessary.

5.1.2 Drainage System

The major streams and lakes in the watershed are shown in Figure 5.4. The average stream density (that is, the number of streams/sq. km of catchment area) in the watershed is 2.2, whereas in the degraded sub basins it is as high as 4.4 (Rowbotham 1995).

Andheri *khola(stream* in Nepali), Sidhane *khola*, and Handi *khola* have

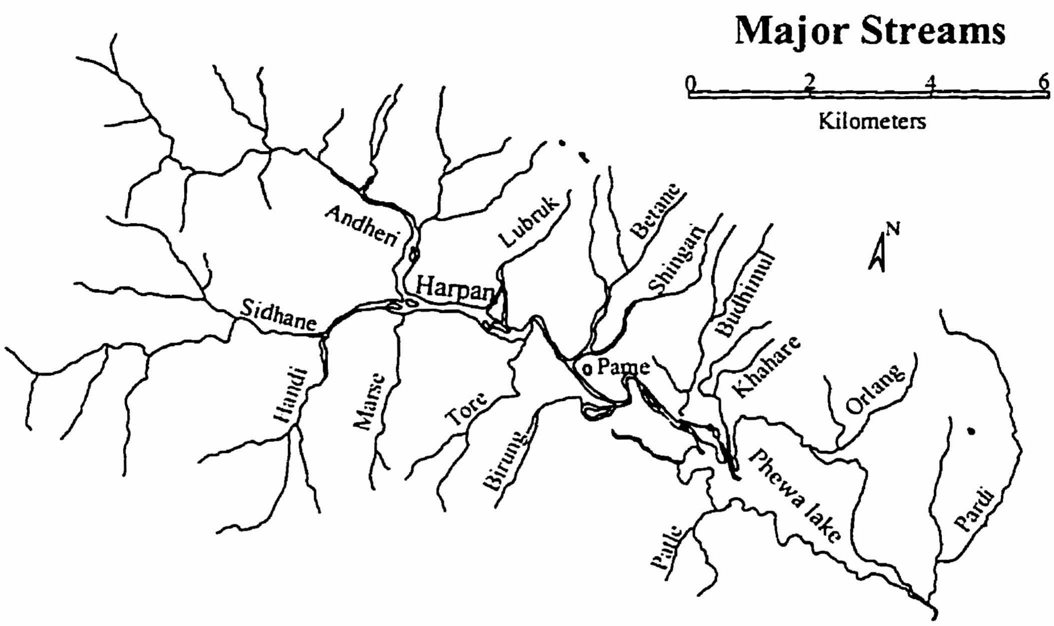

Figure 5.4 Major streams and lake in the watershed

constricted channels compared with other streams and have an average slope of about 10-30% around the pour point. Andheri *khola* originates near Poundur village and Sidhane *khola* originates from Sidhane village. Handi *khola* merges with Sidhane *khola* at about 1000 metre elevation at Ghanti Chhina. Sidhane *khola* and Andheri *khola* meet at about 910 metres at Thulakhet to become Harpan *khola* (Harpan river in Figure 5.4), which flows through the valley and drains into Phewa *tal*. During the dry season, there is no surface flow in Andheri *khola*.

The estimates for the average and the minimum flow in Phewa lake obtained from Nippon Koei (1976) are cited in Rowbotham (1995) as 9.2m^3/sec and 1m^3/sec. The author suggests that these values do not represent the average water flow in the watershed, however, provide an indication as to the variation.

During the RA, flow measurements were taken in Harpan *khola*, Andheri *khola*, Sidhane *khola*, Handi *khola*, Marse *khola*, Tore *khola*, Birung *khola*, and Lubruk *khola*. The data obtained from the field are discussed further in Chapter 6.

5.1.3 Land use pattern

The major land use pattern shown in Figure 5.5 indicates that the watershed is covered mostly with forest in the south and with cultivated land in the north. A direct comparison of 1980 and 1991 maps of the study area shows that the Harpan *khola* valley is expanding. Table 5.2 gives estimates of the land use changes over a decade (between 1980 and 1991). A reduction in the cultivated land and an increase in the forest land in the watershed, because of increased people participation in the watershed management project, is clearly seen from the table.

Table 5.2 Land use changes in Phewatal watershed[1]

Land use type	Area (ha.) in 1991	Changes from 1980
Forests	5,431	+19.2%
Shrub	345	+72.5%
Cultivation	4,728	-8.2%
Grass and Grazing	407	-67.8%
Other	1,343	+101.3%
Total	12,254	

[1] Source: Leminen (1991a)

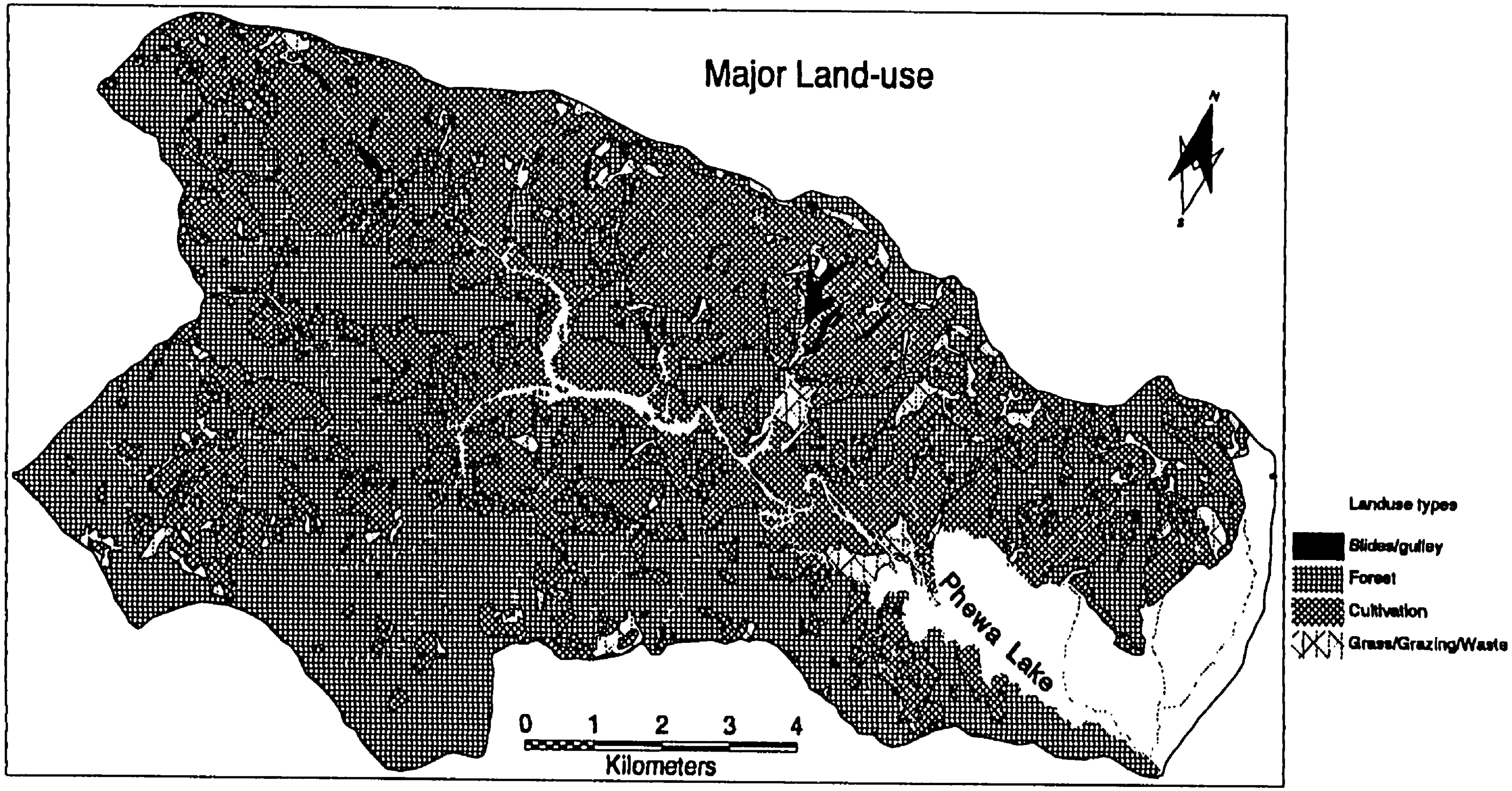

Figure 5.5 Major landuse pattern

About 44% of the land is covered with forests, dominated by hardwood species. About a hectare of pine trees have been recorded at the north eastern part of the watershed. The species indigenous to this watershed are *Shorea Robusta* (sal) between 1000-2000 metres (Gurung 1965 as cited in Rowbotham 1995) and chir pine, especially *Pinus Roxburghii*, and oak forests above 2000 metres (Negi 1994). At present, sub tropical species like Sal, *Castanopsis indica* (Katus),and *Alnus Nepallensis* (Utis) are predominant in the watershed. The species composition has been greatly altered by selective cutting (DSCWM 1980) and replantation (present survey). IWMP (1992) estimates the accessible forest area at about 75% of the total. In the absence of data on the spatial distribution of accessible forest area, forest accessibility is assumed to be the same throughout the watershed.

Data obtained from the Kaski District Forest Office in 1996 show that the government has handed over about 1,891 ha of forests (almost 40% of the total forests area) to the communities in different VDCs. The handover of government forests to community is continuing. In these community managed forests, management of the forest areas and the extraction of fuelwood and timber are controlled by local Consumers Committees.

Almost 39% of the watershed area is cultivated. Paddy, maize, wheat, and millet are the main cultivated crops. The cultivated area is dispersed all around the watershed. While the Harpan *khola* valley is cultivated with one crop a year, the up lands are cultivated with two to three crops annually. DECORE (1991) estimates that the cropping intensity is about 259% in up lands and about 150% in the low lands.

Crop yields vary between the up lands and the low lands. Table 5.3 gives the average crop yields in the watershed. The crop yields in the watershed are lower due to traditional farming practices. The higher yield of paddy in Bari is because of paddy cultivation in small strips and marginal lands (DECORE 1991). The use of chemical fertilizers is almost absent mainly because of a lack of affordability (costs about Rs. 14/Kg.).

Table 5.3 Average crop yields in mt/hectare[1]

Crop	Khet	Bari	Kaski Average
Paddy	1.44	2.00	2.21
Maize	0.93	0.95	1.60
Wheat	0.81	0.61	1.40
Millet	Not Cultivated	0.97	1.20
Potato	2.05	1.83	10.10
Mustard	0.20	0.20	0.68

5.1.4 Demography

As shown in Table 5.4, the total population in the six VDCs in the watershed is 29,669, which is distributed among more than 110 villages. The average population density is 267 persons/sq.km, which is very high compared with the average

[1] Source: DECORE (1991) and ASD (1993)

national population density of 129 persons/sq.km The population density on the northern side is 371 persons/sq.km, whereas that of the southern side is 173 persons/sq. km.

Table 5.4 Population distribution in the watershed[1]

Village Development Council	Population	Household (Number)	Area (sq.km)	Population density
Dhikur Pokhari	7,524	1,526	18.11	*415*
Kaskikot	6,759	1,152	18.18	*371*
Sarangkot	5,405	998	16.78	*322*
Bhadaure Tamagi	4,900	754	23.82	*205*
Chapakot	3,409	584	29.06	*117*
Pumdi Bhumdi	1,672	267	4.84	*345*
Total	29,669	5,281	111.08	*267*

The literacy rates of approximately 64% for males and 34% for females in the watershed are higher than the national average of about 30%. The overall literacy rate is about 48%. About 60% of the population is estimated to be economically active and the average annual labour surplus is estimated as 8.31% (DECORE 1991) of economically active persons.

Almost 47% of the population belongs to Brahman class (the highest caste according to the local religion), who hold an average cultivated land area of about 18 *ropanis* (one ha = 19 *ropanis*). The occupational groups (black smiths, gold smiths,

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[1] Source: Obtained during RA from Kaski District Development Council

shoemakers, and tailors) make up about 29% of the population. This group has an average land holding of about 6.8 *ropanis*. The rest of the population is comprised of Gurung and Tamang (warrior class), Newar (business class), and others. The average land holding in the watershed is about 13 *ropanis* per family, with the lowest for the Tamang groups at 0.75 *ropani* per household. The owners cultivate almost 80% of the land.

5.1.5 Economic condition

Crop farming, livestock rearing, and selling fuelwood and fish are the main economic activities in the watershed. Recently, a few crop grinding mills running on electricity or diesel have been installed in different VDCs. Black smithing and gold smithing are the main traditional activities. The local Consumers Committee do not allow gold smiths to obtain wood for charcoal production. Therefore, they are transferring their business to Pokhara town or elsewhere. Commercial activities like keeping shops, lodges, and restaurants, however, are on the rise.

Livestock are an integral part of most (98.9%) of the households. Buffalos and bulls are the main large livestock, providing nutrition, draft power, fertilizer, and cash when sold. DECORE (1991) estimates that about 13% of the households sell buffaloes and about 7% sell cattle for cash. The rearing of cows is decreasing, however, as cows need to be grazed, whereas buffalos can be stall fed. Stall feeding is increasing as more grazing land is being converted into protected lands and community forests, and grazing in the community forests is being stopped. Stall feeding of large animals could facilitate the installation of biogas plants.

Livestock data for different VDCs in the watershed are given in Table 5.5, which show that the livestock population is largest in Dhikur Pokhari VDC and smallest in Pumdi Bhumdi VDC. The buffalo population in the watershed is almost two and half times to that of cattle and is increasing.

Table 5.5 Livestock population in VDCs.[1]

VDCs	Cattle	Buffalo	Sheep/Goat	Total
Dhikur Pokhari	1,175	2,609	1,281	*5,065*
Kaskikot	587	1,739	1,716	*4,042*
Sarangkot	778	1,996	2,096	*4,870*
Bhadaure Tamagi	460	1,492	701	*2,653*
Chapakot	654	1,483	1,097	*3,234*
Pumdi Bhumdi	190	504	339	*1,033*
Total	3,844	9,823	7,230	*20,890*

DECORE (1991) estimates that the livestock holding per household is the largest in Chapakot VDC (at 5.5) and the lowest in Dhikur Pokhari (at 3.3). Proximity to the forest in Chapakot VDC is the main reason for the large holdings. The average livestock holding per household in the watershed is about four.

In terms of grazing land, the livestock density is about 51 per ha. However,

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[1] Source: Estimated from DECORE (1991)

not all of the grass land is grazed as it is also a source for *Khar;* a type of long grass used for thatching roofs. Farm land and geographically accessible forests close to the village are also grazed.

5.2 Energy Consumption Pattern

The data obtained from earlier surveys showed only the fuelwood consumption in the watershed. Therefore, it was necessary to collect energy consumption data for the watershed. Since the purpose of the thesis is to examine household energy sector, data were collected to establish energy use for household chores.

To obtain the household energy demand, it was decided that households would be selected through a random and multistage sampling process. The population and the number of houses in each VDC were obtained from the Kaski District Development Council (KDDC) office at Pokhara. For the survey area selection, it was determined that all of the VDCs would be surveyed. Each village development council was divided further into wards. The wards for the survey were selected at random. However, in each VDC, the ward where the VDC secretariat is located was visited. This was mainly to discuss development issues and the concerns of the elected officials in that area. The ward numbers and villages visited during the rapid appraisal and survey are given in Table 5.6. Altogether, 52 households were visited for data collection. To capture the variation in energy consumption patterns, households from both the humid subtropical and the cool temperate climatic zones were visited to the extent possible.

The households were surveyed in the winter season so that the families could be interviewed at leisure. During the winter, the harvest of one crop, maize or rice, is finished and farmers take a rest for a few weeks before they start ploughing the field for next crop, mainly wheat.

Table 5.6 Surveyed sample wards and location.

VDCs	Ward Numbers	Villages
Dhikur Pokhari	3	Nagdada
	4	Dare Gouda
	5	Dharapani
	9	Serachour
	9	Soureni
Kaskikot	8	Kaskikot
	9	Baskot
	9	Dada Khet
Sarangkot	1	Sarangkot
	7	Gerhajati
	5	Chankhapur
Bhadaure Tamagi	1	Deurali
	4	Bhadaure
	3	Tamagi
	4	Harpan
	5	Lampate Bazaar
Chapakot	3	Nirbane
	3	Chapakot
	6	Bhatabari
	6	Okhadhungi
	7	Arsal Chaur
	7	Marse
Pumdi Bhumdi	1	Anadu
	5	Simle
	5	Patle
	5	Lamdada

The energy consumption pattern in the watershed is given in Table 5.7. The average per capita secondary energy consumption for household chores in the watershed is estimated at 6.13 GJ per year. Almost 85% of this energy is used for cooking. Similarly, fuelwood and crop residues supply about 92% and 3.6%, respectively of the total energy consumption in a household. A comparative study of biomass energy consumption per person in DCs has been done by Nisanka and Misra (1990), which shows that the total per capita biomass consumption for fuel in developing countries varies from 5.3 GJ to 27.0 GJ per year depending upon the availability of resources. The energy consumption in the study area falls within the range given above.

Table 5.7 Energy consumption in Phewatal watershed in GJ/capita

End-use /Fuel	Cooking	Feed prepa-ration	Light-ing	Space heating	Food process-ing	Applian-ces	Other	Total
Fuelwood	5.15	0.37		0.08	0.08			5.68
Residue	0.09	0.13						0.22
Biogas	0.001							0.00
Electricity			0.09			0.0002		0.09
Charcoal						0.0001		0.00
Kerosene			0.06				0.08	0.14
Total	5.241	0.50	0.15	0.08	0.08	0.0003	0.08	6.13

Almost all of the households in Sarangkot, Kaskikot, Pumdi Bhumdi, and Chapakot VDCs have an access to grid electricity. Electricity is not available in the

Bhadaure Tamagi VDC. Likewise two of the western wards in the Dhikur Pokhari VDC do not have an access to electricity. In the households with no access to electricity, kerosene is the only option for lighting.

Electricity is used mainly for lighting and occasionally for radio, TV, and cloth-ironing. The electricity consumption for appliances is not significant. The high tariff on electricity beyond the consumption of 20 kWh (Rs.4/kWh, increased to Rs. 7/kWh from April 1996) and irregular electricity supply are the main reasons for low electricity consumption. The number of light bulbs varies between two and four in most of the households. The energy consumption estimates obtained during the rural appraisal indicates that the electricity consumption of the households is about half what they are paying for, mainly because of fixed minimum charges and load shedding.

The kerosene consumption for lighting given in the table is the current consumption patterns in households with an access to grid electricity. In other households, the kerosene consumption for lighting is 0.20 GJ/person-yr. The kerosene consumption used for fuelwood kindling is given in the "other" column in the table.

The load shedding is common in the watershed. Therefore, households use kerosene for lighting during load shedding. The survey indicated that if there was no load shedding then the electricity demand for lighting and appliances are about 0.1172 GJ/person-yr and 0.0002 GJ/person-yr, respectively. Equivalently, if the average numbers of electric bulbs being used in the households with kerosene lamp, then the kerosene demand for lighting would be 0.2578 GJ/person-yr.

None of the households surveyed reported the use of animal manure as fuel and it is the only organic fertilizer available in the area. There is no mention in the literature of charcoal use in the households. The existence of occupational castes like black smiths, gold smiths, and tailors indicates that there is some commercial use of charcoal in the watershed. The appraisal revealed that charcoal is made locally and is used predominantly for smithing and tailoring. A few earthen charcoal kilns were seen by this researcher in Chapakot VDC. During the survey, only two households reported the use of charcoal for clothes ironing. However, the consumption is assumed to be insignificant. There are no brick and tile kilns as houses are build with stones, timber, and thatched by *Khar* or corrugated zinc plates. The charcoal consumption for cottage industry types of activities is beyond the scope of this research.

Two hydro turbines are operating (about 5 kW and 10 kW capacity respectively) in Handi *khola* and Sidhane *khola* for grain processing. Similarly, one waterwheel (about 1 kW) was operating at Andheri *khola* during the survey. An effort to generate 1 kW of wind electricity in Sarangkot was made in 1990, but it did not succeed for two main reasons-- technical problems with the wind turbine and lack of interest after the extension of grid-electricity into the area.

Very few households in the watershed have installed biogas plants. The installation is limited to the area around Harpan *khola* valley and is not popular because of a lack of information on subsidies and loans. During the survey, a few households complained of the difficult loan procedure of the Agriculture Development Bank and non-cooperation from the local biogas installation companies in this regard. Some of these issues are also discussed in Pokharel et al. (1991).

Cooking for human consumption is the main energy end-use activity in the watershed. Almost 96% of the cooking energy needs are met by fuelwood, mainly using the traditional stoves. Cooking with crop residues is not popular.

The Sister's Group (Chelibeti Samuha) of the watershed management project had distributed and installed a number of EFSs a few years ago and many of them were well received by local women. The control of fuelwood collection from the community managed forests and the earlier free distributions of EFSs are seen as the main causes for the increased popularity of efficient fuelwood stoves.

Livestock feed preparation is an outdoor cooking activity. Fuelwood and occasionally crop residues like maize stalks and cobs are used (when available) for this purpose. About 15% of the total energy consumed in the households is used for this purpose.

Lighting is another important energy end-use in the watershed. Electricity is the main lighting fuel, however, kerosene is also used equally because of frequent electricity shutdowns. In Bhadaure Tamagi and two wards of Dhikur Pokhari, kerosene is the only lighting fuel. About 2% of the total energy consumed in the households is used for lighting.

Making *Chiura* (beaten rice), distilling alcohol, making *Ghiu* (butter) and yogurt are popular food processing activities in the households. While butter and yogurt are made in almost every households with livestock, distilling alcohol is most common in the households of Gurungs, Tamangs, Newars, and in the occupational castes. Except for making beaten rice in some households, grains are processed in nearby grain mills.

Water heating is not predominant in the watershed. Some households in the higher altitudes use fuelwood for space heating for up to 60 days in a year. The daily heating is required for about two to four hours in those houses. Fuelwood and crop residues such as maize cobs and rice husks are used for space heating.

Among the use of appliances, many households have a radio or a cassette player but most of them run on batteries. A very few number of households have a television. Some households also use electric and charcoal clothes-irons occasionally.

Chapter 6

SPATIAL ANALYSIS AND RESULTS

The spatial model to be incorporated into the proposed DSS was discussed in Chapter 4. The two main modules of the spatial model are the *energy resources module* and the *energy demand module*. The information generated in these modules are combined to obtain energy balance information for the study area. The energy balance information for an area provides a starting point for energy analysis. The energy resources module, the energy demand module, and the energy balance information for the study area are discussed in the following sections.

6.1 Energy Resources Module

The energy resources module considers indigenous biomass and nonbiomass resources. A brief discussion of these resources is given below.

6.1.1 Biomass Resources

The three major biomass resources in the watershed are fuelwood, crop residues, and animal manure. Since animal manure is the only source of fertilizer in the area and it is not burnt directly, only biogas is considered for the energy balance analysis. All of the available biomass resources have been discussed here and the spatial information as obtained from the analysis is shown. Charcoal is not considered as a resource. The demand for charcoal is adjusted with the demand for fuelwood in the energy demand module.

a) *Fuelwood*

As mentioned before, the fuelwood yields from the forests depends upon the geographical conditions, the tree species, and the crown density. Because of greater rainfall, for example, fuelwood yield is almost 20% higher in Pokhara compared with that in Kathmandu (deLucia and Associates 1994). If a 100% crown density is assumed, then hardwood and conifer forests in the Nepalese mountains yield about 5 mt/ha-yr and 1.25 mt/ha-yr, respectively on a sustainable basis (WECS 1987). Wyatt-Smith (1982), however, assumes that the sustainable yield for unmanaged Nepalese forests is between 4-8 mt/ha-yr and for managed forest it is between 10-20 mt/ha-yr. Conservative fuelwood yield estimates for Nepalese mountain forests obtained from WECS (1987) are given in Table 6.1. These estimates are used by MOFSC (1987) and WECS (1987) for estimating fuelwood availability from the forests in Nepal. Since the Phewatal watershed lies in the mountains, these average values of sustainable yield have been used for the analysis.

Table 6.1 Sustainable fuelwood yields in air-dry mt/ha-yr[1]

Fuelwood Source	Notation	Sustainable fuelwood yields
Coniferous Forest (40%-70%)[2]	C3	0.69
Hardwood Forest (<10%)	H1	0.10
Hardwood Forest (10%-40%)	H2	1.25
Hardwood Forest (40%-70%)	H3	2.75
Hardwood Forest (> 70%)	H4	4.25
Shrub	S	0.69
Plantation	PL	0.69
Degraded land	D	0.10

The spatial distribution of different types of forest in the watershed is given in Figure 6.1 and the area covered by different types of forest and sustainable fuelwood availability in the watershed is given in Table 6.2. The data given in Table 6.2 show that hardwood species with a crown cover between 40% and 70% cover almost 50% of the total forest area.

Figure 6.1 shows that H4 types of forests exists mainly in the inner forest areas in the southern areas of the watershed. Table 6.2 shows that 5,689 hectares of

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[1] Source: WECS (1987)

[2] Percentages refer to crown cover

the watershed are covered with forests. This forest area is about 98.5% of the forest area estimate (5,776 ha.) provided by IWMP (1992) for the watershed. Less than one percent of the total forested area falls under the degraded land category.

Table 6.2 Forest area and sustainable fuelwood supply

Forest Type	Plots	Total area (ha)	Fuelwood mt/yr	Energy in GJ
C3	1	1	1	12
H1	24	109	11	182
H2	88	1,030	1,288	21,511
H3	79	2,880	7,921	132,286
H4	33	1,222	5,803	96,912
S	54	335	231	3,864
PL	14	78	54	895
D	12	33	-	-
Other	2	1	-	2
Total	304	5,689	15,309	255,663

Data from Table 6.1 are used in the forest coverage to obtain the spatial distribution of forests with different fuelwood supply intensities. The spatial distribution of fuelwood intensity areas is shown in Figure 6.2.

Table 6.2 also shows that the sustainable fuelwood supply in the watershed is 15,300 mt/yr or 256,000 GJ of secondary energy. This suggests that about 516 kg/person-yr or 8.6 GJ/person-yr of fuelwood energy could be sustainably used in the watershed.

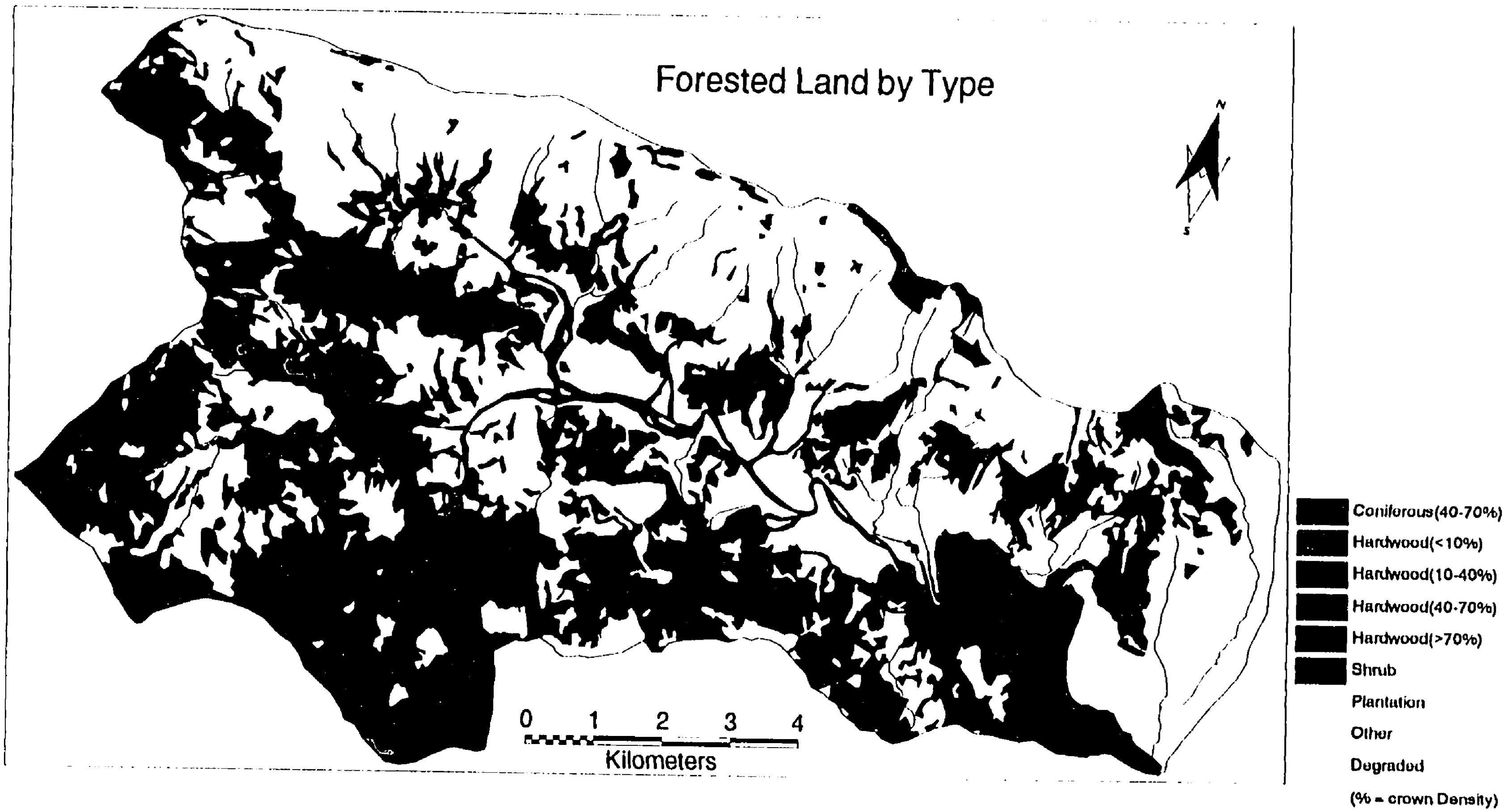

Figure 6.1 Forest types in the watershed

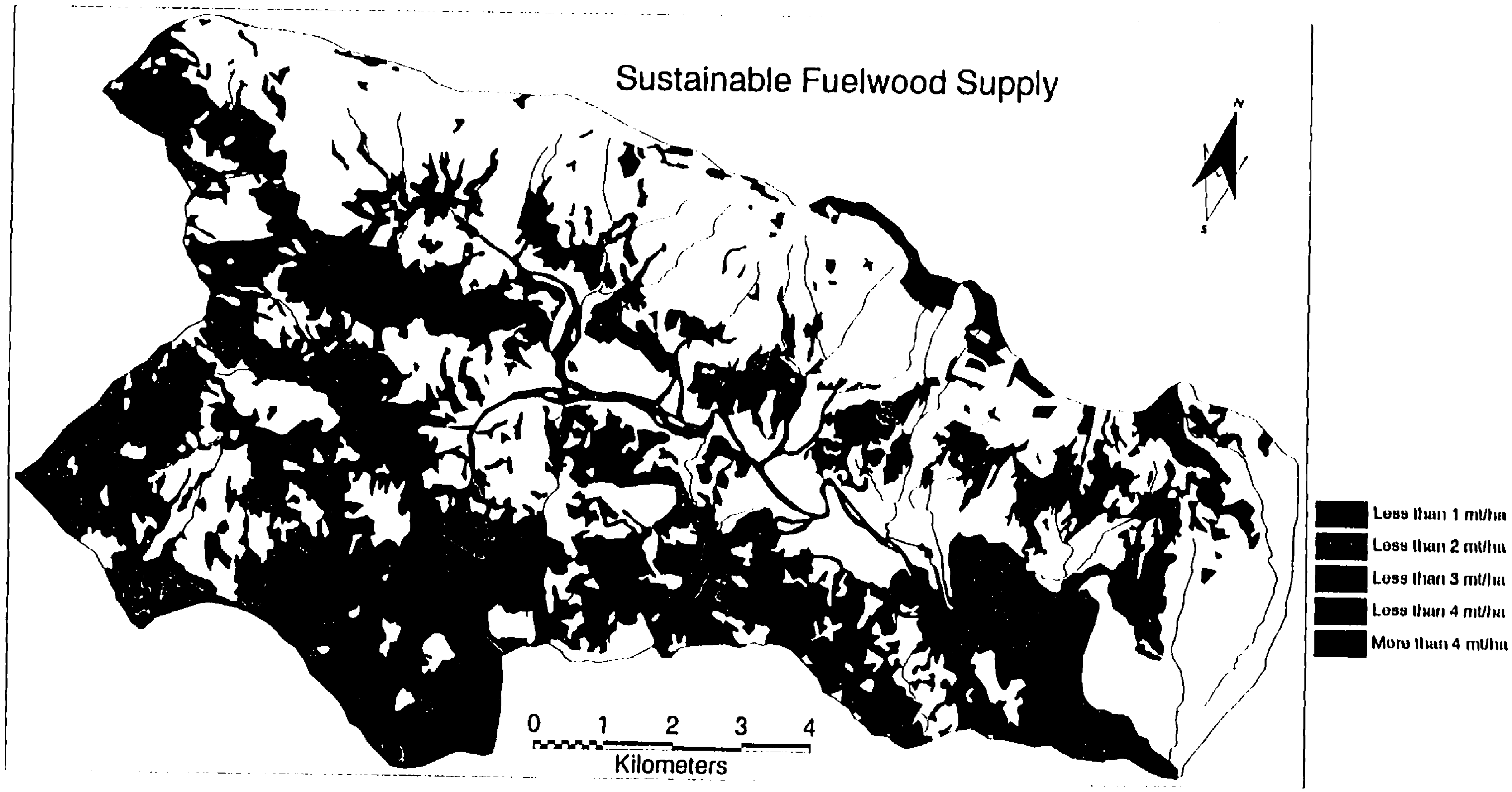

Figure 6.2 Area representing fuelwood intensity

IWMP (1992) has shown that about 75% of the forest is accessible for fuelwood collection. In the absence of VDC level data on accessibility of the forests, the same percentage of accessibility is assumed for all VDCs. Based on these assumptions, it is estimated that only about 11,500 mt/yr of fuelwood could be used on a sustainable basis in the watershed, which translates to about 386 kg/person-yr of fuelwood or 6.4 GJ/person-yr of secondary energy.

In terms of fuelwood consumption, earlier studies estimate the fuelwood consumption to lie between 378 to 875 kg/person-yr (Levenson 1978 as cited in DSCWM 1980). DECORE (1991) estimates the consumption to be about 3600 kg/household-year (about 600 kg/person-yr). The measurements carried out during the survey reveal the current fuelwood consumption averages to be about 340 kg/person-yr. This indicates that if sustainable fuelwood production is managed, there will be no encroachment on forests for fuelwood.

The data in Table 6.3 show that if the VDCs are examined separately in terms of fuelwood production and the same average per capita fuelwood consumption is assumed for all VDCs, there exists a fuelwood deficit in the northern VDCs. Since people need fuelwood to cook, and since fuelwood is seldom purchased, the figures clearly indicate a cross VDC fuelwood flow from the southern forests to the northern villages (or settlements) or encroachment on the nearby forests mainly in the northern VDCs.

Table 6.3 Accessible fuelwood supply situation in different VDCs

VDCs	Fuelwood supply in mt/yr	Fuelwood supply in kg/person	Fuelwood Surplus (+) or Deficit(-)
Dhikur Pokhari	1,364	181	(-)
Kaskikot	823	122	(-)
Sarangkot	948	176	(-)
Bhadaure Tamagi	3,095	632	(+)
Chapakot	4,590	1,346	(+)
Pumdi Bhumdi	660	395	(+)
Total	11,482	386	(+)

b) *Crop residues*

The spatial distribution of cultivated land in the watershed is given in Figure 6.3. Spatial analysis shows that about 38.4% (that is 4,659 ha.) of the land in the watershed is cultivated. This estimate of cultivated land obtained from the model is close to 98% of the cultivated land area estimate (4,727 ha.) given in IWMP (1992).

Cultivation depends upon the type of land. While *Khet* (valley, tars and fans) is cultivated with two crops at the most, *Bari* (sloped land and terraces) is cultivated with at least three crops per year. On average about 75% of the total cultivated land is suitable for cultivation and the overall cropping intensity (cropped area/suitable area) is about 282%. That is, in most of the cultivated land areas more than two crops are grown each year.

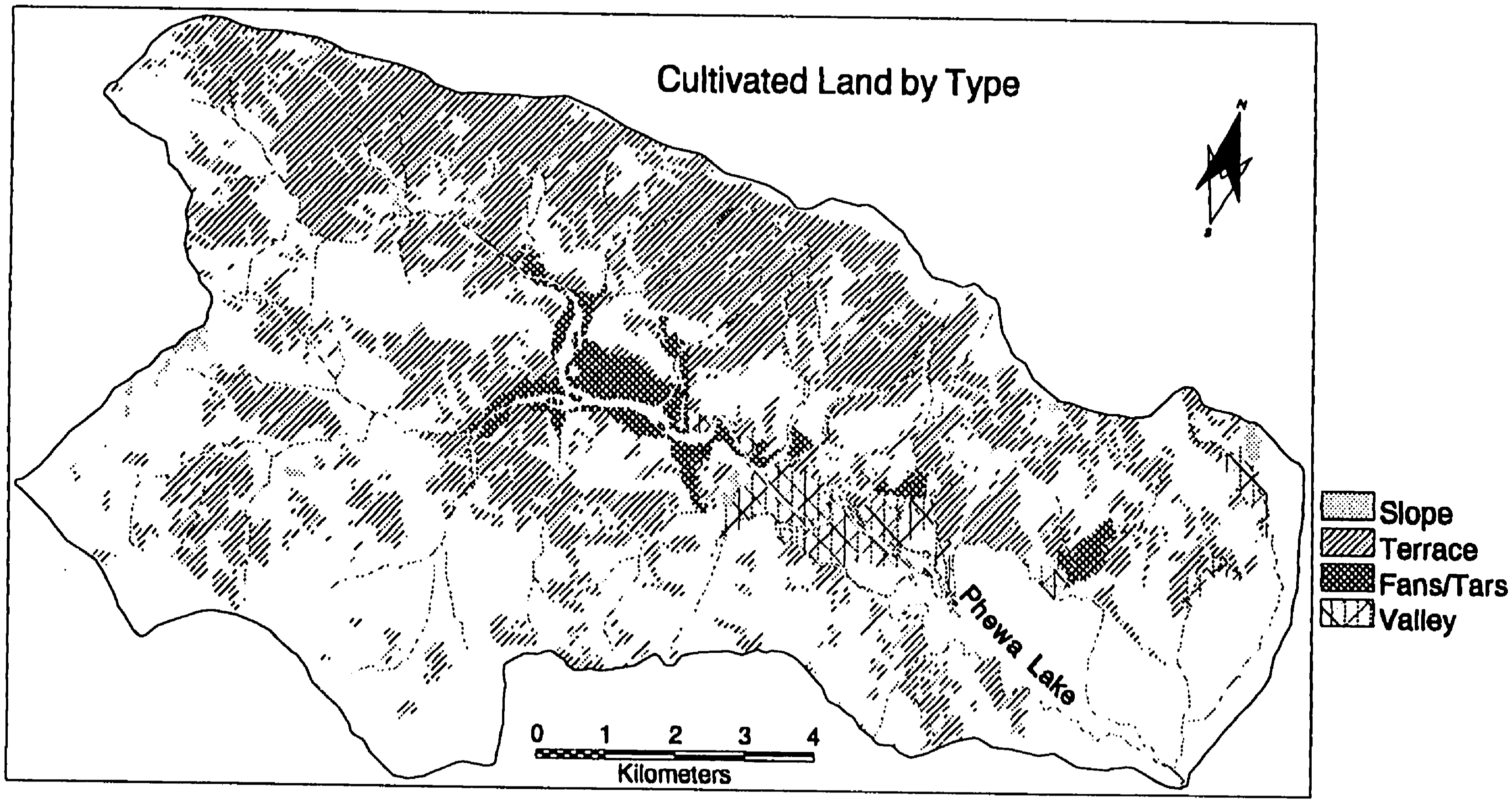

Figure 6.3 Spatial distribution of cultivated land

The cultivation intensity of crop land (that is the area of a farm land suitable for cultivation) also varies with altitude. While land in Harpan *khola* valley has a cultivation intensity of 100%, terraces have a cultivation intensity of as low as 38%.

Table 6.4 outlines the types of land and the cropped area in the watershed. Most of the cultivated land is in the higher altitudes (in *bari*). The cultivated terraces makes up about 85% of the total cultivated area.

Table 6.4 Area under cultivation and total cropped area in hectares

Land type, notation	Cultivated	No. of plots	Total area	Suitable area	Cropped area
Level terrace, T1	25-50%	26	188	71	212
Level terrace, T2	50-75%	130	2,079	1,310	4,072
Level terrace, T3	75-100%	70	1,681	1,479	4,605
Sloped terrace, SL2	50-75%	8	37	23	57
Sloped terrace, SL3	75-100%	2	2	2	5
Tars/Fans, F1	25-50%	12	45	17	26
Tars/Fans, F2	50-75%	9	76	48	72
Tars/Fans, F3	75-100%	8	217	191	284
Valley	100%	14	334	334	485
Total		279	4,659	3,475	9,818

Paddy is a dominant crop in *khet*, while maize is a dominant crop in *bari*. The crop yield, the estimated total residue production, and the residue quantity that could be used for energy purposes are given in Table 6.5. The table shows that the average production of crop residues in the watershed is about 12,700 mt/yr, which is about 1.3mt/ha-yr.

The ratio of crop residues that are used for fodder is obtained from IWMP (1992), which estimates that about 50% of paddy residues, 80% of maize residues, 90% of wheat residues, and 50% of millet residues are used as fodder in the watershed. Based on the above assumption, only about 19% (2,400 mt) of the total crop residues are available for energy purposes. The energy value of this quantity of crop residues is about 30,000 GJ. The spatial distribution of average residue production intensity is given in Figure 6.4.

Table 6.5 Total cropped area and residue production in different VDCs

VDCs	Cropped area, ha.	Crops, mt	Residue, mt	Residue for energy, mt	Energy value in GJ
Dhikur Pokhari	3,062	2,522	3,627	532	6,695
Kaskikot	2,806	2,510	3,701	695	8,739
Sarangkot	1,258	1,212	1,842	471	5,916
Bhadaure Tamagi	1,320	1,179	1,696	253	3,174
Chapakot	1,152	1,071	1,617	394	4,946
Pumdi Bhumdi	217	176	248	32	400
Total	9,818	8,670	12,731	2,377	29,870

Kaskikot VDC and Pumdi Bhumdi VDC produce the largest and the smallest quantities of residues respectively, that could be used for energy purposes. Only a small area of Pumdi Bhumdi VDC lies in the watershed. Therefore, much of the cultivated land in Pumdi Bhumdi lies outside of the watershed boundary.

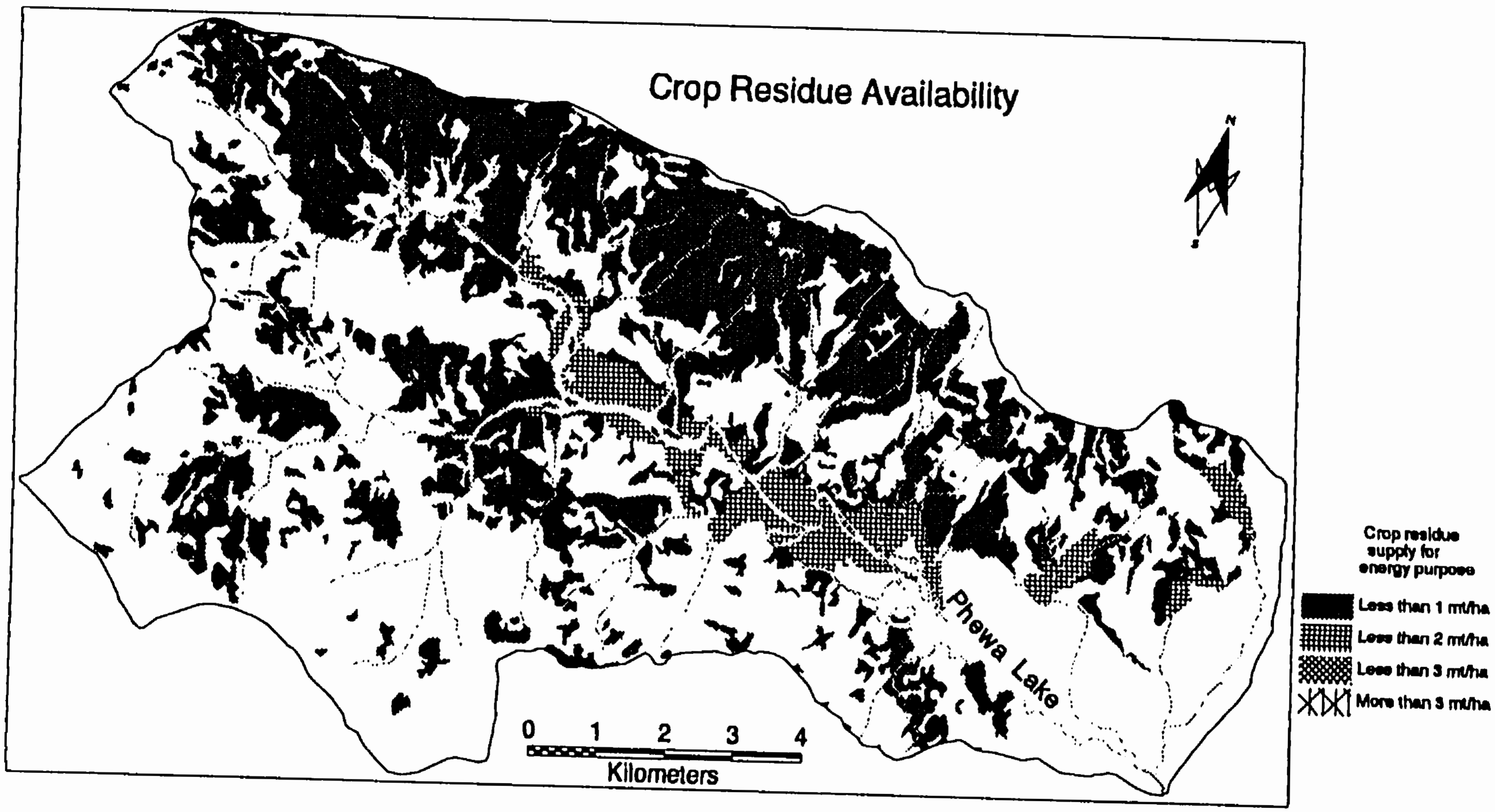

Figure 6.4 Residue production intensity

c) *Livestock manure*

WECS (1994a) estimates that about 55% of the animal manure produced in Nepal can be collected and used. Assuming this ratio for the collection of animal manure in the watershed, about 10,000 mt of dry animal manure is available each year in the watershed. The total manure produced in the watershed and its potential energy use is given in Table 6.6. As indicated previously, only the possibility of installing a biogas plant is examined here.

Biogas plants could be installed in areas with higher average daily temperatures. The climate in the watershed up to 1,000 m elevation is classified as humid subtropical with an annual average temperature of about 19°C and the lowest average monthly temperature of about 13°C in January (IWMP 1992). This area is expected to be suitable for biogas production.

Table 6.6 Livestock manure for energy use in VDCs.

VDC	Total manure, mt	Manure for energy use, mt	Energy value of available manure, GJ
Dhikur Pokhari	5,006	2,753	29,185
Kaskikot	3,250	1,787	18,947
Sarangkot	3,864	2,125	22,527
Bhadaure Tamagi	2,625	1,443	15,304
Chapakot	2,886	1,587	16,825
Pumdi Bhumdi	940	517	5,480
Total	18,571	10,241	108,269

The spatial analysis shows that one village in each of Dhikur Pokhari and Kaskikot, two in Bhadaure Tamagi, eleven in Chapakot, three in Pumdi Bhumdi, and four in Sarangkot are suitable for biogas installation. This information is obtained by overlaying contour coverage and villages (or settlements) coverages. The spatial distribution of such villages and the potential number of biogas plants are shown in Figure 6.5. While Pame village in Kaskikot VDC lies in the humid subtropical region, this area is mainly a shopping stop. Therefore, no biogas potential is shown for this particular area.

GGC (1990) suggests that for a household size of less than six members (as in the watershed), a $10m^3$ capacity biogas plant is required. By applying the rule of thumb given by Pokharel et al. (1995), this plant produces a maximum of $1.8m^3$/day of biogas. Such a plant requires 60 kg of fresh dung every day, which in turn requires four or more stall fed cattle and buffaloes.

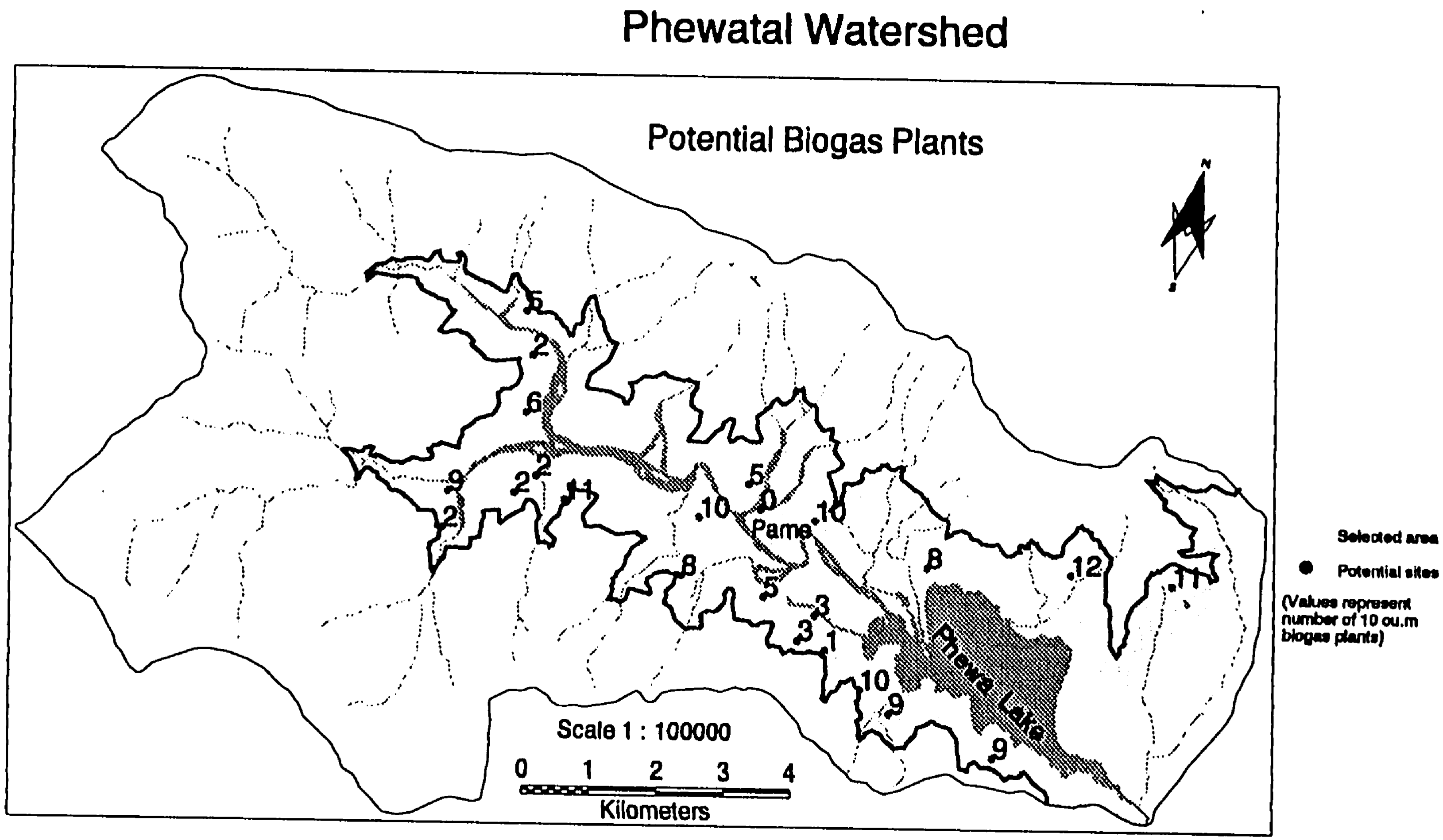

Figure 6.5 Locations suitable for biogas installation

About 20% of the households in each VDC in the watershed hold more than four cattle and buffalo (survey) and are, therefore, potential households for biogas installation. The analysis suggests that there is a potential to install more than 140 biogas plants of $10m^3$ capacity. The average annual biogas production and fuelwood that could be saved by using all of the generated biogas in different VDCs are given in Table 6.7, which shows that there is a high potential for biogas installation in Chapakot, Sarangkot, and Pumdi Bhumdi. This information at the village level helps in formulating a better distribution plan for biogas installation.

Table 6.7 Biogas potential in VDCs.

VDC	Total plants	Biogas in cu.m.	Energy Value, GJ	Annual fuelwood saved, mt
Dhikur Pokhari	5	2,700	65	9
Kaskikot	5	2,700	65	9
Sarangkot	41	22,140	536	77
Bhadaure Tamagi	8	4,320	105	15
Chapakot	56	30,240	732	105
Pumdi Bhumdi	28	15,120	366	53
Total	143	77,220	1,869	268

Rowbotham (1995) indicates that biogas is poorly received in the watershed because of the belief that the diversion of dung to biogas deprives the fields of manure. Therefore, to make biogas plants successful, proper awareness, technical backup, and a proper loan mechanism are necessary. In the absence of a proper loan mechanism (Pokharel et al. 1990), the penetration of a biogas programme into the area would be difficult.

There has been some attempt to introduce biogas plants in the area under the watershed management program. The author visited three operating biogas plants in Marse, Soureni and Dharapani. However, the total number of biogas plants installed in the watershed is not known because of poor data keeping by the biogas companies working in the area.

6.1.2 Nonbiomass Resources

Solar, wind, and hydropower are the three nonbiomass energy sources which can be harnessed in the watershed. However, the data do not currently exist to establish wind regimes in the watershed, therefore, the wind energy potential is not considered in the spatial model. If the data were available as to the wind velocity in different areas, the wind energy density map could be drawn and the potential for wind energy extraction in those areas could be established.

The sections below discuss the small scale hydropower potential and the solar energy potential in the watershed. Other nonbiomass energy sources, kerosene and grid-electricity, are considered in the energy consumption module as these resources are not generated in the watershed.

a) *Hydropower*

The high intensity of rainfall, the large number of streams, and the lake at the eastern end of the watershed suggest the feasibility of hydropower in the watershed. There is an existing electricity generation station, that uses the water discharge from Phewa lake to produce one megawatt of electricity. The electricity generated by this station is connected to the Nepalese national electricity grid. Recently, some power generated by this facility has been diverted back to the watershed, under the rural electrification program.

Basin analysis shows that only three basins in the watershed -- Andheri *khola*, Sidhane *khola* and Handi *khola*-- have more than five square kilometre of catchment areas. Therefore, if there is a potential for small hydropower generation, then these three basins could be considered first. The electricity generated in these basins could be used either for mechanical purposes or for electricity generation or both. Considering the fact that the current electricity consumption is only for lighting, it is assumed that the third option of generating both mechanical (in the day) and electrical power (in the night) is a technically viable option. However, only lighting and the use of appliances are considered here.

In the absence of any data on the stream flow, the following relation is used to calculate the average stream flow,

$$D_v = D_{\min} * \frac{CA_v}{TCA}, \qquad (6.1)$$

where D_{min} refers to the minimum discharge at Phewa lake ($1 m^3/s$ as given in section 5.1.2), D_v refers to the discharge from stream v, CA_v refers to the catchment area of stream v, and TCA refers to the total catchment area of the watershed (≈ 122 sq.km). Using this relation, it is estimated that the minimum water contribution to Phewa lake is $0.008\ m^3/s$ by every square kilometre of the watershed area.

During the RA in January 1996, the pour points of Harpan *khola* (near Pame) Andheri *khola*, Sidhane *khola*, Handi *khola*, Marse *khola* and Tore *khola* were measured using a cubical wooden float. Other streams had hardly any surface flow in that period. The estimated minimum discharge of the streams obtained by using equation (6.1) and the discharge obtained by float measurements are given in Table 6.8. The percentage contribution of a stream is the ratio between the measured flow at the pour point of each stream and the measured flow at Harpan *khola*.

Table 6.8 Estimated and measured discharges in some streams

Stream	Catchment area sq.km.	Estimated minimum discharge, m^3/s	Measured discharge, m^3/s	Percentage contribution
Andheri	16.9	0.14	0.18	14%
Sidhane	19.1	0.16	0.37	29%
Handi	9.3	0.07	0.31	24%
Marse	2.2	0.02	0.05	4%
Tore	3.7	0.03	0.04	3%
Harpan	--	--	1.27	100%
Phewa	122.2	1.00	--	

Measured discharge figures show that Sidhane *khola* and Handi *khola* contribute the most to the water flow in Harpan *khola*. The researcher was told during the RA that in the dry season, Andheri *khola* "dies down" before meeting with Harpan *khola*. At the time of measurement, Tore *khola* and Marse *khola* had a very good water flow at their pour points but had seeped under after that.

Although the surface water flow in Harpan *khola* is good, the water head is not available for small scale hydropower generation. Therefore, only the pour points of Andheri *khola*, Sidhane *khola*, and Handi *khola* are considered for small hydropower generation. To calculate the discharge (D_v) from stream v, equation (6.1) is modified by including the percentage contribution given in Table 6.8. The modified equation is given in equation (6.2).

$$D_v = (Percentage\ contribution)_v * D_{min} \tag{6.2}$$

The estimated stream discharge available for hydropower generation (by assuming that only about 80% of the minimum water flow in each of the potential streams is used for hydropower generation), the potential hydropower capacity at a waterfall of 20 m, and the delivered electricity for lighting (at 4 hours per night) are given in Table 6.9. The hydropower generation at these sites could be increased by increasing the waterfall. The stream basins with more than one square kilometre of catchment area are shown in Figure 6.6. The stream basins which are potential sites for hydropower generation have been shaded in the figure.

Table 6.9 Estimated discharge and hydropower production

VDC	Stream	Discharge, m^3/sec	Potential, kW	Annual kWh	Energy, GJ
Dhikur Pokhari	Andheri	0.11	16	14,950	54
Bhadaure Tamagi	Sidhane	0.24	34	31,769	114
Chapakot	Handi	0.20	27	24,294	91
Total	—	0.55	77	71,013	259

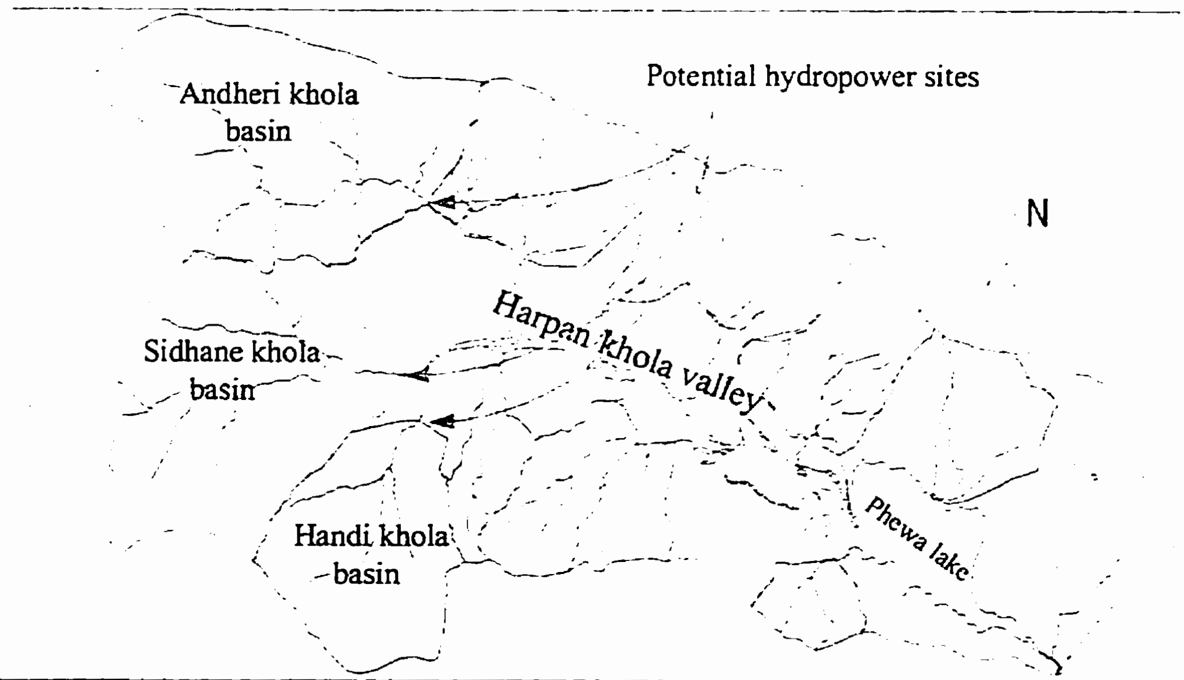

Figure 6.6 Potential basins for hydropower generation

The table shows that Sidhane *khola* can provide almost half of the total electricity generation in the watershed. Assuming a 65% external efficiency, these three sites can produce about 260 GJ/yr of electricity for use in the households.

b) *Solar energy*

Estimates for annually received global radiation at different weather stations in Nepal including Pokhara (latitude 28.22 degrees, longitude 84 degrees and elevation 854 metres) and Lumle (latitude 28.18 degrees, longitude 83.8 degrees and elevation 1645 metres) are given in WECS (1984), which show that the lowest monthly solar radiation on a horizontal surface in Pokhara and Lumle are 315 W/m^2 and 344 W/m^2, respectively.

As a worst case scenario, it is assumed that a minimum of 315 W/m^2 of solar radiation fall on a horizontal surface in the watershed. However, for the optimum absorption of solar energy, the surface should be inclined to an angle equal to the latitude of the site. Duffie and Beckman (1980) provide charts (see Figures 1.7.1a to 1.7.1e pp 19-21) to convert solar absorption on the horizontal surface to inclined surface for beam radiation. These values are used to calculate the geometric ratio (R_b) between the solar incidence on a horizontal surface (θ_z) and on an inclined surface (θ) as,

$$R_b = Cos\theta / Cos\theta_z \tag{6.3}$$

which comes out to be 1.4 for the study area. Therefore, the worst case optimum solar absorption in the watershed is 440 W/m^2. For a day length of 10 hours, the average energy absorbed by an inclined surface would be about 4.5 kWh/m^2-day or 6.8 GJ/m^2-year.

The worst case estimates of the average solar energy availability in Nepal are provided by Solarex Corporation (1992) as 4.5 - 5 kWh/m^2/day. From this comparison, it is concluded that for the preliminary calculation of the solar energy availability, such a solar insolation map would be sufficient. For installing a solar photovoltaic system at a site, however, long term data are necessary.

Solar energy can be used for either water heating or PV based electricity generation. Since there is a very limited demand for water heating, only photovoltaic-based electricity generation is considered here. Stout et al. (1979) suggest that an 11% conversion efficiency and an 85% inverter efficiency (converting from direct current to alternating current) are most realistic in PV applications. The efficiency of energy storage batteries and the battery control unit are assumed to be 70% and the efficiency of distribution as 75%. Therefore, the solar energy that could be delivered to the consumer reduces to 0.28 GJ/m^2/year. That is, the overall efficiency of converting solar energy to electricity and distributing it to the consumer is only about 5%. Therefore, in the watershed, to generate one kilo-Watt hour of energy per day, 4.5 m^2 of PV modules would be necessary.

It is assumed that PV modules could be installed on a portion of barren and abandoned land. Recalling the heavy distribution losses incurred while extending low voltage electricity distribution lines, it is assumed that PV modules should be installed within a 500 metre horizontal radius from the nearest village. As an illustration for understanding the feasibility of solar energy extraction in the watershed, it is assumed that about 1% of the selected land sites could be committed to PV based electricity generation. Based on Kodari PV-installation in Tatopani, Nepal, it is estimated that only 50% of that land could be used for installing PV-modules. Spatial analysis with the above assumptions shows that there are 11 sites suitable for solar-based electricity generation. These sites could serve the lighting need of at least 12 villages. The analysis indicates that Pumdi Bhumdi is not suitable for PV installation because there is no barren and abandoned land close enough to the settlements. The spatial distribution of selected sites and electricity potential is given in Figure 6.7 and details of the potential for each site is given in Table 6.10.

If a household illuminates two 40 W bulbs for four hours a day, then about 1.5 sq.m of PV modules would be required for each household to meet the lighting energy demand. If units are installed in each household, then about 1.2 sq.m of PV modules would be necessary because of reduced distribution losses.

Solar cookers are not considered here because the currently marketed solar cookers take long time in cooking. Also, cooking is limited to boiling, a method which does not match to the culinary practices in the watershed.

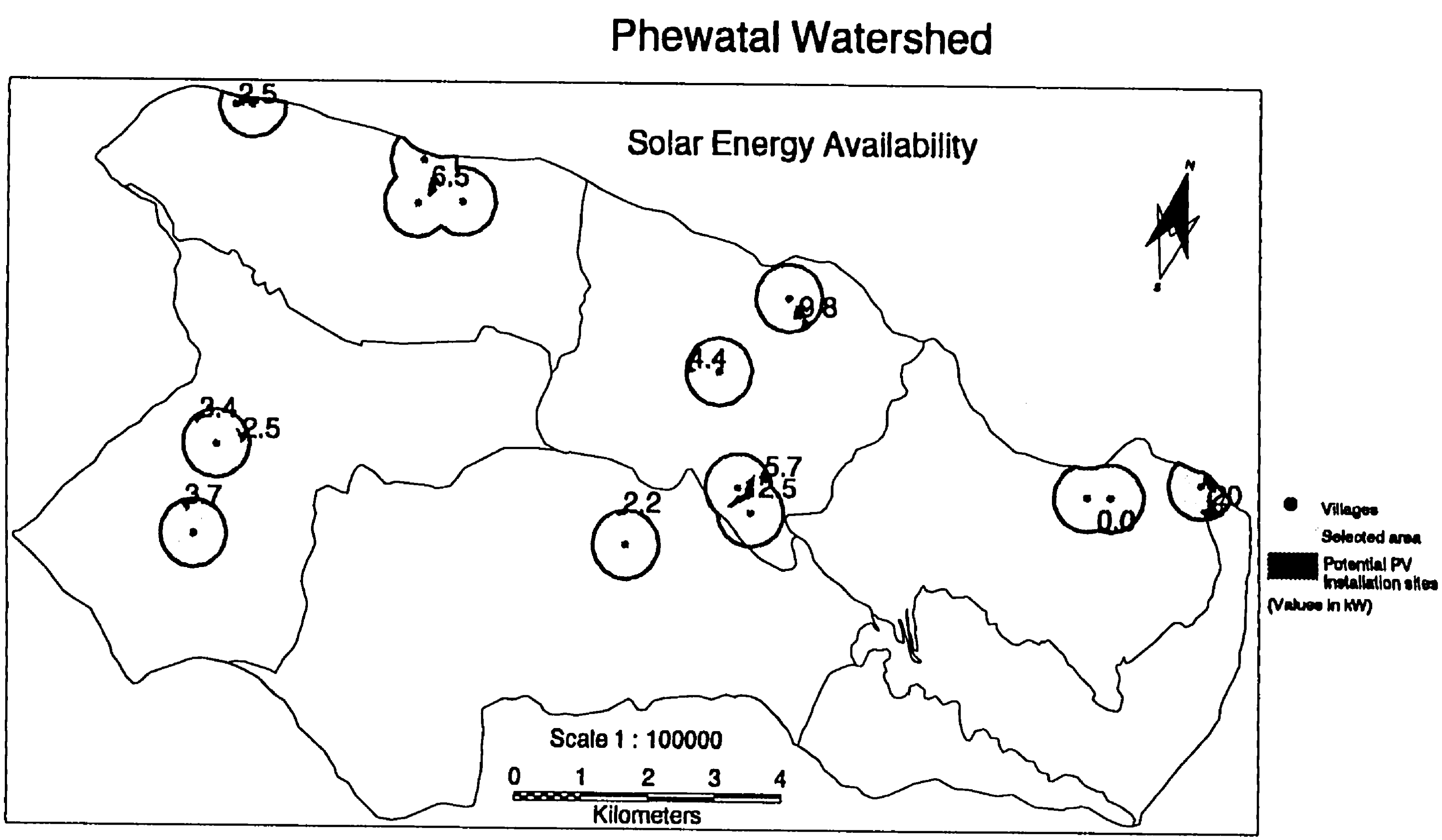

Figure 6.7 Potential solar energy sites

Table 6.10 PV based electricity generation potential

VDCs	Villages	Suitable sites	Potential PV-kW_p	Energy GJ/yr	Served no. of households
Dhikur Pokhari	Kot Gaun Dhikur Pokhari	1	2.5		
	Sera Chour Bhirmuni	1	6.5	53	*81*
Kaskikot	Karki Gaun	1	9.8		
	Dhawa	1	4.4		
	Dada Khet	1	5.7		
	Pame	1	12.5	190	*288*
Sarangkot	Rote Pani	1	20.8	122	*185*
Bhadaure Tamagi	Kudwi Dada	2	5.9		
	Sidane	1	3.7	56	*85*
Chapakot	Damai Dada	1	2.2	13	*20*
TOTAL		11	74	434	*659*

6.2 Energy Demand Module

The energy demand is the quantity of energy used when there are no restrictions in supply and when the available energy sources are affordable. Since, the goal of this work is to formulate energy policy oriented towards sustainability, the current energy consumption pattern is assumed as the energy demand. To obtain an energy demand module, therefore, the energy demand attributes are added to the population coverage. This way, energy demand maps are obtained to show the demand by fuel type and by end-use types. These maps are shown in Figures 6.8 and 6.9. Detailed data on energy demand are presented in Tables 6.11 and 6.12.

Table 6.11 Energy consumption in GJ by fuel type

VDCs	Fuel-wood	Resi-due	Char-coal	Biogas	Kero-sene	Electri-city	Total
Dhikur Pokhari	42,736	1,655	2	8	1,204	603	46,208
Kaskikot	38,391	1,487	1	7	946	610	41,442
Sarangkot	30,700	1,189	1	5	757	488	33,140
Bhadaure Tamagi	27,832	1,078	1	5	1,372	0	30,288
Chapakot	19,363	750	1	3	477	308	20,902
Pumdi Bhumdi	9,497	368	0	2	234	151	10,252
Total	168,519	6,527	6	30	4,990	2,160	182,232

As seen from the tables, the secondary energy consumption in Dhikur Pokhari is the highest and that in Pumdi Bhumdi is the lowest because of the difference in population distribution. It is seen that about 137 kl (1 kl = 36.3 GJ) of kerosene and 620 MWh (1 MWh=3.6 GJ) of electricity is being consumed in the watershed annually. Table 6.12 shows that a very high percentage of the total energy is required for cooking.

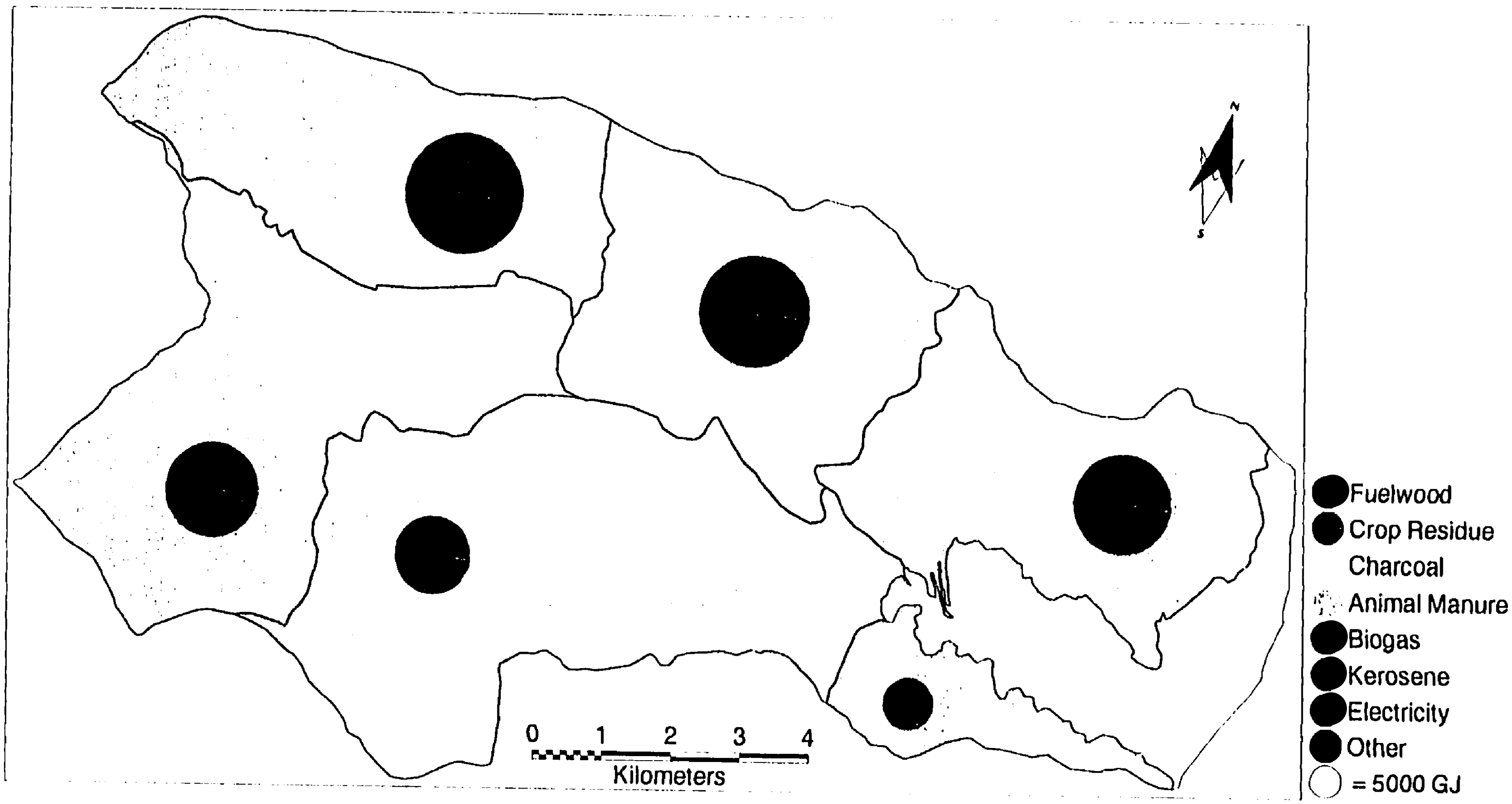

Figure 6.8 Energy consumption by fuel types

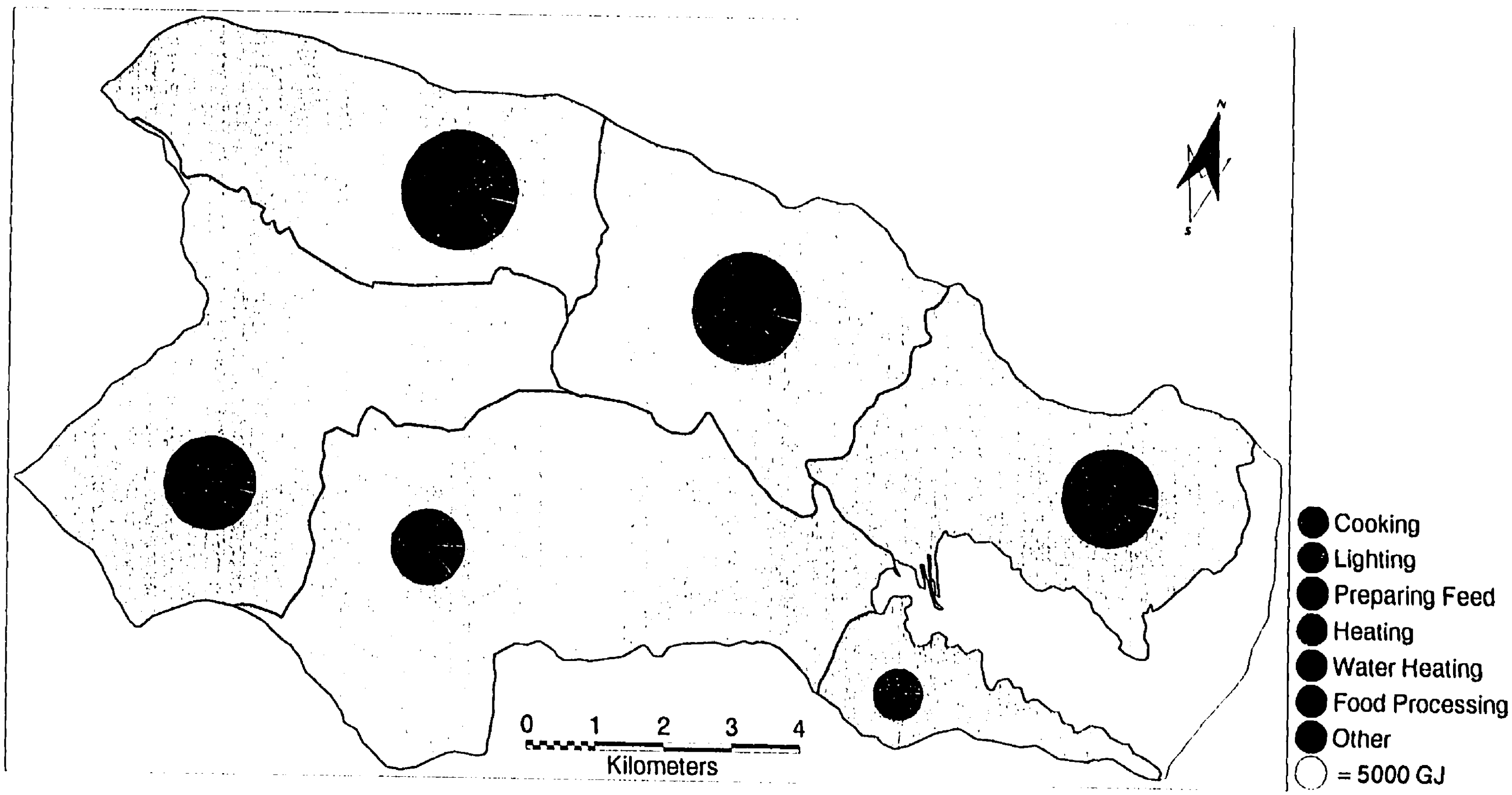

Figure 6.9 Energy consumption by end-uses

Table 6.12 Energy consumption in GJ by end-use

VDCs	Cooking	Feed	Space Heating	Lighting	Food Processing	Appliance /others	Total
Dhikur Pokhari	39,433	3,762	602	1,204	602	605	46,208
Kaskikot	35,424	3,379	541	1,014	541	543	41,442
Sarangkot	28,328	2,703	432	811	432	434	33,140
Bhadaure Tamagi	25,681	2,450	392	980	392	393	30,288
Chapakot	17,867	1,704	273	511	273	274	20,902
Pumdi Bhumdi	8,763	836	134	251	134	134	10,252
Total	155,496	14,834	2,374	4,771	2,374	2,383	182,232

An estimate of final energy consumption is essential to analyse the possibility of interfuel and intermode substitution (Pokharel et al. 1992). The external efficiency of some fuels and end-use efficiency of some devices were presented in Table 4.3. End-use efficiencies used in this study are given in Table 6.13. It is assumed that cooking is primarily done on traditional fuelwood stoves.

Table 6.13 End use efficiency for different devices

Stove	Cooking	Feed	Lighting	Space Heating	Food Processing	Appliance	Others
Trad. stove	10%	10%	--	100%	10%	--	--
EFS	20%	20%	--	--	20%	--	--
Electricity	--	--	100%	--	--	100%	--
Kerosene	45%	--	100%	--	--	--	0%
Charcoal	--	--	--	100%	--	100%	--
Biogas	40%	--	--	--	40%	--	--

The efficiency of kerosene for other end-uses has been assumed as 0% because it is assumed that kindling is a wasteful use of energy as it does not provide any heat for the intended end-use. However, kindling is necessary if the fuelwood is not dry enough for burning. In this case, kerosene would be used for steaming away a part of moisture contained in the fuelwood, therefore it does not provide heat directly for the intended end-use. Moreover, when fuelwood with higher moisture content is used, the gigajoules obtained for heating would be lower, since part of the heat is required to remove the moisture from fuelwood.

The emphasis here is to provide and use air-dried fuelwood, which has a lower moisture content. Therefore, when such practices are adopted there would be no need to use kerosene to ignite fuelwood.

The final energy consumption for the watershed obtained by using end-use efficiencies given above are illustrated in Tables 6.14 and 6.15 and Figures 6.10 and

6.11. The estimates of final energy consumption are required to obtain energy allocation for different end-uses in the watershed.

Table 6.14 Final energy consumption in GJ by fuel type

VDCs	Fuelwood	Residue	Charcoal	Biogas	Kero-sene	Electri-city	Total
Dhikur Pokhari	4,815	165	2	3	602	603	6,190
Kaskikot	4,326	149	1	3	405	610	5,494
Sarangkot	3,459	119	1	2	324	488	4,393
Bhadaure Tamagi	3,136	108	0	2	980		4,226
Chapakot	2,182	75	1	1	205	308	2,772
Pumdi Bhumdi	1,070	37	0	1	100	151	1,359
Total	18,988	653	5	12	2,616	2,160	24,434

The final energy consumption for cooking is about 63%, followed by lighting, which is almost 20%. Fuelwood, kerosene, and electricity are the main fuels in terms of final energy consumption as they supply almost 77%, 11%, and 9% of the total final energy, respectively. The overall efficiency of energy use is only about 13%.

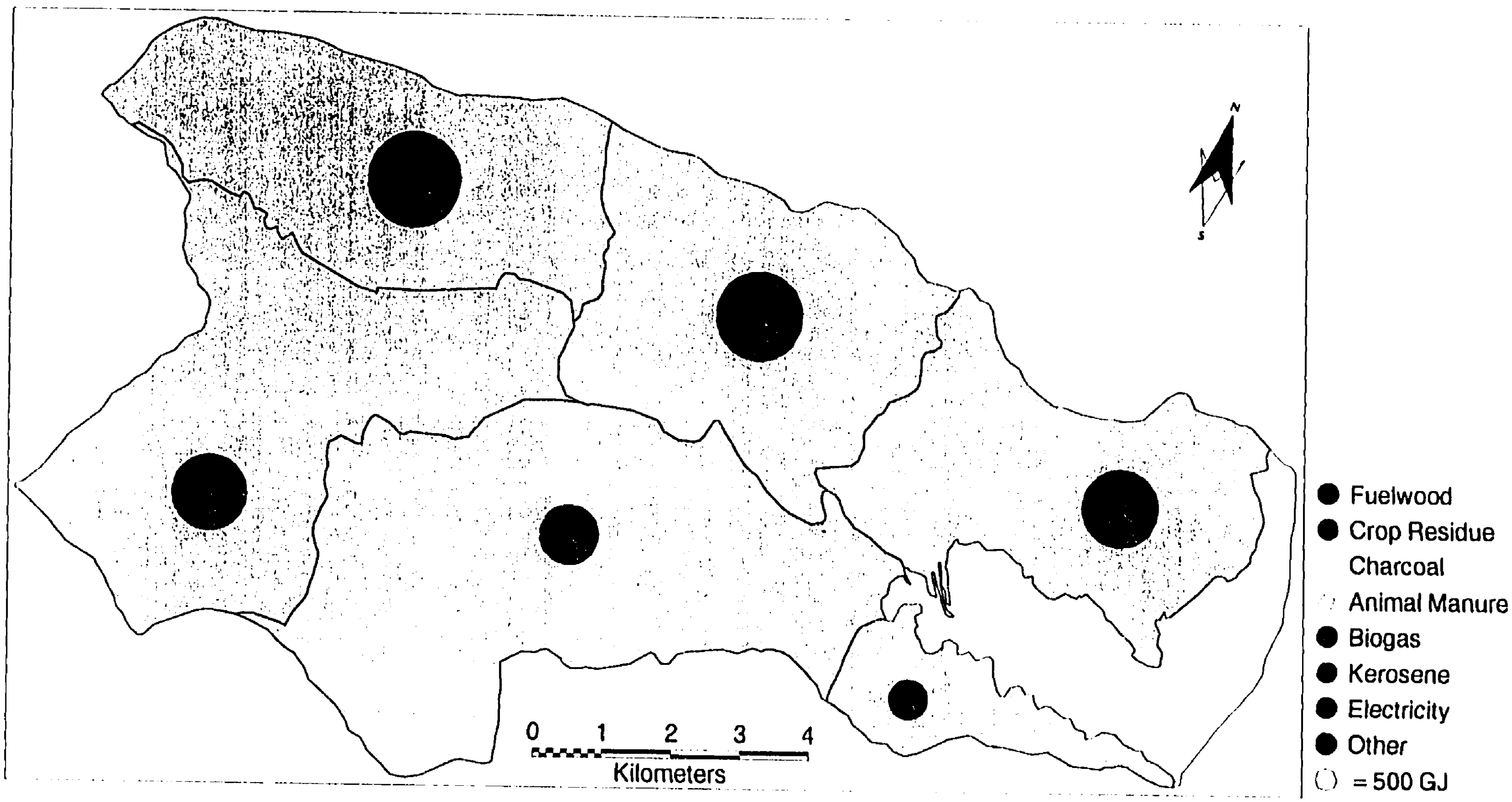

Figure 6.10 Final energy consumption by fuel type

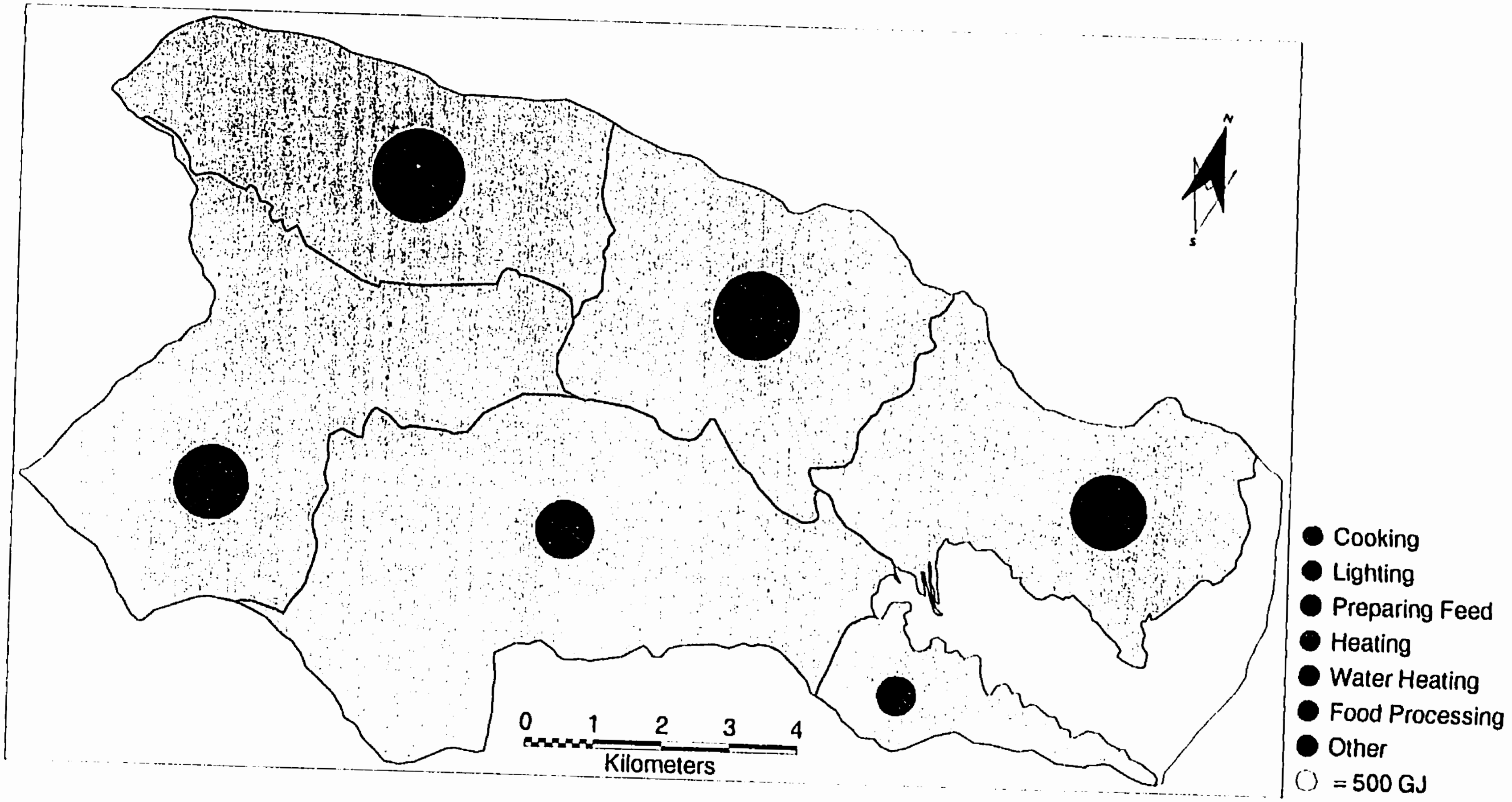

Figure 6.11 Final energy consumption by end-use type

Table 6.15 Final energy consumption in GJ by end-use

VDCs	Cooking	Feed	Space Heating	Lighting	Food Processing	Appliance	Total
Dhikur Pokhari	3,946	376	602	1,204	60	3	6,191
Kaskikot	3,544	338	541	1,014	54	3	5,494
Sarangkot	2,834	270	432	811	44	2	4,393
Bhadaure Tamagi	2,570	245	392	980	39	0	4,226
Chapakot	1,788	170	273	511	27	1	2,770
Pumdi Bhumdi	877	84	134	251	13	1	1,360
Total	15,559	1,483	2,374	4,771	237	10	24,434

6.3 Energy Balance

The information on biomass and nonbiomass energy sources given in section 6.2 could be combined to produce an energy resource map for the watershed as shown in Figure 6.12. The figure shows that fuelwood dominates the energy availability in the watershed. Biomass sources constitute almost 99.8% of the total energy resource availability. The energy demand map shows that fuelwood is the most used energy source in the watershed.

The energy balance sheet for the watershed given in Table 6.16 and Figure 6.13 shows that there is a net surplus of energy in the watershed. If interfuel substitution was technically and economically feasible and if all the energy resources were exploited, then the watershed should have been able to support a

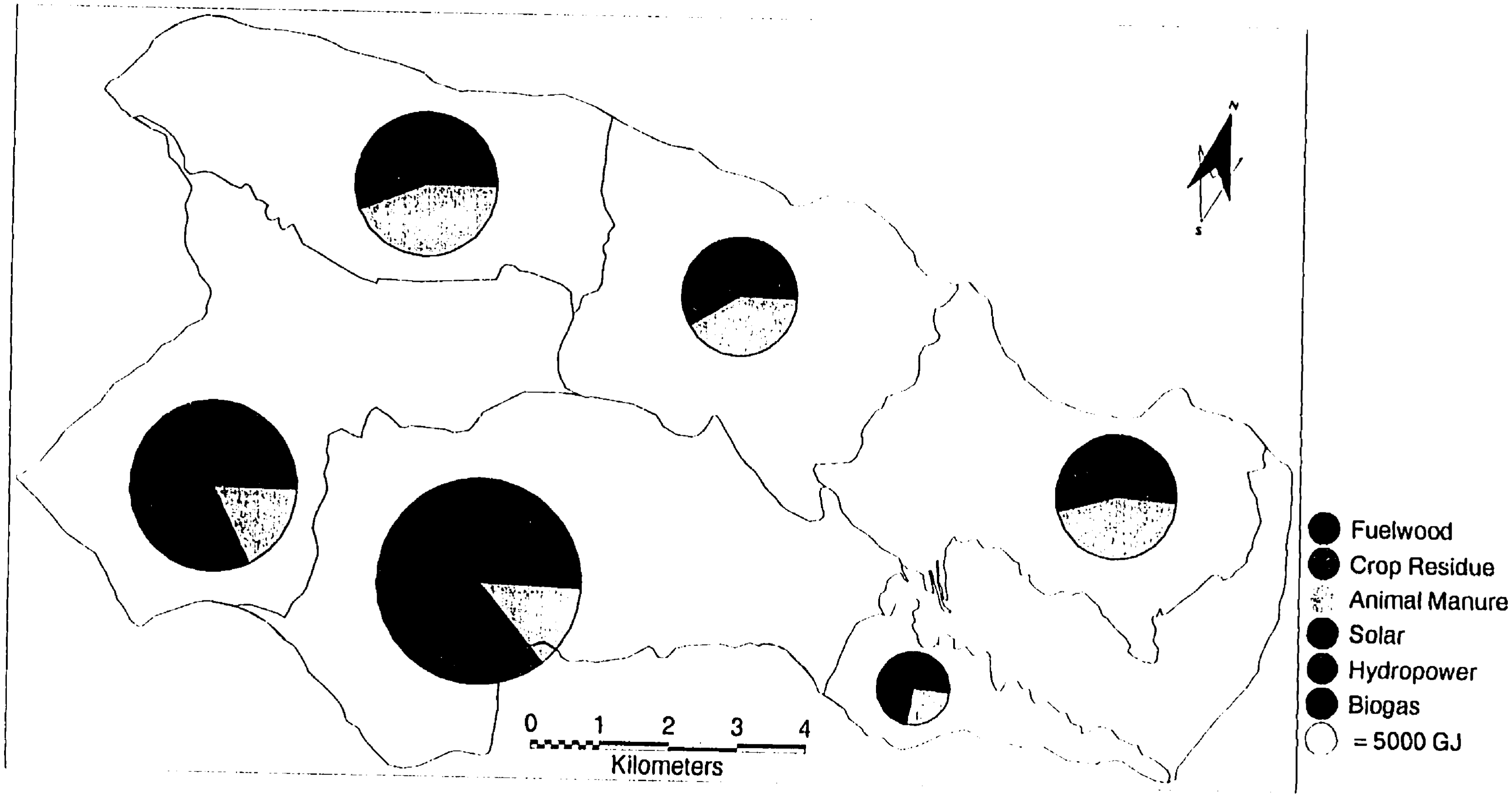

Figure 6.12 Energy resource map

self sustaining energy system for some time. However, the examination of fuelwood consumption shows that there is a fuelwood deficit in the northern VDCs of the watershed; although there is a net surplus in the watershed as a whole (Figure 6.14). This indicates a cross VDC flow of fuelwood and an encroachment on nearby forests particularly in the northern VDCs. Similarly, with crop residues there is surplus supply in all VDCs.

Table 6.16 Energy surplus (+) and deficit (-) VDCs

VDCs	Fuelwood	Residue	Manure	Biogas	Electricity	Kerosene	Total
Dhikur Pokhari	-12,360	5,040	29,181	58	-496	-1,203	20,220
Kaskikot	-20,067	7,252	18,943	58	-419	-946	4,821
Sarangkot	-9,586	4,727	22,523	530	-365	-757	17,072
Bhadaure Tamagi	41,079	2,096	15,301	100	170	-1,372	57,374
Chapakot	82,838	4,196	16,823	728	-204	-477	103,904
Pumdi Bhumdi	5,204	32	5,479	364	-151	-234	10,694
Total	87,108	23,343	108,250	1,838	-1,465	-4,989	214,085

The data show that even if all of the hydropower and PV potential in the watershed were exploited, electricity required for lighting and the use of appliances would still be in a deficit as shown in Figure 6.15. This means that either more PV installation should be promoted (by committing more land area for PV generation) or electricity should be imported through grid extension. The electricity supply in Bhadaure Tamagi VDC is in surplus because electricity is not currently available in this VDC. In the case of kerosene, since it is imported for use in the watershed, it is shown in a deficit in Figure 6.16.

Sarangkot VDC is closest to the urban area where most of the biogas plant installing agencies are located. Since fuelwood shortage has already been felt in this VDC, a public awareness campaign could be created to promote the installation of biogas plants. Although the potential for biogas is highest in Chapakot, the proximity of the households to the forest, and hence the ease of access to fuelwood, impede an enthusiastic response to a biogas program there.

6.4 Summary

The development of a spatial model for energy analysis is a contribution made by the researcher towards energy planning. The chapter has demonstrated that the extraction of energy information from spatial data and attribute information is possible. The information was broken down by using a GIS capability to see the resource and demand distribution in each VDC. Although the area considered here is very small, it is expected that the methodology can be seamlessly transferred to larger areas.

Usually energy analysis starts with information on the total energy balance for a particular region as a whole. Such information is of little value because of technological and economic limits. It is also shown that an area-wise spatial analysis helps in locating potential sites for energy generation, such as, biogas, hydro, and solar. Such information is very helpful in identifying location specific energy programs. For example, by knowing fuelwood deficit areas, authorities could initiate or encourage energy conservation and fuel substitution programs targeted to that area.

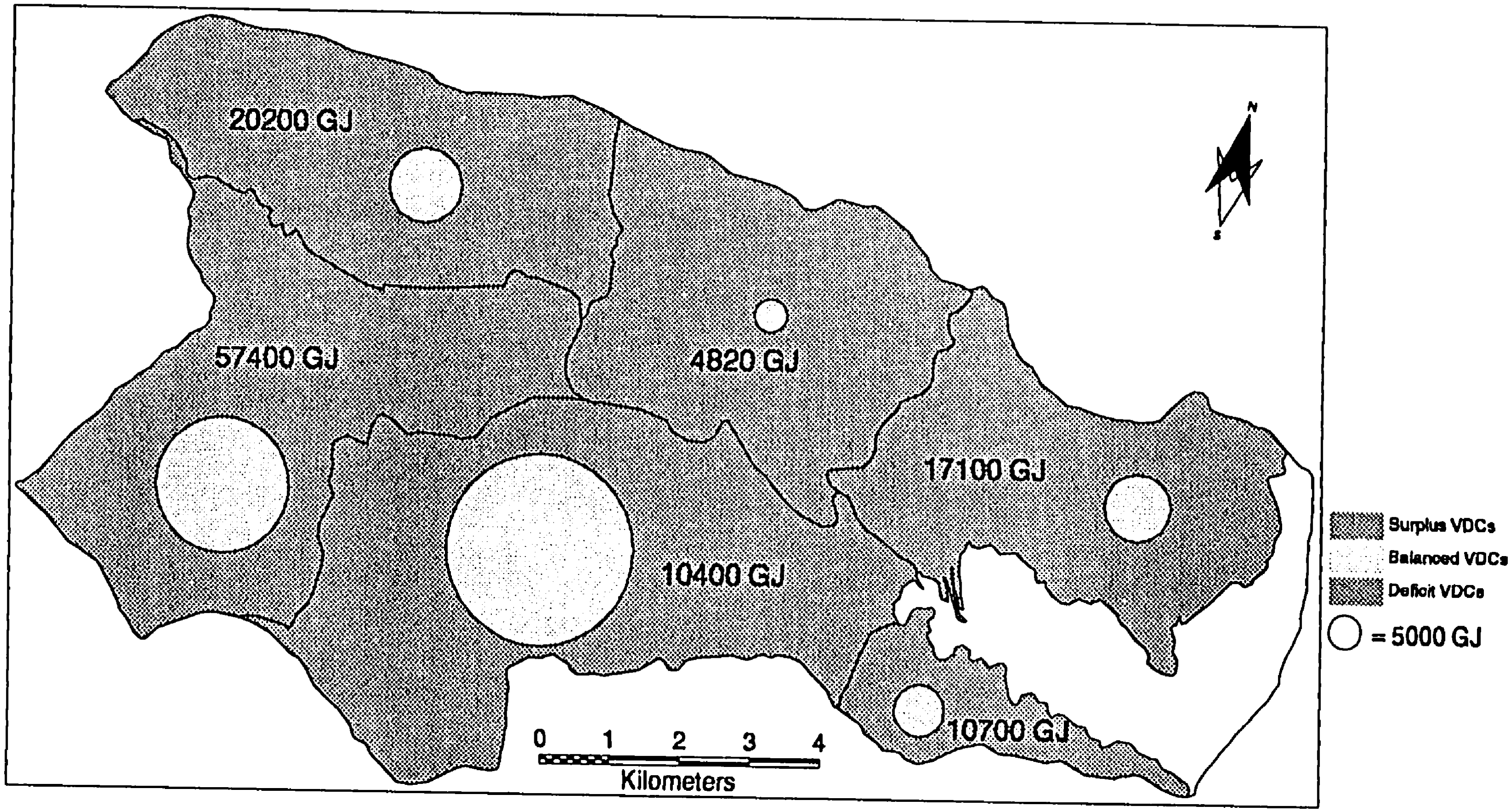

Figure 6.13 Total energy balance for the watershed

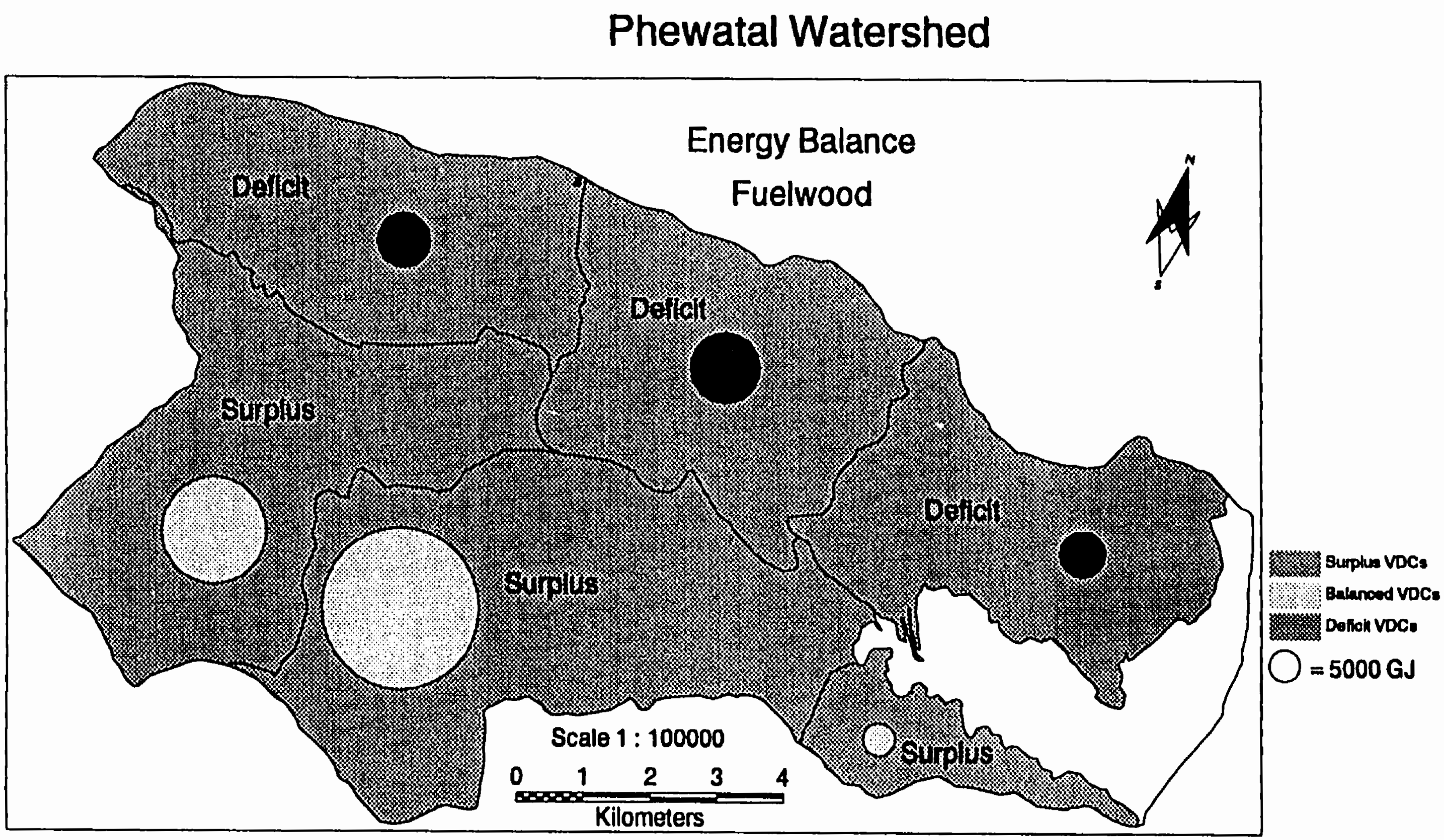

Figure 6.14 Fuelwood balance in the watershed

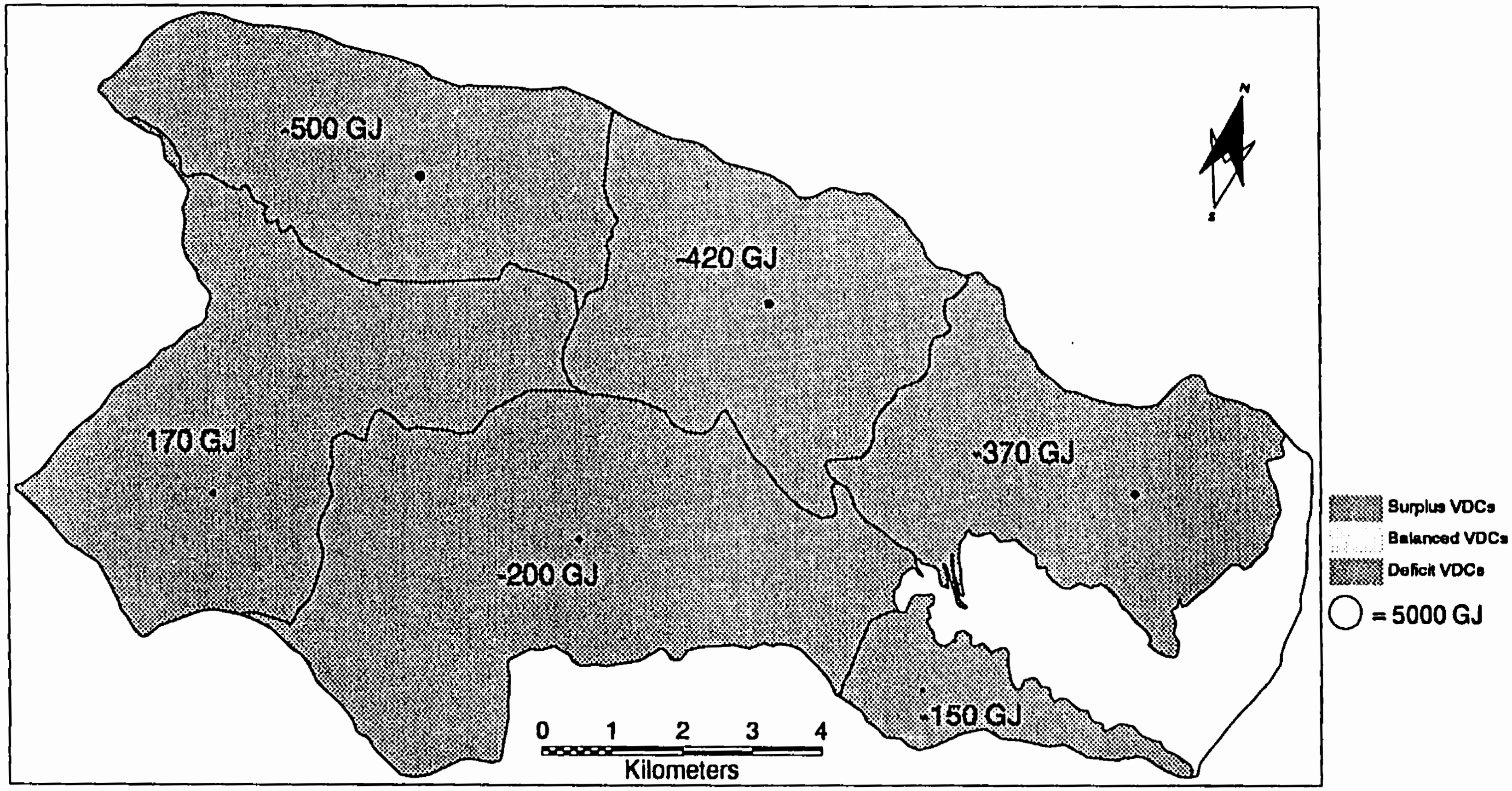

Figure 6.15 Electricity balance in the watershed

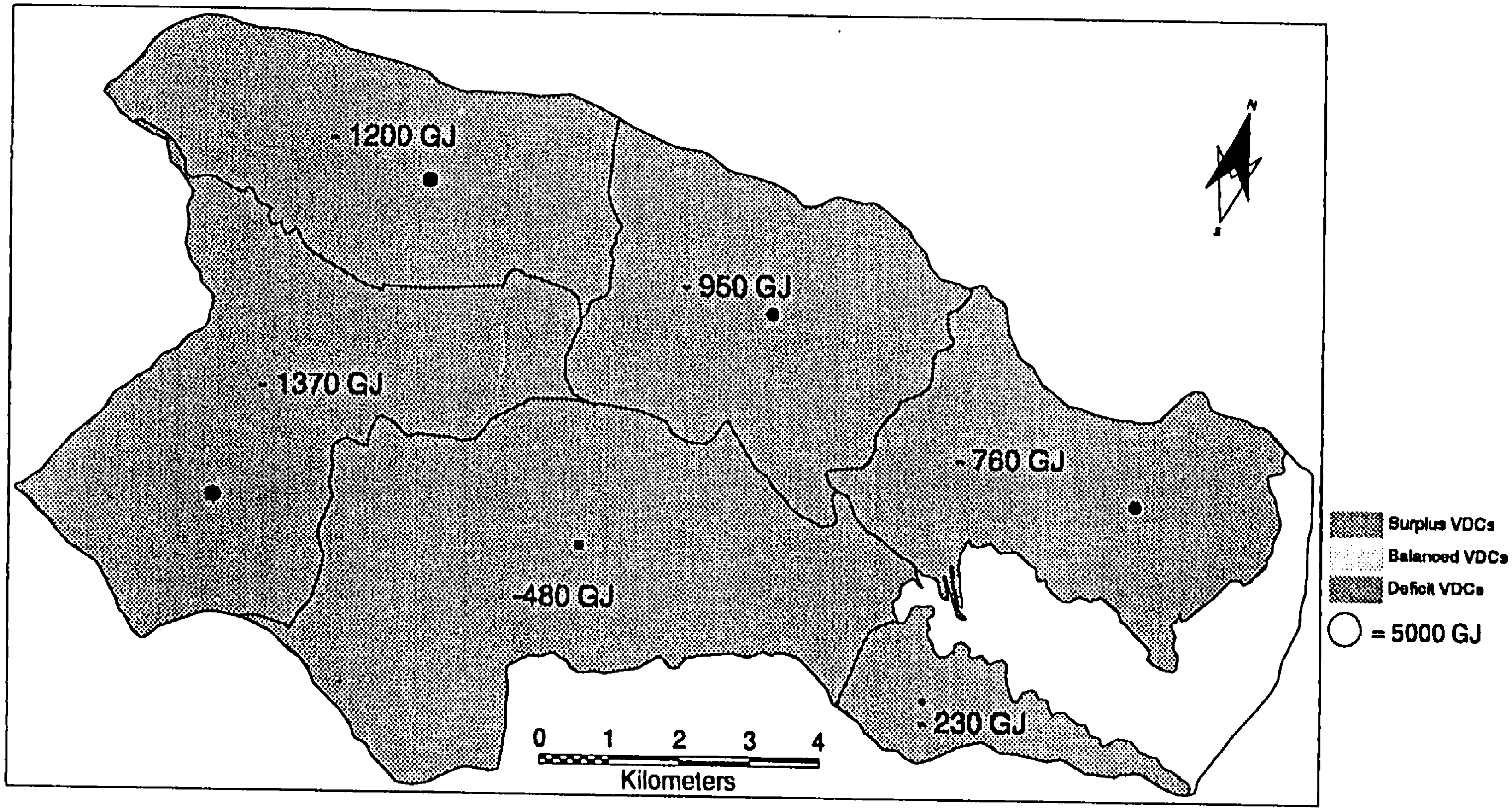

Figure 6.16 Kerosene balance in the watershed

Chapter 7

MULTIOBJECTIVE ANALYSIS AND RESULTS

In this chapter, the resource and consumption data obtained from the spatial model are used to search for an energy solution for the study area. As mentioned in section 4.2.1, coefficients of energy variables are required to formulate objective functions and constraints. Such coefficients may represent energy cost, end-use device efficiencies, employment coefficients, and pollution coefficients. The efficiencies of end-use devices to be used in this research are given in Table 6.13. The cost and employment coefficients are discussed in sections 7.1.1 and 7.1.2.

Three planning objectives and two case studies are examined in the multiobjective model. In the first case study, all of the resources and consumption levels are aggregated for the whole watershed and an energy solution is examined. This approach is used extensively by single objective optimization and goal programming methods in energy analysis. In the second case, both the energy resources and the average energy consumption have been disaggregated to the VDC-level, that is, to the smallest area chosen for the planning. This case has been examined to illustrate that it is better to choose a level of disaggregation for energy analysis as it provides an opportunity for identification of energy surplus and energy deficit areas in the planning region. This information is critical for the formulation of relevant local energy policy. As a test case Pokharel and Chandrashekar (1996b) have used such a disaggregation to formulate an energy policy for one particular VDC in the watershed.

For both case studies, in addition to individual optimization of objectives, two iterations of the STEP-method are performed. The energy balance for the watershed has been tabulated for one of the solutions.

7.1 Energy Coefficients

When the objective functions for energy planning are to be formulated, energy coefficients such as costs, employment, and efficiency are required. As mentioned in Figure 2.1, the derivation of these coefficients are external to the proposed DSS. Therefore, only a brief discussion on these coefficients is given below.

7.1.1 Immediate/Economic/Financial costs

As outlined in section 4.2.1, three types of costs are generally considered in policy formulation. The approach used to calculate these costs for small scale energy projects in developing countries is given in UN (1989).

The immediate costs refer to the costs to be allocated immediately by the government for the implementation of an energy program. When energy programs are to be promoted, funds should be allocated for implementation immediately either by the national government or by the regional or local government. Therefore, the immediate (or implementation) cost would be of much relevance for program initiatives.

The economic costs refer to the costs of the project to the government over the life time of the project. The financial costs refer to the cost of the project for a project developer, or the cost of the product in the proposed scheme to the user. Economic costs are generally obtained by using the shadow prices on the financial costs (NPC 1995).

Some energy alternatives could be attractive to the nation (that is lower economic costs), but may not be financially viable. In such cases, the government needs to promote the programs by creating public awareness, developing infrastructure, and delegating authority. Even if the chosen alternative is financially attractive, an effective public awareness campaign may still be required for the better use of resources.

Owing to the different service periods of different types of energy alternatives, the calculation of the economic costs and the financial costs may pose problems in the analysis. In such cases, the service period of an energy alternative with a maximum operating life time (or with a maximum investment) should be taken as the standard service period and the economic and financial costs should be calculated for all the energy alternatives (Pokharel and Chandrashekar 1995). This will help in comparing the economic and financial costs of various energy alternatives.

The cost estimates used in this research are shown in Table 7.1. An explanation of how these cost coefficients were obtained for use in this research is given in Appendix B. The economic and financial costs shown in the table are extracted from NPC (1995). It should be noted that the cost estimates are site specific.

Table 7.1 shows that the cost coefficients associated with energy variables representing solar energy are very high compared to other energy sources. Moreover, the planning and implementation of a PV system requires more than two years. Therefore, solar energy is not considered in MOP analysis.

Table 7.1 Various energy costs in US$/GJ

Fuel/device	Immediate cost	Economic cost	Financial cost
Fuelwood	8.30	2.10	0.30
Efficient fuelwood stove	0.20	0.06	0.06
Traditional fuelwood stove	0.00	≈ 0.00	≈ 0.00
Crop residues	0.00	2.36	0.34
Animal dung	0.00	2.56	0.36
Biogas	26.70	0.60	0.64
Micro hydro	1.64	34.20	17.70
Solar	1,700	1,500	17.70
Electric bulb	≈ 0.00	≈ 0.00	≈ 0.00
Kerosene	0.96	6.06	5.10
Kerosene Lamp (wick)	≈ 0.00	0.07	≈ 0.00
Kerosene Stove	≈ 0.00	0.44	0.36

7.1.2 Employment coefficients

All new energy programs or ongoing energy programs provide employment opportunities. In this thesis, only direct rural employment that would be generated because of new energy programs is considered with an objective to show the linkage between employment generation and energy programs. The reduction in employment due to a shift away from an energy source as a result of the implemented energy program is not considered here. It is assumed that any savings in labour can be used for useful household purposes and social and other economic activities.

The estimates of employment coefficients used in this thesis are given in Table 7.2. A brief discussion on how the employment coefficients are estimated for use in this research is given in Appendix C. It must be noted that like cost coefficients, employment coefficients are also site specific.

Table 7.2 Employment coefficients in person-yrs/GJ

Energy option	Immediate employment	Long term employment
Fuelwood	0.007	0.0007
Biogas	0.15	0.13
Micro Hydro	0.029	0.02
Solar	0.009	0.006
Efficient Fuelwood stove	0.003	0.0015
Kerosene	0.003	0.003

7.2 Energy Policy Analysis

Energy Variables

The energy variables used in this thesis represent the energy flow path shown in Figure 1.2. The energy variable, x, discussed in Chapter 4 has i, j, k, and p indices, where i refers to the type of fuel (energy resource), j refers to the type of end-use device (the utilization phase), k refers to the end-use, and p refers to a particular area. The possible energy variables that can be used in the analysis can be obtained by examining the energy flow path. However, if a particular flow path is not to be considered in the analysis, then the definition of energy variable for that particular energy flow should be blocked in the MOP model. For example, the energy variables representing briquettes--stoves--end-uses have not been considered in the present model. This way, the effect of desired input parameters can be studied for policy analysis.

On the other hand, if the installation of additional energy technology is to be considered in the model, then a fifth index should be added in the definition of energy variable. Therefore, an index, *N*, is assigned to the energy variable to represent additional installations of an existing energy technology. For example, in the case study in this thesis, the energy variable for installation of additional biogas (*i=7*) plants for cooking (*j=6 for biogas stove, k=1*) in disaggregated area *p* (p=1,2,..,6) is written as x_{761pN}.

Energy Planning Objectives

The application of the proposed model in energy planning is illustrated by considering three pressing conflicting objectives (*q=3*) as discussed below. The first two objectives considered here are generally used separately in single objective energy analysis. The third objective adds an important dimension to rural energy planning.

First Objective: Minimizing the costs of any program to reallocate energy sources.

In order to promote the better use of resources, the government could initiate forest management or interfuel substitution programs and meet the energy deficit either by developing new energy sources or by importing energy. This requires that the national or local government should allocate funds for such energy programs immediately. For better economic efficiency, it would be better for the government if the energy programs could be implemented at a lower cost. Therefore, it is assumed that the main focus of the government is to minimize the immediate costs for delivery of energy services.

Second Objective: Minimizing the energy use from the current level.

Energy planners are concerned with the inefficient use of resources. Therefore, their objective is mainly to reduce the total energy input into a rural energy system so that interfuel and intermode substitutions can be promoted. Therefore, the second objective has been formulated as the minimization of the total energy requirements in the watershed.

Third Objective: Maximizing the local employment that could be generated by an energy program.

Another aspect of the planning objective is to show that local employment would be generated and subsequently that the local people could benefit from the proposed energy program. This illustration is expected to help in creating a positive perception of rural energy programs. Therefore, the objective to maximize local employment is considered here.

Case Studies

In order to illustrate the use of MOP analysis in the decision support system, two case studies have been analysed in this thesis. In the first case study, the watershed is treated as one region and in the second case, the watershed is divided into six sub regions. In each case, the objectives and constraints are first formulated. Then each objective is optimized individually to generate the ideal solution.

In actual decision making environment, the decision makers analyse each of these solutions and decide on further action. They may negotiate to choose one of the ideal solution as the best compromise solution or instruct the analyst for further analysis with the STEP-method. To illustrate the decision-making process in this dissertation, however, the author has acted both as the decision maker and the analyst.

7.3 Case 1: Watershed as One Region

In this case, it is assumed that there would be a free flow of energy resources from one part of the watershed to another. That way, any deficit in a fuel in one area is met by a supply of the same fuel from another area, by energy conservation (such as by using EFSs), and by interfuel substitution (such as using a biogas system for cooking instead of using a fuelwood system), however, there could be some exceptions to this assumption.

The watershed enjoys a net fuelwood surplus. However, because of an access and affordability to kerosene and difficulty in transportation of fuelwood, some of the households may prefer to use kerosene for cooking, if available. Also, electricity generated by small hydropower units may not possible to distribute all around the watershed because of the small hydroelectric potential. Therefore, localized electricity consumption around the generation sites might have to be considered.

In the Phewatal watershed, the three potential hydropower sites are located in Bhadaure Tamagi VDC ($p=1$) , Chapakot VDC ($p=2$) and Dhikur Pokhari VDC ($p=3$). Therefore, all the electricity generated in these sites can only be distributed in the surrounding areas. In addition to small hydropower potential, households in Dhikur Pokhari and Chapakot also have an access to grid electricity. In the remaining VDCs, Kaskikot ($p=4$), Pumdi Bhumdi ($p=5$), and Sarangkot ($p=6$), only grid electricity is available.

All households in Chapakot VDC are connected to the grid extension. Therefore, electricity generated in Handi *khola,* would have no household use in Chapakot VDC. However, the electricity generated at this site can be distributed in Bhadaure Tamagi VDC, which is very close to the potential hydropower site in Chapakot.

The formulation of the three objectives and constraints are given in Appendices D.1.1 and D.1.2. The results obtained by analysing these objectives and constraints are discussed here.

7.3.1 Results for Case 1

a) *Individual optimization*

The results obtained from the individual optimization of the formulated problem are given in the payoff matrix shown in Table 7.3. Each individually optimized solution falls in the non-inferior set as shown in Figure 3.1. Therefore, individually these solutions constitute the compromise solution. The pay-off matrix shows that if the minimizing cost criterion is chosen by the decision makers, then the government has to allocate about US $ 1.22 million for the program. However, if the minimizing energy requirement criterion is chosen then almost 166 TJ[1] of primary energy would be required to fulfil all of the energy demand compared with the current energy consumption of 182 TJ.

The minimization of energy input also minimizes the cost and appears to be an attractive solution. The examination of resource allocation shows that while minimizing the costs, more crop residues are allocated to reduce the cost of the program. As we may recall, there are no immediate cost coefficients associated with the variables representing crop residues.

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[1] TJ = 10^3 GJ

The maximum value of employment that could be generated in the watershed is about 1,400 person-years. However if this option is chosen by the decision makers as the best compromise solution, both the immediate costs and the energy requirements need to be increased to maintain this level of employment.

Table 7.3 Payoff matrix for Case 1

Objectives	f_1, Investment in US $('000)	f_2, Energy in TJ	f_3, Employment in person-years
f_1	**1,220**	178	1,060
f_2	1,220	**166**	1,060
f_3	1,620	214	**1,400**

Since optimal values for all the objective functions define an ideal point, only one of these solutions can be chosen as the best compromise solution. If one of these solutions is chosen by the decision makers for implementation then the analysis process is stopped here.

b) *First iteration*

If the decision makers cannot agree on any one of the above solutions, and want to negotiate and explore other compromise solutions, then the first iteration of the STEP-method should be performed. The formulation for this iteration is given in Appendix D.1.3.

An analysis of this formulation yields another compromise solution, which shows that the next alternative would be to invest about US $ 1.36 million and to accept an employment level of about 1,180 person-years. However, with this solution the energy requirements would increase to 187 TJ. This energy requirement is greater than the present energy consumption level, however, if the resources are to be managed and employment is to be created, then higher consumption might be justified. If this compromise solution is accepted as the best compromised solution, then the following policy options are to be adopted:

* Manage forest areas and extract only about 164,000 GJ or 9,800 mt of dry fuelwood for energy purposes. This would allow the protection of other forest areas. Forest protection is very important especially in the areas close to the settlements. By protecting degraded forest, regeneration would be faster and forest density would be increased.
* Promote the use of crop residues for feed preparation, heating, and food processing.
* Exploit all of the hydro resources available. It is to be noted that the electricity generated in Chapakot is to be distributed in Bhadaure Tamagi.
* Allocate the stipulated quantity of kerosene for lighting in Bhadaure Tamagi and Dhikur Pokhari. Any surplus kerosene should be promoted for cooking in fuelwood deficit VDCs.
* Promote the installation and use of all 600 EFS in the watershed area. This could be distributed in the fuelwood deficit northern part of the

watershed.

* Do not promote further installation of biogas as it could be very costly for the government in the short term. Since, the cooking and food processing demand is met by reallocation of fuelwood throughout the watershed, the installation of biogas plants may not be necessary.
* Reduce the current load shedding to the extent possible in order to reduce kerosene consumption for lighting.

These policy options are implementable, if there is a desire on the part of the government and the local recipients. These options emphasize the use of fuelwood and crop residues.

The decision makers representing cost objective and energy objective may feel that the immediate costs and energy requirements are still higher. These higher values are required to maintain a higher employment level. Therefore, reduction in the cost and energy requirements could be obtained by decreasing the employment level.

Let it be assumed that the decision makers negotiate to reduce the employment level to 1,100 person-years (from 1,180 person-years) so that a reduction in both immediate costs and energy requirements can be obtained. This requires the reformulation of the problem for the second iteration.

c) *Second iteration*

In the second iteration, no weight is associated with the third objective because a level of employment has been set. The reformulation of the MOP problem for this iteration is given in Appendix D.1.4.

The analysis of this reformulated problem yields another compromise solution with a reduced implementation cost of about US $ 1.26 million and reduced energy requirements of about 169 TJ. These values are slightly higher than their optimal values shown in Table 7.3. However, in actual decision-making environment, the decision makers may ignore such a small increment in immediate costs and energy requirements and decide to choose this solution as the best compromise solution.

The energy allocation by fuel types for this compromise solution is given in Table 7.4, which shows that fuelwood and crop residues need to be promoted in the watershed. These two resources are sufficient to meet energy demands for cooking and food processing and the installation of biogas plants would not be necessary. This is also in-line with the perception of biogas companies in Pokhara; that there is no demand for biogas plants because of an abundant fuelwood supply.

Table 7.4 Resource allocation with second iteration

Fuel type	GJ allocated
Fuelwood	152,000
Crop residue	13,000
Biogas (old)	30
Biogas (new)	0
Local electricity	260
Grid electricity	2,790
Kerosene	1,000
Total	169,080

In this case study, five compromise solutions were examined. If the decision makers choose one of these solutions, the detailed resource allocation could be examined and the policy options could be drawn up. The decision makers may also want to seek the energy allocation and consequent policy options before deciding upon any one solution. If the decision makers do not agree on the choice of any of the presented solutions, then one more iteration can be performed or as explained in section 4.3, sensitivity analysis can also be performed on one of the objective functions.

7.4 Case 2: Watershed as Sub-regions

In Case 1, it was assumed that there would be a free flow of local resources in the watershed. However, if the forests are handed over to the community for management and use, at some point, allowing the free flow of fuelwood from one part of the watershed to another would be difficult. Also, with increasing decentralization, VDCs may not be willing to share their resources for free. Therefore, a local self sustaining energy program should be designed, where possible. For such an analysis, it is necessary to understand the energy balance situation in each VDC and analyse the policy options for each of them. This aspect of policy analysis is considered in this section. The formulation of the objective functions and constraints for this case are given in Appendices D.2.1 and D.2.2.

In comparison to Case 1, the objectives and constraints are restricted in this case. When the problem was analysed with the level of resources which gave a compromise solution in Case 1, an infeasible solution was produced for Case 2. A close look at the GAMS® output indicated that the cooking energy demand constraints for the northern VDCs had been violated. In such a situation, either the decision makers have to end the iteration by saying that there is no feasible solution or they have to explore energy solutions with an increased amount of one or more resources. The second option was tested with various levels of kerosene imports as it is the only resource which could be increased for a feasible solution. A value of 10,160 GJ of kerosene imports produced the closest feasible solution and, therefore, this value is taken as the upper limit for kerosene supply in the watershed.

The key point here is that if the decision makers choose to plan at the disaggregated level and if there is no flow of energy resources from one VDC to the next, then this is the only option they can examine under the given decision making environment. This example further demonstrates the advantage of a detailed and small-region approach in energy analysis – an aggregate model, which considers just one region for the whole watershed, would easily have missed this situation.

7.4.1 Results for Case 2

As in Case 1, the results are obtained first by optimizing the objectives individually and then by using the STEP-method.

a) *Individual optimization*

The payoff matrix obtained by optimizing each of the objectives separately is shown in Table 7.5, and shows that the minimum cost of the energy program with the restricted formulations is less than one million US dollars. The minimum energy requirement is about 134 TJ and the maximum employment that could be generated by the program is about 1,420 person-years.

Table 7.5 Payoff Matrix for Case 2.

Objectives	f_1, Investment in US $ ('000)	f_2, Energy in TJ	f_3, Employment in person-years
f_1	**890**	147	800
f_2	890	**134**	800
f_3	1,630	223	**1,420**

This solution is an improvement over the solution obtained in Table 7.2 mainly because of the increased upper limit on kerosene imports. The allocation of more kerosene to avoid a violation of the cooking energy constraints in the northern VDCs has produced a result which is less expensive than the result obtained in the first case study. This allocation caused energy requirements to decrease and the employment level to increase mainly because of the lower cost, higher efficiency, and higher employment coefficients attached to the variables representing kerosene use.

As in Case 1, a minimization of the energy input also minimizes the immediate costs. This is because of the maximum allocation of crop residues while optimizing the cost objective, as explained in Case 1.

If the decision makers agree to adopt one of the optimal solutions as their best compromise solution, then analysis is stopped. Otherwise, further iterations of the STEP-method should be performed.

b) *First iteration*

The formulation for the first iteration on Case 2 is given in Appendix D.2.3. The analysis of the modified formulation yields another compromise solution for this case. The solution shows that by increasing the investment to about US $ 1.24 million, the energy requirements for the various end-uses would increase to about 177 TJ, which is lower than the current level of energy consumption (182 TJ).

However with this solution, employment level is decreased to about 1,100 person-years from its optimal level of 1,420 person-years.

The energy resources allocation for this compromise solution is given in Table 7.6. In Chapakot, it is important to note that there is a wasteful extraction of fuelwood. This would be necessary nonetheless to maintain the employment level at 1,100 person-years.

Table 7.6 Resource allocation in GJ with first iteration (Case 2)

VDC	Fuelwood	Residue	Biogas	Electricity	Kerosene
Dhikur Pokhari	22,800	3,000	44	820	2,053
Kaskikot	13,800	7,550	44	794	4,781
Sarangkot	15,800	5,920	313	635	2,504
Bhadaure Tamagi	28,900	0	5	204	822
Chapakot	55,100	0	3	400	0
Pumdi Bhumdi	11,000	400	2	196	0
Total	147,400	16,870	411	3,049	10,160

The following points give a direction for policy options if this compromise solution is chosen by the decision makers.

- Use all sustainable fuelwood yields in Dhikur Pokhari, Kaskikot, Sarangkot, and Kaskikot. However, since there is a fuelwood surplus in other VDCs, it provides an opportunity to protect the degraded forests in those VDCs. The protection of such forests could allow faster regeneration and consequently provide more fuelwood in the future.

* Crop residues should be taken as the second alternative to fuelwood and should be promoted in all VDCs except Chapakot and Bhadaure Tamagi. These two VDCs are fuelwood surplus VDCs and, therefore, the use of residues may not be an attractive option here.
* Exploit all of the hydro resources available for electricity generation.
* Allocate the stipulated quantity of kerosene for lighting only in Bhadaure Tamagi and Dhikur Pokhari VDCs. The cooking energy deficit in the three northern VDCs should be met partly by kerosene.
* Promote the installation and use of all 600 efficient fuelwood stoves in Dhikur Pokhari VDC.
* Promote the utilization of all of the biogas potential in Sarangkot, Dhikur Pokhari and Kaskikot. However, do not promote any new biogas installation in other VDCs. There would be a potential to install 51 new biogas plants if this policy is adopted.
* Load shedding should be reduced, as it drains money from the local people to pay for lighting and drains valuable foreign reserves from the nations coffers due to the increased import of kerosene for lighting.

After studying these options, if the decision makers believe that they are feasible to implement in the watershed, then it could be chosen as the best compromised solution. Otherwise, second iteration should be performed.

c) *Second iteration and Standard sensitivity analysis*

The formulation for this iteration is given in Appendix D.2.4. In this iteration, the analysis is performed by assuming that the decision makers choose to analyse the MOP problem with different employment levels, that are lower than the value obtained in the first iteration, so that improvement on other objectives can be studied. This type of sensitivity analysis, as explained in section 4.3, is called the standard sensitivity analysis. The result of sensitivity analysis with three employment levels-- 850, 900, and 1000 persons-- is given in Table 7.7, which shows that by increasing the employment level, both cost and the energy requirements would increase. That is, for every unit of increase in employment the immediate cost is increased by about a thousand dollars. Similarly, to achieve a unit increase in employment, the allocation of energy use should be increased by about 180 GJ. This type of analysis helps the decision makers in understanding the tradeoffs among objective functions. Such an opportunity can lead to further negotiation and selection of a better solution.

Table 7.7 Simulation study in second iteration

Objectives	Scenario 1	Scenario 2	Scenario 3
f_1 (US $ in thousands)	950	1,000	1,120
f_2 (Energy in TJ)	155	162	176
f_3 (Employment in persons)	850	900	1000

For the purpose of illustration, Scenario 2 is assumed to be chosen by the decision makers. The resource allocation with this option is given in Table 7.8. The solution indicates that with this option, the use of crop residues should be promoted in all VDCs and 51 new biogas plants should be promoted in fuelwood deficit VDCs. If this option is to be adopted then about one million dollars would be necessary and the energy requirement would be about 162 TJ, which is lower than the current level of energy consumption (182 GJ).

Table 7.8 Resource allocation in GJ with second iteration (Case 2)

VDC	Fuelwood	Residue	Biogas	Electricity	Kerosene
Dhikur Pokhari	22,800	6,700	44	820	2,053
Kaskikot	13,800	8,740	44	794	4,781
Sarangkot	15,800	5,920	313	635	2,504
Bhadaure Tamagi	25,700	3,170	5	204	822
Chapakot	29,200	4,950	3	400	0
Pumdi Bhumdi	11,000	400	2	196	0
Total	118,300	29,880	411	3,049	10,160

Comparing the results shown in Table 7.8 with energy demand shown in Table 6.11, it can be seen that this option allocates more crop residues for use in the watershed. Chapakot and Bhadaure Tamagi are fuelwood rich VDCs, therefore, the use of crop residues may not be so practical in these VDCs.

As in Case 1, five compromise solutions were explored in this case study. If the decision makers do not agree to adopt any of the solutions then one more iteration of the STEP-method can be performed. Otherwise, it should be concluded that there is no best compromise solution for the problem being considered here.

7.5 Energy Balance

The energy balance sheet could be developed for any of the solutions discussed in the case studies. However, only the solution in the first iteration of Case 2 is discussed here for illustration.

The energy balance information presented in Table 7.9 shows that kerosene and electricity are in deficit, as these resources are imported into the watershed. In the case of electricity in Bhadaure Tamagi, all hydro energy developed locally is consumed and, therefore, the electricity is balanced. Any remaining lighting energy deficit would be met by kerosene. In Dhikur Pokhari, micro hydro is not sufficient to meet all of the lighting energy demand. Therefore, the households without an access to grid electricity or local electricity generated in the VDC, would continue to use kerosene. For grid connected households, about 766 GJ of electricity needs to be imported.

The energy balance information also shows that fuelwood consumption in the four VDCs is balanced by the chosen energy option. The energy deficit in these VDCs would be met by crop residues and biogas.

The energy balance information shows that all of the crop residues available in Sarangkot and Pumdi Bhumdi has been allocated for different end-uses. For biogas, however, there is surplus in all VDCs.

Table 7.9 Energy surplus and deficit (-) VDCs with a chosen solution[1]

VDCs	Fuelwood	Residue	Biogas	Electricity	Kerosene
Dhikur Pokhari	0	3,690	21	-766	-2,053
Kaskikot	0	1,190	21	-794	-4,781
Sarangkot	0	0	223	-635	-2,504
Bhadaure Tamagi	22,780	3,170	100	0	-822
Chapakot	21,550	4,950	729	-400	0
Pumdi Bhumdi	0	0	364	-196	0
Total	44,330	13,000	1,458	-2,791	-10,160

The energy balance map for each fuel can be obtained by fitting the resource allocation data obtained from the MOP analysis back into the energy information system. As an illustration, the energy balance map for fuelwood has been given in

[1] Because of data reporting in terms of significant digits in this table, the data for crop residues reported here are more than the data presented in Table 6.5.

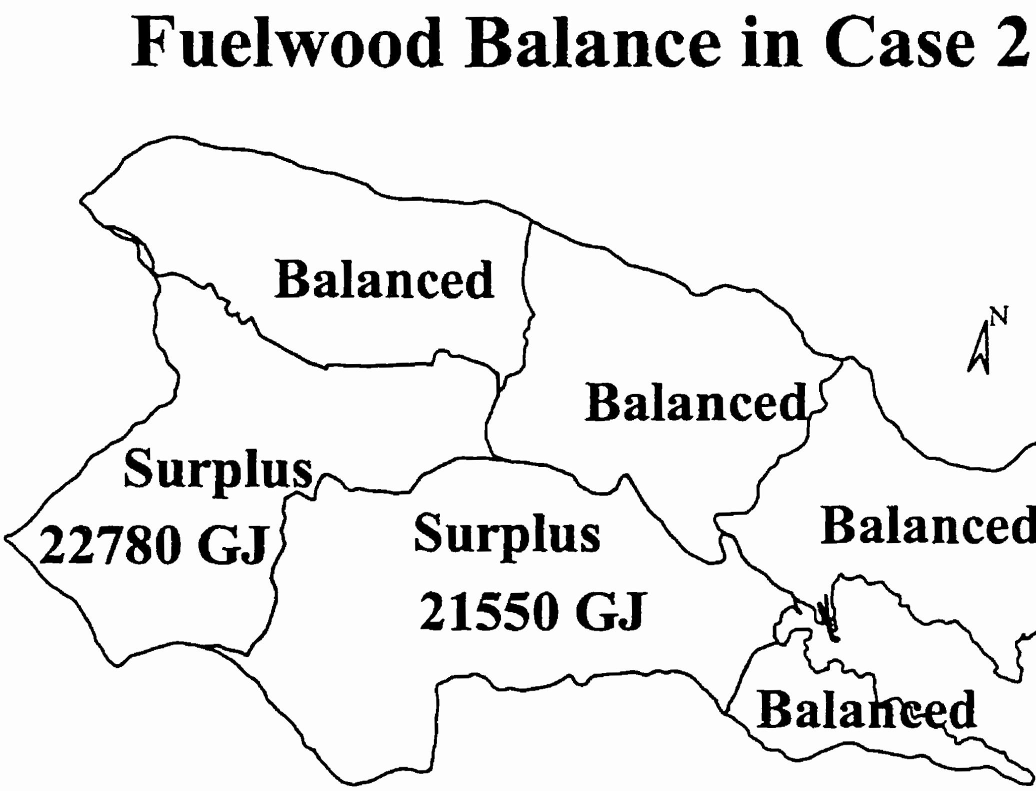

Figure 7.1 Fuelwood balance (for Case 2) after the MOP analysis

Figure 7.1, which shows a total fuelwood surplus in two VDCs and a fuelwood balance in the rest of the VDCs after the proposed allocation of energy resources. Such maps can be drawn for all energy sources and are very useful in illustrating the impact of the energy resource allocation on each VDC.

7.6 Sensitivity Analysis

The sensitivity of the three objectives being analysed in this thesis to the input parameters is examined here. For each of the optimal solution in the STEP-method iteration $t=0$, the resource allocation might be different. Therefore, the marginal costs would be different too. The marginal costs for each of the constrains given in this section is obtained from GAMS output. The units of the marginal costs depends upon the units used in the constraints. For example, demand constraints represent the final energy, whereas supply constraints represent the secondary energy. The units of marginal costs can be calculated by using equation (4.10).

In the Tables below, (.) means no marginal cost (MC) and "EPS" means a very small value for the marginal cost associated with the constraint. A positive value for the marginal cost of a constraint means that if an additional unit of "resource" (that is, right-hand side value) is available, then the objective function will increase by the value of the marginal cost and the reverse is true for negative values of marginal costs.

7.6.1 Sensitivity on Case 1

The sensitivity of input data, as explained in section 4.3, is discussed here. The value of the resources allocated while optimizing each of the objectives and the associated marginal costs for Case 1, as obtained from GAMS output, are given in Table 7.10. The significance of various input parameters as to the change in the ideal solution in this Case is explained in the following paragraphs.

The first conclusion to be made from the table is that there would be no change in the optimum value of employment with a small change in any of the demand or supply constraints. There are no marginal costs associated with the supply constraints for fuelwood and crop residues. This indicates that fuelwood and crop residues are not scares resources. As we may recall from Table 6.16, there is a surplus in fuelwood and crop residues under the existing energy consumption pattern.

Table 7.10 Marginal costs for Case 1

Constraint	Objective functions					
	Cost		Energy		Employment	
	Value	MC	Value	MC	Value	MC
Cooking	15500	83	15500	10	20400	(.)
Feed Preparation	2710	(.)	1480	10	1480	(.)
Heating	2370	(.)	2370	1	2370	(.)
Lighting (Bhadaure Tamagi)	575	83	575	10	575	(.)
Light with kerosene and hydro in Dhikur Pokhari	117	83	117	10	117	(.)
Lighting (grid electricity)	2790	(.)	2790	1	2790	(.)
Food Processing	237	(.)	237	10	237	(.)
Hydro- Sidhane khola	114	-82	114	-9	114	EPS
Hydro- Handi khola	91	-82	91	-9	91	EPS
Hydro- Andheri khola	54	-81	54	-9	54	EPS
EFS installation	9840	-6	9840	-1	9840	(.)
Kerosene supply	1000	-36	1000	-4	1000	(.)
Crop residue supply	29900	(.)	29900	(.)	29900	(.)
Fuelwood supply	191000	(.)	191000	(.)	191000	(.)
Existing biogas	30	-33	30	-3	30	(.)
New biogas	1070	-6	1070	-3	1070	EPS

Table 7.10 shows that the marginal cost for cooking constraints are 83 for the first objective and 10 for the second objective. This means that if the final energy requirement were to increase by an additional unit, then the cost of the program would increase by US $ 83 and an additional 10 GJ of secondary energy would need to be supplied to meet this change. This also means that the additional energy for cooking should be used in a traditional stove. In a traditional stove 10 GJ of secondary energy would be required to generate 1 GJ of final energy.

If the demand for grid electricity increases by an additional unit, there would be no impact on the implementation cost. Since electricity is used for lighting and using appliances with a very high end-use efficiency, additional units of demand should be met by supplying an additional unit of electricity. However, in Bhadaure Tamagi and Dhikur Pokhari, this requirement increases to 9 GJ because of interfuel substitution possibilities between electricity and kerosene.

If the efficiency of efficient fuelwood stoves could be increased, less secondary energy would be required in the watershed. Therefore, if the EFSs to be installed in the watershed can produce more final energy for use with an input of one more unit of secondary energy, then the cost of the energy program would decrease by US $ 6.4.

The marginal cost of kerosene shows that the an increase in the supply of kerosene by one GJ would decrease the total implementation cost by about US $ 36 and decrease the energy requirement by 3.5 GJ. While comparing this with the hydropower potential, it can be stated that increasing the hydropower production might be a better option than increasing the kerosene supply. Hydropower can replace the kerosene used for lighting in Bhadaure Tamagi and Dhikur Pokhari.

For biogas plants, the data indicate that it would be much better to use an additional unit of biogas produced by existing plants than to supply biogas from new plants. However, the reduction in the cost with existing biogas plant is much larger compared with the new biogas plants. Therefore, if the energy demand increases slightly in households with biogas plants and if the demand could be met technically by existing biogas plants then this option would be better than the installation of new biogas plants.

It can be concluded that, for the aggregated case, the objective functions representing immediate costs and energy requirements are sensitive to the estimation of the cooking energy demand, the hydropower potential, the kerosene supply, and the current use of existing biogas plants. The employment objective is insensitive to small changes in the energy supply and demand.

7.6.2 Sensitivity on Case 2

The values of the resources allocated while optimizing. each of the objective functions and the associated marginal costs for Case 2 are given in Tables 7.11 through 7.16. From all the data tables to follow in this sub section, it can be seen that the objective function representing employment is not sensitive to small changes in the supply and demand.

Table 7.11 indicates that any additional requirement of final energy for cooking requires 10 GJ of secondary energy and costs US $ 83 in the southern VDCs (that is, the cost to supply an additional GJ of fuelwood) and US $ 104 in the northern VDCs. In the northern VDCs, since all fuelwood has been allocated, additional units of energy have to be supplied by other sources and therefore it becomes more expensive.

Table 7.11 Marginal costs for cooking in Case 2

Constraint	VDC	Objective functions					
		Cost		Energy		Employment	
		Value	MC	Value	MC	Value	MC
Cooking	Bhadaure Tamagi	2570	83	2570	10	5190	(.)
	Chapakot	1790	83	1790	10	7830	(.)
	Dhikur Pokhari	3950	104	3950	10	3950	(.)
	Kaskikot	3540	104	3540	10	3540	(.)
	Pumdi Bhumdi	880	83	880	10	1100	(.)
	Sarangkot	2830	104	2830	10	2830	(.)

The data in Table 7.12 show that if the demand for feed preparation increases by one unit, then the cost would increase for two of the southern VDCs. An examination of the energy resource allocation indicates that crop residues have been allocated for feed preparation and all of the available crop residues have been used. Therefore, fuelwood must be supplied to meet an increase in the energy demand. The marginal values indicate that, for such an option the cost of the program would increase by US $ 83 and the energy requirements would increase by 10 GJ.

Table 7.12 Marginal costs for feed preparation in Case 2

Constraint	VDC	Objective functions					
		Cost		Energy		Employment	
		Value	MC	Value	MC	Value	MC
Feed Preparation	Dhikur Pokhari	744	(.)	376	10	376	(.)
	Kaskikot	766	(.)	338	10	338	(.)
	Sarangkot	506	(.)	270	10	270	(.)
	Bhadaure Tamagi	245	83	245	10	245	(.)
	Chapakot	442	(.)	170	10	170	(.)
	Pumdi Bhumdi	84	83	84	10	84	(.)

The data presented in Table 7.13 refer to the outputs representing heating constraints. The marginal costs indicate that since a heating stove is assumed to have 100% efficiency, an increase in the heating energy demand by an additional unit would increase the energy requirement by one unit. The figures also indicate that the cost for increasing the heating energy demand in Bhadaure Tamagi and Pumdi Bhumdi would increase the immediate cost by US $ 8.3/GJ. Since all the crop residues have been allocated for different end-uses in these VDCs, the only option to meet an increased heating energy demand is to provide more fuelwood.

Table 7.13 Marginal costs for heating in Case 2

Constraint	VDC	Objective functions					
		Cost		Energy		Employment	
		Value	MC	Value	MC	Value	MC
Heating	Dhikur Pokhari	602	(.)	602	1	602	(.)
	Kaskikot	541	(.)	541	1	541	(.)
	Sarangkot	432	(.)	432	1	432	(.)
	Bhadaure Tamagi	392	8.3	392	1	392	(.)
	Chapakot	273	(.)	273	1	273	(.)
	Pumdi Bhumdi	134	8.3	134	1	134	(.)

The values and marginal costs for food processing for each VDC are given in Table 7.14. The data indicate that the implementation cost would increase only if the demand is increased in Bhadaure Tamagi and Pumdi Bhumdi because of the allocation of crop residues for food processing. For an increase of one unit of final energy for food processing, 10 GJ of additional secondary energy would be required.

Table 7.14 Marginal costs for food processing in Case 2

Constraint	VDC	Objective functions					
		Cost		Energy		Employment	
		Value	MC	Value	MC	Value	MC
Food Processing	Dhikur Pokhari	60	(.)	60	1	60	(.)
	Kaskikot	54	(.)	54	1	54	(.)
	Sarangkot	43	(.)	43	1	43	(.)
	Bhadaure Tamagi	39	8.3	39	1	39	(.)
	Chapakot	27	(.)	27	1	27	(.)
	Pumdi Bhumdi	13	8.3	13	1	13	(.)

The marginal costs and allocated values for lighting are given in Table 7.15, which indicates that where grid electricity is available, the additional demand for lighting (and using appliances) could be met by the existing grid capacity without increasing the immediate cost. This is true because no cost has been assigned for variables representing grid electricity. In Bhadaure Tamagi, demand for additional lighting energy has a very high cost because no grid electricity is available in that VDC. The same is true, if the households without access to grid electricity in Dhikur Pokhari VDC demand an additional unit of energy for lighting.

The marginal costs for grid electricity indicate that one unit of additional energy should be supplied for every unit of increased lighting energy demand in a VDC. In Bhadaure Tamagi and Dhikur Pokhari VDCs, for an additional lighting energy demand, the requirement of secondary energy increases by 10 GJ because of the interfuel substitution possibility between electricity and kerosene.

Table 7.15 Marginal costs for lighting in Case 2

Constraint	VDC	Objective functions					
		Cost		Energy		Employment	
		Value	MC	Value	MC	Value	MC
Lighting	Bhadaure Tamagi	575	104	575	10	575	(.)
	Dhikur Pokhari (other)	117	104	117	10	117	(.)
	Grid supply	2791	(.)	2791	1	2791	(.)

The values and marginal costs related to the resource constraints are given in Table 7.16. The data indicate the scarcity of crop residues in Bhadaure Tamagi and Pumdi Bhumdi. However, in other VDCs, additional units of crop residues are available for energy purposes. In the case of fuelwood, its relative scarcity in the northern VDCs is indicated by a small marginal cost, indicating that cheaper options may be available to supply an additional unit of energy.

Table 7.16 shows that there would be a decrease in the immediate cost and energy requirements with an increase in a small amount of energy supplied by efficient fuelwood stoves. In the case of kerosene, supply of an additional unit would reduce the immediate costs by US $ 45 and the energy requirements by 3.5 GJ.

The marginal costs for hydroelectricity shown in Table 7.16 indicates that an increase in the hydropower capacity would decrease the kerosene required for lighting. The decrease in the cost for a small increase in the hydropower capacity is about US $ 100.

In the case of biogas plants, as mentioned in the first case, every unit of available biogas would decrease the total energy requirement by 3 GJ. However, increasing the supply, if possible, from the existing biogas plants is much better than installing new biogas plants.

The data presented in Table 7.16 also show the relative scarcity of different fuels in each VDC. In the table, the reduction in the total cost by supplying kerosene for cooking in the northern VDCs is shown by the decreased marginal cost. The relative cost savings of new biogas plants shows that it might be much better to start introducing biogas plants in the northern watershed, where fuelwood scarcity is being felt and where the cost savings to the government to supply an additional unit of energy would be greater.

The above mentioned parameters clearly show their significance in the objective formulation and the development of the compromise solutions. These values give guidelines as to the approximation of the energy demands and the energy supply in the multiobjective model.

Table 7.16 Marginal costs for supply of energy sources in Case 2

Constraint	VDC	Objective functions					
		Cost		Energy		Employment	
		Value	MC	Value	MC	Value	MC
Fuelwood	Dhikur Pokhari	22800	-2	22800	EPS	22800	(.)
	Kaskikot	13800	-2	13800	EPS	13800	(.)
	Sarangkot	15800	-2	15800	EPS	15800	(.)
	Bhadaure Tamagi	25500	(.)	25500	(.)	51700	(.)
	Chapakot	16200	(.)	16200	(.)	76600	(.)
	Pumdi Bhumdi	8600	(.)	8600	(.)	11000	(.)
Crop Residues	Dhikur Pokhari	6700	(.)	3000	(.)	3000	(.)
	Kaskikot	8700	(.)	4400	(.)	4400	(.)
	Sarangkot	5900	(.)	3500	(.)	3500	(.)
	Bhadaure Tamagi	3200	-8	3200	EPS	3200	(.)
	Chapakot	4900	(.)	2200	(.)	2200	(.)
	Pumdi Bhumdi	400	-8	400	EPS	400	(.)
Hydropower	Dhikur Pokhari	54	-101	54	-9	54	(.)
	Bhadaure Tamagi	114	-103	114	-9	114	(.)
	Chapakot	91	-103	91	-9	91	(.)
Kerosene		10160	-46	10160	-3.5	10160	(.)
EFS		9840	-8	9840	-1	9840	(.)
Biogas Plants	Dhikur Pokhari	8/37	-(41)/-(14)	8/37	-3	8/37	(.)
Existing/New	Kaskikot	7/37	-(41)/-(14)	7/37	-3	7/37	(.)
	Sarangkot	5/308	-(41)/-(14)	5/308	-3	5/308	(.)
	Bhadaure Tamagi	5/60	-(33)/-(7)	5/60	-3	5/60	(.)
	Chapakot	3/420	-(33)/-(6)	3/420	-3	3/420	(.)
	Pumdi Bhumdi	2/210	-(33)/-(7)	2/210	-3	2/210	(.)

7.6.3 Sensitivity to Changes in the Constraint Coefficients

The above sections dealt with the changes in the energy demand and energy supply. For the purpose of illustration, the changes in the constraint coefficients is discussed here. The change in the objective function due to a small change (*e*) in the coefficient attached to an energy variable x_{ijkp} in a constraint (*s*) is tested by using an empirical relation given by Scharge (1986) as shown in equation (7.1).

$$\partial f_i = x_{ijkp} * MC_s * e \quad \text{for constraint } s \tag{7.1}$$

The efficiencies of end-use devices are attached to most of the constraints in the multiobjective model. Let us examine the cooking constraint in the first case. This constraint is given in equation (7.2).

$$0.1x_{121} + 0.2x_{131} + 0.4x_{761} + 0.4x_{761N} + 0.45x_{551} \geq 15559; \tag{7.2}$$

The coefficient of efficient fuelwood stoves represented by energy variable x_{131} is 20%. An examination of the GAMS output indicates that the value of the energy variable, x_{131}, for all of the three objective functions at *t=0* is 8863 GJ. If the EFSs are slightly more efficient than expected, then the energy use would go down as would the cost. Let us say the efficiency is increased to 21%.

While optimizing the first objective function, the marginal cost for the cooking constraint is obtained as US $ 83 (Table 7.10). Therefore, the decrease in the cost by increasing the efficiency by 1% is about US $ 7,350 (that is, 83 * 8863 *

0.01). This shows that if more efficient stoves could be installed then the cost of the program would reduce considerably.

While optimizing the second objective function (energy requirements), the marginal cost for the constraint is obtained as 10GJ (Table 7.10). This means that if the efficiency of EFSs is increased by 1%, then the energy requirement would be reduced by about 886 GJ (that is, 10 * 8863 * 0.01). In the case of employment objective, it does not have any effect for such a small change because no marginal cost is attached to cooking constraint. This analysis indicates that cost and energy requirements are very sensitive to the efficiency of fuelwood stoves.

This type of sensitivity analysis could also be performed on other coefficients to understand the implications of changes in the coefficient of other energy variables.

7.6.4 Normalized Sensitivity

In order to rank the sensitivity of objective functions with respect to the input data and parameters, the normalized sensitivity values need to be calculated. As an illustration, the normalized sensitivity values for Case 1 as obtained by using equation (4.11) and the marginal values presented in Table 7.10 are given in Table 7.17.

Obviously, when a parameter does not have any marginal value, it does not have any influence on the changes in the objective functions. Since, none of the parameters produced any significant marginal value for the employment objective (as shown in Table 7.10), there are no normalized sensitivity values for the employment objective.

In the table above, values reported in **Rank** columns refer to the ranking of parameters in terms their normalized sensitivity values. A positive normalized value indicates the percentage increase in the value of an objective function due to one percent increase in the input parameter. A negative normalized value indicates the percentage decrease in the value of an objective function due to one percent decrease in the input parameter.

The values indicate that cooking demand is a sensitive input parameter both in terms of immediate cost and in terms of energy requirements. If final energy demand for cooking increases by one percent (that is, by 156 GJ), then the cost of the program would increase by US $ 13,000 (that is, 0.0106 * US $ 1.22 million) and the energy requirement would increase by 1,560 GJ (that is 0.0094 * 165,898) of secondary energy. This information is also obtained directly by multiplying 1% of cooking energy demand with the marginal values for each of the objectives (shown in Table 7.10). However, by ranking the normalized values of the parameters, the significance of changes in the input parameter can be directly visualized.

Table 7.17 Normalized sensitivity values for Case 1

Constraint	Objective functions			
	Cost		Energy	
	Normalized sensitivity values	Rank	Normalized sensitivity values	Rank
Cooking	1.060	1	0.940	1
Feed Preparation	0	--	0.070	2
Heating	0	--	0.014	6
Lighting (Bhadaure Tamagi)	0.040	3	0.030	3
Light with kerosene and hydro in Dhikur Pokhari	0.008	5	0.007	7
Lighting (grid electricity)	0	--	0.016	5
Food Processing	0	--	0.014	6
Hydro- Sidhane khola	-0.008	5	-0.016	5
Hydro- Handi khola	-0.006	5	-0.005	8
Hydro- Andheri khola	-0.003	7	-0.003	9
EFS installation	-0.050	2	-0.060	3
Kerosene supply	-0.030	4	-0.021	4
New biogas	-0.005	6	-0.020	4

Table 7.17 shows that the percentage changes in the value of the objective function with changes with other input data are not large. This leads to the conclusion that the estimation of cooking energy demand could be a single factor that can influence the choice of a particular compromise solution when the watershed is analysed as one single region.

7.6.5 Data uncertainty

The sensitivity analysis presented above deals with small changes in the MOP output for small changes in the input data. However, owing to the uncertainty in the estimation of the input data, one would expect uncertainty in the estimation of the values of the objective functions.

As an illustration of the impact of uncertainty in input data, three examples are examined here. Among the three examples, the first is the analysis of uncertainty in the objective function coefficient, the second is the analysis of uncertainty in the constraint coefficient, and the third is the analysis of uncertainty in the constraint limit. These three examples cover the type of uncertainty that might have to be analysed in energy policy formulation. The importance of these input parameters and their impact on uncertainty in the values of the objective functions are discussed below.

a) **Uncertainty in the estimates of coefficients of the objective functions.**

To illustrate the impact of uncertainty in the values of the objective function because of the uncertainty in the estimates of its coefficients, the first objective of cost minimization is considered here. Since fuelwood is the major energy source in the watershed, the uncertainty in the estimates of its cost coefficient might have a significant impact on the optimal value of the immediate cost.

The estimation of cost coefficient for the base case is discussed in Appendix

B.1 and the optimal value of immediate cost obtained by using the base case cost coefficient is given in Table 7.3. The cost coefficient for fuelwood is obtained by dividing the cost of forest management with the possible energy output from the forests being managed. Therefore, if there exists an uncertainty in the cost estimates for forest management or the energy output from the forest, then the estimates of cost coefficient also becomes uncertain. The uncertainty in the estimation of cost coefficients might lead to a significant impact on the optimal value of the immediate cost. This case is examined below.

For the purpose of illustration, let the uncertainty for both the cost estimates and the fuelwood availability be assumed to fall in a range of ±10% from their base case estimates. Let the base case cost estimates be represented as B_C and the base case gigajoules estimate be represented as B_{GJ}. Then the range of cost coefficient (cost/GJ), owing to these uncertainties, can be calculated with the following equation as suggested by Andrews and Ratz (1996). The term on the left hand side of the equation (7.3) gives the lowest possible value and the term on the right hand side gives the highest possible value for the cost coefficient owing to the uncertainty explained above.

$$\frac{B_C - 10\% * B_C}{B_{GJ} + 10\% * B_{GJ}} \leq Cost/GJ \leq \frac{B_C + 10\% * B_C}{B_{GJ} - 10\% * B_{GJ}} \tag{7.3}$$

Using the above equation, the term on the left hand side produces a minimum value of coefficient as US \$ 6.7/GJ and the term on the right hand side produces a maximum value of US $ 10.0/GJ, implying a ±20% change in the estimate of cost coefficient from the base case (that is, from US $ 8.3/GJ). Therefore, if there were a ±10% uncertainty in the estimates of cost for forest management and energy obtained from the forests, then the estimates for the cost coefficient would be in a range of about ±20% of its base case. When this range of cost coefficient is used in the MOP model, the optimal value of the immediate cost is found to be in the range of about US $ 1 million and about US $ 1.5 million. These values lie also within a range of about ±20% of the base case optimal cost shown in Table 7.3. This means that the uncertainty in the estimates of the immediate cost is almost the same as the uncertainty in the estimates of cost coefficients for fuelwood. Therefore, the decision makers might want to decide on a range of immediate cost to cushion the impact of uncertainty in the estimates of cost coefficients.

b) Uncertainty in the estimates of the constraint coefficients

The impact of uncertainty in the estimates of the constraint coefficient is analysed by choosing one of the major constraint coefficient in the watershed. As discussed above, fuelwood is the main energy source in the watershed. Fuelwood is burnt mainly in the traditional fuelwood stoves for cooking. Therefore, if the efficiencies of the traditional stoves were to change in the actual circumstances, then the energy requirements and the immediate cost would also change.

The field efficiency of a traditional stove could be as low as 5% (Dayal 1993) and as high as 15% (Pokharel 1992). For a 5% efficiency of traditional stove, the model produced an infeasible solution. An examination of GAMS output indicated that the constraint representing the cooking energy demand was violated. The lowest value for the efficiency that produces a feasible solution is 8%. Therefore, if the efficiencies of the traditional stoves in the watershed were less than 8%, then the decision makers should also focus on supply of other energy alternatives such as kerosene to meet additional cooking energy demand.

When the efficiency range of 8% to 15% were analysed in the model, the estimates in the optimal immediate cost ranged between US $ 1.5 million and less than US $ 1 million. The energy requirements for these efficiency estimates ranged between 203 GJ and 116 GJ. This indicates that for a 20% reduction in the efficiencies of the traditional stoves, the optimal values for immediate cost and energy requirements increase 22% from their base case optimal values. However, if the traditional stoves are 50% more efficient, then the optimal values for the immediate cost and energy requirements would decrease by about 30%. This shows that when there is an uncertainty in the estimate of efficiencies of traditional stoves, it would also have a significant impact on the immediate cost and energy requirements.

c) **Uncertainty in the estimates of the limits on the constraints**

The uncertainty in the limits on the constraints can be studied for either resources or demands in the MOP model discussed here. The limits for minimum energy requirement for cooking is examined here.

The data indicate that as much as 85% of secondary energy used in the households in the watershed is required for cooking. Therefore, an uncertainty in the estimates of cooking energy demand can have significant impact on the values of the objective functions.

For the purpose of illustration, let it be assumed that under the actual circumstances, the cooking energy demand varies within a range of ±10%. That means the final energy required for cooking in the watershed falls in a range of 14 TJ to 17 TJ. For this range in cooking energy demand estimates, the optimal value for the immediate cost lies in the range of less than US $ 1 million and about US $ 1.3 million, which is about ±8% of the base case optimal cost. Similarly, owing to this uncertainty in the cooking energy demand estimates, the energy requirements ranges between 150 TJ and 180 TJ, which is about ±9% of the base case optimal energy requirements.

The analysis indicates that there is no change in the maximum employment level with this change in energy demand. This is because, while optimizing the third objective for the base case, all the possible employment level had already been attained.

The above discussion on data uncertainty was to illustrate the impact of estimates in the availability of main fuel source, the use of main end-use device, and the main energy end-use in the watershed. The analysis indicates that the optimal values for immediate costs and the energy requirements are sensitive to the uncertainty in the estimates of fuelwood availability, efficiency of traditional stove, and cooking energy demand. Therefore, care should be given to reduce uncertainty in the estimation of these data. This also shows that the decision makers may want to cushion the cost of implementation and energy requirements within a range to absorb uncertainties in input data.

7.7 Summary

The main objective of this chapter was to show that there is a possibility of using spatial data in a multiobjective model. It is noted that the multiobjective model does not need to handle the data management part and the spatial model does not have to proceed with analytical modelling. They act as separate entities, but together produce a powerful tool with the properties of data handling, visual display, and analytical modelling.

Altogether, five solutions were explored in each of the two case studies. The decision makers may choose any of the compromise solutions to their satisfaction. The purpose of the model is to instigate a dialogue and facilitate the choice of an educated and logical solution by iteratively exploring various solutions. This type of iterative exploration is expected to provide a better understanding of the solutions and their meaning.

If the decision makers are not satisfied with any of these solutions, then the design process for the formulation of a better energy policy should be continued. That is, either sensitivity analysis on one of the objectives should be done further, or one more iteration should be performed, or the objectives and constraints should be reformulated. If none of the above options of the design process satisfies the decision makers, then it should be concluded that there is no best compromise solution for the given problem.

In this chapter, sensitivity of the objective functions to the input data and parameters were also tested. The sensitivity with respect to input parameters helps in recognizing important input parameters for the model.

As a case study, the sensitivity of the objective functions with respected to each other was also tested for the disaggregated case by performing the standard sensitivity analysis on the value of one of the objective functions. The sensitivity of the objective values helps the decision makers to understand the tradeoffs among the objective values.

The model presents the analytical solutions to the given problem. Therefore, it should be emphasized here that the values of the objective functions and resource allocations obtained from the analysis should be taken as *guiding factors* and not in absolute terms.

Chapter 8

CONCLUSIONS AND RECOMMENDATIONS

Almost 75% of the world's population live in the developing countries, most of which have, in recent years, experienced a significant growth in urban population. Consequently, energy policy research and analysis is often focussed on addressing the energy needs of these urban areas.

Significantly, however, about three quarters of the population of developing countries live in the rural areas where biomass is the main energy resource and the use of energy resources is not efficient. Moreover, limitations in resource availability, lack of alternate fuels, and lack of affordability of imported fuels have degraded rural life. Therefore, there exists a real and pressing need both for rural energy policy research and analysis and for state-of-the-art tools to facilitate this analysis. The objective of this thesis is thus to develop and illustrate the utility of a rural energy policy analysis tool, IREDSS, which combines the data handling and presentation capability of a GIS and analytical capability of a multiobjective programming method.

One way to improve the rural energy condition is to make more energy resources available in the rural areas. There have been some attempts to augment the energy supply in the rural areas, but such programs have been *ad-hoc* and have often lacked sustainability. As aforementioned, rural energy planning is either absent or overshadowed by urban oriented energy planning. Some reasons for this situation are the lack of understanding of the rural energy problems and a lack of analysis of various energy options.

Many studies conducted so far attempt to analyse the rural energy problem with a single objective formulation and often shy away from managing voluminous data. Since those formulations can only address one criterion of energy planning, the best option chosen has often failed to generate public acceptance of the implemented programs.

This study suggests that if the principles of geographical information systems are applied, then it becomes much easier to manage the voluminous energy resources data on a rural area and simultaneously it becomes possible to visualize the energy balance information to a chosen level of disaggregation. Such information is helpful to isolate critical areas and to design location specific energy programs.

An energy program should address issues like investment, inefficient use of resources, local participation, and environmental degradation, which is beyond the scope of a single objective optimization. Therefore, a suitable multiobjective programming method is recommended for the analysis energy policy options. It is expected that, by including local participation in one form or another in the national or regional energy planning process, public awareness can be increased, which might increase the chance for the programs' sustainability.

8.1 Decision Support and its Application

The proposed DSS is tested on a rural watershed in western Nepal, where forest denudation for fuel has caused severe environmental degradation. Data on energy resources for the watershed were extracted from the available information as maps and digitized data. A reconnaissance survey, also called a rural appraisal, was done to validate the information obtained through the spatial analysis and to understand the energy consumption by type for different end-uses. This was very important because the information on the use of crop residues and animal dung for fuel would not have been obtained from the desk study. The survey was particularly helpful in understanding the flow characteristics of the streams in the watershed. It was found that three streams contribute most of the water flow in the watershed. Such a study was done by the researcher at this stage. When a decision support system is implemented in a particular rural area, local participants can help to provide such information. The rural appraisal was also helpful in evaluating the viability of the DSS concept.

8.2 Specific Results from DSS

The application of the DSS in Phewatal watershed shows that although the whole watershed as a region has an energy surplus, there are pockets of energy deficit areas, especially in the northern watershed. Since technology may limit the conversion and use of one form of available energy to another, such an energy surplus was found to have no meaning. However, it should be noted that in most energy planning process, establishing the energy balance sheet at this level marks the end of the process. Further disaggregation, at least to one more level, is suggested here.

The resource availability in different VDCs is presented in Table 8.1. If all of these resources could be used economically to meet local energy demand, then the watershed would have an energy surplus. However, the spatial model shows that the northern side of the watershed is in fuelwood deficit, which has caused forest encroachment for fuel. The spatial analysis is also used to locate areas with potential for biogas, hydropower, and solar energy extraction.

Table 8.1 Energy resource in the study area (values in GJ)

VDC\Fuel	Fuelwood	Crop residue	Manure	Biogas	Hydro	Solar
Dhikur Pokhari	30,300	6,700	29,200	65	54	53
Kaskikot	18,300	8,700	18,900	65	0	190
Sarangkot	21,100	5,900	22,500	536	0	122
Bhadaure Tamagi	68,900	3,200	15,300	105	114	56
Chapakot	102,200	4,900	16,800	732	91	13
Pumdi Bhumdi	14,700	400	5,500	366	0	0
Total	255,500	29,800	108,200	1,869	259	434

Data obtained from the spatial analysis are analysed in the multiobjective model with three objectives for minimizing cost, maximizing local employment, and minimizing energy input. Two cases are studied to underline the consequences of developing energy programs by analysing the watershed as one region and as sub regions. The data obtained from the analysis are presented in Table 8.2, which show that if a disaggregated planning option is chosen, then it can provide more employment in the watershed. The optimal values of the immediate costs of the program and energy requirements are less in the disaggregated case.

Table 8.2 Optimum values of objectives in three cases

Cases/Objectives	f_1, Investment in US $('000)	f_2, Energy input in TJ	f_3, Employment in person-years
Case 1:aggregated case	1,220	166	1,400
Case 2: disaggregated case	890	134	1,420

Table 8.3 shows four additional energy options for consideration by the decision makers obtained for each of the cases studied in this thesis. These solutions provide the decision makers with an opportunity to initiate a dialogue for a possible choice of a course of action in the design of a rural energy program.

Table 8.3 Analysis with the STEP-method in two iterations

Iterations	First Iteration			Second Iteration		
Cases\ Objectives	f_1, US $('000)	f_2, TJ	f_3, person-years	f_1, US $('000)	f_2, TJ	f_3, person-years
Case 1:aggregated case	1,360	187	1,180	1,260	169	1,100
Case 2:disaggregated case	1,240	178	1,100	1,000	162	900

The multiobjective model requires the analyst to specify many input parameters which are subject to change due to macro economic impacts, technological improvements, and data collection methodology. Changes in the input parameters lead to changes in the compromise solutions. The sensitivity analysis helps in identifying input parameters that lead to significant changes in the solutions.

The sensitivity analysis indicates that cooking energy demand is the most important input parameter in the MOP model used here. Therefore, care should be given as to its estimates. The illustrated analysis of data uncertainty indicates that the percentage changes in the optimal values of the cost and energy requirements are almost the same as the percentage changes in the cost coefficient for fuelwood management, efficiencies of traditional stoves, and cooking energy demand.

Therefore, the analyst may want to reduce the uncertainty in these data. By knowing such impact on the values of the objective functions due to data uncertainty, the decision makers may be able to choose a better decision that cushions the effect of data uncertainty in the planning area.

8.3 Limitations

The prime objective of the research was to show that the development of an effective decision support system for rural energy planning is possible by combining spatial analysis and multiobjective programming. Having produced energy resource potential and energy balance information and by analysing the output in a multiobjective model, the researcher has met this goal and has contributed towards further understanding and analytical capability in energy planning. Although the attempt was made to make the model as generic as possible, the requirement of digitized data or thematic maps might make it difficult to implement this model in all areas.

The collection of demand data poses some problem too. For the researcher, at least, obtaining information from the households in the estimated time was very difficult. To avoid any confusion with several surveys conducted to date in the watershed, it became very essential to establish the purpose of the research and its relevancy in most of the households visited. This made the survey process very slow although very informative. However, it might pose little problems, if the local people are made aware of the data collection and the importance of their participation in the decision-making.

The model presents analytical results and not subjective judgement and, therefore, requires a user who can interpret the proposed solution. Formulation of the objective functions and constraints might be a problem initially.

8.4 Posterior

The proposed model marks the beginning of the research to seek an energy decision support system by using a geographical information system and multiobjective programming. Although this thesis is developed around a rural region in a developing country, the concept could be applied to any other area with an energy problem. The model, when applied to Phewatal watershed has provided promising results. The following specific areas could be explored for future research in the energy decision support system.

- This procedure should be tested in other regions so that a more robust decision support system could be developed in the future. Further testing could be done by applying additional objectives, more local resources, and extending to end-uses at non household levels.

- At present the spatial model calculates the hydro energy potential by using basin analysis and user provided hydropower sites. In future, damming possibility for hydropower generation and automatic generation of length of water canal and maximum possible net water head should be considered. Additional coefficients like surface runoff, seepage, and evapotranspiration can also be considered to calculate stream flow.

- The model is set up in ARC/INFO® software on a UNIX platform. This might hinder the dissemination of the DSS concept. Therefore, work should be done to develop a microcomputer-based DSS so that it could be provided faster and cheaper to the energy planners in the developing countries.

- The slopes map could be generated from contour information. This information and soils information would be helpful to add an additional feature for watershed management.

- Public participation can be one of the key factors in the analysis and implementation of energy policies. Future work on the decision support system can be carried out to seek ways to include public participation in the DSS model.

Appendix A

SURVEY FORM

Survey format for

Rapid Rural Appraisal of Phewatal Watershed

VDC Name________________________________

Village________________________________

Date:________________________________

by: Shaligram Pokharel

HH Number		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1. HH size	Adults									
	<14 yrs									
2. Livestock	Cattle #									
	Buffalo#									
	Sheep/Goats#									

HH Number		1	2	3	4	5	6	7	8	9
	Other (large)									
3. Fuelwood	Collect month/yr									
	Farm m/yr									
	Purchase m/yr									
To collect	Cut T/B/Floor									
Gr/Fw used	..../yr									
4. Crops	Paddy /yr									
produced	Maize									
...(unit)	Wheat									
	Millet									
	Barley									
	Mustard									
	Potato									
	Soybean									
Residue collected ...(unit)	Paddy straw/husk									
	Maize Cobs/stalk									
	Wheat Stalk									
	Millet Stalk									
	Barley Stalk									
	Mustard stalk/bran									
	Soybean stalk/husk									
	Potato stalk									
Residue use	Fuel									
	Fodder									
	Other (what?)									

HH Number		1	2	3	4	5	6	7	8	9
If residue as fuel	Paddy straw/husk									
	Maize cobs/stalk									
	Millet stalk									
	Wheat stalk									
	Barley Stalk									
	Mustard stalk/bran									
	Soybean stalk/husk									
	Other (what?)									
5. Dung use	Manure									
	Fuel									
Collected	in wet.......(unit)									
6. If Biogas	Capacity									
used	hr/day									
	days/year									
7. Kerosene	Local purchase									
	Urban purchase									
	Price/litre									
Bought	litres/year									
8. Charcoal	Make/buy									
	cost/unit									
fresh/wet	FW->charcoal (wt)									
	Used .../month									
9. Electricity	G/M/Diesel									
	Cost/month									
10. Cooking	Meals/day									
	Fuelwood									

HH Number		1	2	3	4	5	6	7	8	9
...(unit)/yr	Residue(what)									
	Charcoal									
	Manure									
Biomass Stoves #	Biogas(burners)									
	Kerosene(W/P)									
	Electricity(stove)									
	Other (what?)									
	Open/Trad/EFS									
11. Animal Feed Fuel used	O/T/E									
	hr/day									
	days/yr									
	Abbreviate									
	Unit/yr									
12. Lighting	Tuki #									
	hr/night(avg)[1]									
	Lantern#									
	hr/night									
	Petromax#									
	hr/night									
Electric	Total Bulbs #									
only used	Total Watts									
	hr/night(avg)									
Biogas	lamp #									
	hr/night(avg)									
cum	biogas/hr									

[1] if two, one and two hrs, use 1.5 hrs

HH Number		1	2	3	4	5	6	7	8	9
13. Room Heating mt/yr	days/yr									
	hr/day									
	Fuelwood									
	Residue									
	Kerosene									
	Electricity									
	Other (what?)									
14. Food Processing kg/yr	Rice Flakes									
	Parboiled Rice									
	Bread									
	Sweetmeat									
	Alcohol									
	Other (what?)									
Stoves	O/T/E									
Fuel/yr	Fuelwood									
	Residue									
	Other (what?)									
15. Water heating	O/T/E stove									
	hr/yr									
Fuel (unit/yr)	Abbreviate									
16.Appliance	TV"(B/C), Watts									
	hr/yr									
Press Iron(E)	Watts									
	hr/yr									

HH Number		1	2	3	4	5	6	7	8	9
PressIron(c)	kg/hr (cap)									
	hr/yr									
Fridge	Watts									
	hr/yr									
Radio	W/V									
Cassette	hr/yr									

Remarks:

Appendix B

COST COEFFICIENTS

In this appendix, the immediate cost coefficients are calculated for use in the thesis. The approach to obtain economic and financial cost coefficients is briefly outlined.

B.1 Fuelwood

The immediate cost required for forest management is estimated from deLucia and Associates (1994). Based on the literature, it is estimated that about US $ 370 (1 US $ = Rs. 50) is required immediately to put every hectare of forest under management in Nepal. Forest area covers almost 57 sq.km in the watershed and produces almost 256,000 GJ of primary energy annually, if used sustainably. Therefore, the average cost for fuelwood management in the watershed would be US $ 8.3 per GJ. This is the immediate cost coefficient to the energy variables representing fuelwood consumption.

The economic cost of fuelwood is the cost to the government to replace an equivalent quantity of fuelwood in the watershed by growing it in the watershed or by extracting fuelwood from a source outside the watershed, or the cost incurred to correct negative impacts caused by fuelwood extraction. Since the analysis to obtain environmental impact costs are complex and it was not possible to obtain these data from the reviewed literature, only the first option, that is to replace the fuelwood consumed, is considered here.

The financial cost is the cost of labour required to collect fuelwood. If it were purchased then the purchase price would be considered as the financial cost.

B.2 Crop residues

If energy uses for crop residues have to be promoted further, then they might have to be collected and redistributed. However, due to a lack of data, no immediate cost is assumed for the government.

The economic cost of crop residues refers to the cost of collecting, storing, and distributing crop residues, when it has to be promoted for energy use. It could also be the cost of generating an equivalent quantity of energy or fodder from other sources. Since there is no opportunity to collect residues to produce energy sources like briquettes, only the second option of costing could be considered here. The financial cost of crop residues is the cost to the consumer if it has to be purchased.

B.3 Animal manure

The economic cost of animal manure is the cost required to replace manure use by an alternative fertilizer of equivalent value. Generally, the value of chemical fertilizer is taken as the replacement cost for animal manure. The financial cost is the cost to produce an equivalent quantity of dry manure, if this is the sole by-product, or the cost to purchase animal manure from a source external to the household.

Since, animal manure is the only input to the field, it would have negative consequences if diverted for fuel use. Therefore, it is assumed that the use of dung for energy would not be promoted.

B.4 Biogas

If the government provides a subsidy on the cost of biogas plant, then this subsidy should be taken as the immediate cost because the government needs to provide this money for the installation of biogas plant. In Nepal, US $ 200 is provided as a subsidy for every installed biogas plant. It is assumed that such a plant produces 13 GJ of secondary energy. However, if biogas is promoted for cooking and food processing then, based on the current consumption pattern, about 7.5 GJ of biogas energy would be used for cooking and food processing. Therefore, the cost for subsidy would be about US $ 26.7 per GJ irrespective of the plant size.

The economic cost of a biogas plant is the cost required by the government to pay as a subsidy over the operating life of a biogas plant or the economic cost of the fuel replaced by biogas. A methodology for the calculation of the economic cost of a biogas plant is given in Pokharel et al. (1991).

The financial cost of biogas includes the cost of livestock, if biogas generation is the sole purpose for keeping livestock. However, then the revenue obtained by selling milk or manure should be subtracted. Also, if the milk and manure produced by livestock replace the earlier purchases, then these factors should also be taken into account. A detailed treatment of the calculation of the financial cost of a biogas plant is also given in Pokharel (1992).

B.5 Fuelwood stoves

The immediate cost for promoting efficient fuelwood stoves is the cost of production and training. The cost of various types of efficient fuelwood stoves used in India are given in FAO (1993a). Rijal and Graham (1987) have made a study on the cost of EFSs in Nepal. Based on this study, it is estimated that about US $ 4/EFS is required to produce an EFS with about 20% end-use efficiency (and an operating life of two years), train the trainees and the stove-users, and to install the stoves in the watershed. On average, 32.8 GJ/yr of primary energy is used by a household for cooking, feed preparation, and food processing if a traditional fuelwood stove is used. If this activity is replaced by an EFS mentioned above, only about 16.4 GJ of energy would be required to fulfil the same end-uses. Therefore, the average cost of introducing an EFS would be US $ 0.2/GJ. Therefore when the fuelwood costs are added, the energy-use cost for an EFS becomes US $ 8.5/GJ. Since traditional stoves are made by the households themselves, there would be no additional cost involved for the government.

The economic cost of a traditional stove is the economic cost of the material used for making the traditional stove. If an EFS has to be built (some models) and distributed, then the economic cost of an EFS would be the economic cost of production (or cost of purchasing the produced EFS), transportation, training individuals, and installation. The financial cost is the cost to the end-user to install a traditional stove or to get an EFS installed.

B.6 Micro hydro

Micro hydro based electricity generation is promoted by the government with a subsidy of US $ 140 per plant to cover a part of the electricity generation cost. Therefore, if electricity generation is to be promoted in the watershed, the three identified sites would require about US $ 420, which averages to about US $ 1.64/GJ.

Micro hydro replaces either diesel consumption, if used as a grain processing unit or kerosene, if electricity is generated. The generation of electricity specifically would avoid the generation of an equivalent amount of electricity elsewhere and extending electricity grid to the area. deLucia and Associates (1994) recommend that the Long Range Marginal Cost (LRMC) of electricity could be taken as the economic cost for electricity generation and expansion. However, it should be noted that the LRMC depends upon the type of resource exploitation envisaged by energy planners. The financial cost of electricity to the consumer is the cost for wiring, installing ballasts or switch/sockets and the incandescent bulbs or fluorescent tubes, and the cost for the electricity used.

B.7 Solar photovoltaic

The immediate cost for a solar photovoltaic installation is the cost of land acquisition, materials, equipment, and installation of the system. Based on GTZ (1992), the average cost of a PV module is estimated at about US $6-8 per peak-watt ($W_p$). For a PV system with battery control units, batteries, invertors, and transmission, the cost increases to more than US $ 10/W_p.

From Table 6.12, it is seen that a PV-module with 1 kW_p capacity can produce 5.8 GJ of annual energy. Therefore, the immediate cost for installation of a solar photovoltaic system is US $ 1,700 per GJ, which is very high compared with the hydropower and kerosene options for lighting.

The economic cost of a solar photovoltaic system is the cost to import the PV-modules, transport them to the site, install the generation and battery storage system, distribute the electricity, and maintain the system. The economic cost of the solar PV system is higher in Table 7.1. This is because of higher cost of the whole system when the solar PV system was installed in Nepal. The cost of a solar PV system is decreasing over the years because of the advancement in PV technology. The financial cost is the same as the financial cost for hydro based electricity.

B.8 Kerosene

In Nepal, every kilo litre (kl) of kerosene is sold at US $ 35.2 below its economic price (as a subsidy) to discourage the use of fuelwood for cooking, at least in the urban areas. The immediate impact of kerosene use is in the import and the subsidy amount, that is US $ 0.96 per GJ. The subsidy amount is an added cost to the government and is taken as the immediate cost.

The economic cost of kerosene refers to the cost incurred to explore, distil, and distribute kerosene, if the country produces a sufficient quantity of kerosene. Otherwise, it refers to the cost of import, storage, and distribution. The financial cost is the cost paid by the end-user in the open market.

B.9 Electric bulbs

Since electric bulbs are to be purchased by the public, the only immediate cost to the government would be the cost to import or produce an increased number of these devices. It is assumed that there is no direct significant cost to the government with such an increased consumption.

The cost to import electric bulbs or to import the raw material and skills to produce electric bulbs is taken as the economic cost. The financial cost is the cost to the consumer.

B.10 Kerosene lamps and stoves

Kerosene lamps and kerosene stoves are purchased by the end-user. Therefore, no immediate cost is assumed for the government. The economic costs of these devices are the economic cost of the raw material for production. The financial cost is the purchase price of these devices.

Appendix C

EMPLOYMENT COEFFICIENTS

The employment coefficients associated with the third objective discussed in Chapter 7 are elaborated upon here.

C.1 Fuelwood

As mentioned before, properly managed forests can yield fuelwood to the tune of 2.5 to 5 times that from a non-managed forest. In the Phewatal watershed, fuelwood yields could be increased three fold if forests were managed (IWMP 1992). The government has nothing to lose from managed forest areas. The current practice of handing over some of the forest areas to the local community should be lauded in this regard. However, the local people do not have enough expertise on forestry management. It was seen that the local communities were protecting the forest but cutting it down unsystematically. Therefore, the training of local people in conjunction with the hand over of more forest is highly recommended.

Employment in the forestry sector depends upon the forest area to be managed and available infrastructures. Better road access would allow for better and more effective management as compared with inaccessible areas. The larger the forest area, the lower is the employment factor. Similarly, if the forest area is closer to the habitation, then more employment might be necessary to check pilferage and unauthorized livestock grazing.

For forestry management, people are required for nursery development, guarding forests, forest foremen, and rangers. These personnel could be recruited at the local level. The employment estimates used here are based on deLucia and Associates (1994) for a hectare of land (extracted from Table 3G-2C), which shows that about 0.3 person-years would be required in the first year and 0.03 person-years in the longer term to manage and redistribute fuelwood from a hectare of land. From Table 6.2 it is known that the current fuelwood yield is about 256,000 GJ from 5,700 hectares of forest. Therefore, the short term employment generated by forestry management in the watershed is about 0.007 person-years/GJ.

C.2 Crop residues

The employment for crop residues would be for the collection, storage, and management of the residues. However, due to a lack of data, no additional employment due to the use of crop residues is assumed here.

C.3 Biogas

If the decision is taken to install biogas plants, then employment generated by biogas should be considered. Every ten cubic metre biogas plant (which is considered here for dissemination as most of the new installations in Nepal are of this size) requires 45 person days of unskilled labour (that is, 0.12 person-years) that could be employed locally. In the case of long term labour generation, at least one person is required (as a keeper) for tending livestock, cleaning, feeding livestock, and operating the biogas plant. One biogas plant is expected to provide 7.5 GJ that could be used for cooking and food processing in the watershed. That means, short term labour (including the keeper) generated by biogas installation would be 0.15 person-yrs/GJ.

C.4 Micro hydro

Like biogas, micro hydro also has both long term and short term employment opportunities. In the short term, employment would be created for the transportation of materials, construction of canals, installation of equipment, and construction of a turbine house.

Based on Pokharel (1990), it is assumed that at least two persons would be required to maintain the facility. In this watershed, since two steel turbines have already been installed, immediate labour requirements in these cases would be lower. In the case of a wooden waterwheel, if a steel turbine needs to be added, then it would require labour for improvement of canal and installation of turbine too. The number of unskilled labourers required depends upon the site, the length of the canal to be constructed, the power output, and the transportation of material and equipment. Based on the researchers' survey of micro hydro plants in Nepal in 1989 and 1993 and his work as a production engineer at Balaju Yantra Shala Kathmandu between 1985 and 1986, it is assumed that about 30 person-months of labour (except house wiring) are required for the construction of a new micro-hydro plant and five person-months for *add-on* installations below 20 kW capacity. The total estimated output capacity in the watershed is 260 GJ in three sites. Therefore, short term employment would be about 0.009 person-years/GJ for a new plant and 0.0017 person-years for the *add-on* installation. When operating persons are included, then it would be 0.029 and 0.022 person-years/GJ for new and *add-on* installation respectively. However, about 0.02 person-years/GJ of employment would be required in the long term.

C.5 Solar photovoltaic

For solar-based electricity generation, long term employment is required for the maintenance of the system if it is to be considered as a central distribution system. Short term employment is generated for the transportation of materials and equipment, the construction of a site and generation house, and the house wiring. In the absence of data, the short term employment is assumed to be the same as that of a new micro hydro unit. In the case of the long term employment coefficients, inference could be drawn from a 25 kW (electricity distribution capacity) PV generation unit in Tatopani, Nepal. The facility is currently manned by three unskilled employees, three administration staffs, two metre readers and one technician (in 1993). That means, if the operation is handed over to the community then, except for the technician, a maximum of eight local people could be employed there. This facility produces and distributes about 1,350 GJ of solar energy per year. The average employment provided by the facility, therefore, is 0.006 person-years/GJ. In an isolated household system, however, both long term or short term employment may not be created.

C.6 Kerosene

Assuming that every person can transport 20 litres of kerosene per day from the urban centre to the clustered settlements, a person can transport about 265 GJ of kerosene each year. This is assumed as both the short and long term employment for the kerosene option. No short term and long term employment has been assumed for end-use devices using kerosene fuel due to a lack of data.

C.7 Efficient fuelwood stoves

If one trained person is allocated to install 20 EFSs annually and to train the end-user to use it, then total energy produced by 20 EFS would be 328 GJ. That means, the short term employment with an EFS would be 0.003 person-years. Since, the operating life of an EFS is assumed as two years, half of the short term employment would be required every year to replace an older EFS.

Appendix D

FORMULATION OF OBJECTIVES AND CONSTRAINTS

As shown in section 4.2, the energy variable used in this thesis is x_{ijkp}, where i refers to the type of fuel, j refers to the type of end use devices, k refers to the end-use (or energy service), and p refers to a particular area. Also recall from section 7.2 that when additional energy technologies are to be analysed for implementation, an additional index N is added to the energy variable. The assumptions made for the formulation of the objective functions and constraints are given below.

Hydro and Grid Electricity

The electricity is used for lighting and appliances. Therefore, it is expected that if a new micro hydro plant of capacity, λ_p, is installed in VDC p, then the constraint could be written as,

$$x_{693p} + x_{607p} \leq \lambda_p;$$

However, only a portion of the electricity would be used for appliances. The survey indicated that if electricity could be supplied uninterrupted, then the consumption would be about 0.1172 GJ/capita for lighting and 0.0002 GJ for using appliances. Therefore, the binding constraint for allocation would be,

$$(1/0.1172)\ x_{693p} - (1/0.0002)x_{607p} = 0;$$

Or, $x_{607p} = 0.0017\ x_{693p}$;

Or, $x_{693p} \leq \lambda_p/1.0017$;

Kerosene Consumption

In terms of energy value, the present consumption patterns indicate that kerosene demand for lighting is 2.2 times greater than electricity demand. Therefore, the demand for lighting energy, Λ_p, is written as,

$$x_{693p} + 0.45\ x_{693p} \geq \Lambda_p;$$

Efficient Fuelwood Stove (EFS)

A traditional stove requires 32.8 GJ of primary energy for cooking, feed preparation, and food processing in a household (average size 5.62 persons). If an EFS could be used for the same purpose, because of increased end-use efficiency, it would require only half that energy. Therefore if an EFS is to be used, and if ς_p number of EFS installations is planned, then the constraints could be written as,

$$x_{131p} + x_{132p} + x_{135p} \leq \varsigma_p * 16.4;$$

However, as seen from Table 5.7, the energy required for all three end-uses is different. Therefore, if an EFS is to be used for these end-uses, then the constraints could be written as,

$$(1/5.24)\ x_{131p} - (1/0.5)\ x_{132p} = 0; \text{ and}$$

$$(1/5.24)\ x_{131p} - (1/0.08) x_{132p} = 0;$$

Therefore, $x_{131p} \leq \varsigma_p * 16.4/1.1102;$

Biogas Installation

The efficiency of a biogas stove is assumed as 40%. Therefore the energy required by a biogas stove for cooking and food processing is ¼ that required by a traditional stove. It is assumed that a biogas stove is used for cooking and food processing only. The potential number of biogas plants has been identified in Table 6.7. Each plant should supply 7.5 GJ of primary energy for the proposed end-uses in a household. If the number of potential biogas plant in a VDC is ψ_p, then the constraint could be written as,

$$x_{761p} + x_{765p} \leq \psi_p * 7.5;$$

Since only a portion of biogas will be used for food processing,

$$(1/5.24)x_{761p} - (1/0.08)\ x_{761p} = 0;$$

Therefore,

$$x_{761p} \leq \psi_p * 7.5/(1.0152);$$

D.1 Case 1

In this case, the watershed is assumed as one region and no restriction on the supply of energy is assumed.

D.1.1 The objectives

a) ***Minimizing the cost allocation for the program implementation***:

The cost minimization objective is given below. The cost coefficients are the immediate costs given in Table 7.1. Since, production of hydro electricity in the three sites is different, the cost per gigajoules is also different.

$$\text{Minimize } 8.3(x_{121} + x_{122} + x_{124} + x_{125}) + 8.5(1.1102 * x_{131}) +$$
$$26.7(1.0152 * x_{761N}) + 1.0017\,(1.2\, x_{6931} + 1.6 x_{6932} + 2.6\, x_{6933}) +$$
$$0.96(x_{551} + x_{5831} + x_{5833});$$

b) ***Minimizing total energy input***:

The objective could be written as the minimization of the total energy input for different end-uses in the system and is formulated as,

$$\text{Minimize } x_{121} + x_{122} + x_{125} + x_{124} + x_{222} + x_{224} + x_{225} + 1.1102\, x_{131} + x_{551} +$$
$$x_{5831} + x_{5833} + x_{761} + 1.0152\, x_{761N} + 1.0017\,(x_{6931} + x_{6932} + x_{6933} + x_{9932} +$$
$$x_{9933} + x_{9934} + x_{9935} + x_{9936});$$

c) ***Maximize rural employment:***

In the objective function formulated below, the employment coefficients are expressed in 1/1000 GJ. These values of immediate employment are obtained from Table 7.2. The local employment for micro hydro installation is not the same for all three identified sites because the installations in Bhadaure Tamagi and Chapakot are only *add-on* types. Therefore, the employment coefficients for micro hydro installations in the above sites are lower.

$$Maximize\ 7(x_{121} + x_{122} + x_{124} + x_{125}) + 10\ (1.1102\ x_{131}) + 15(1.0152x_{761N}) +$$
$$3(x_{551} + x_{5831} + x_{5833}) + 20 * 1.0017\ (x_{6931} + x_{6932}) + 29 * 1.0017x_{6933});$$

D.1.2 Constraints Set

The limitations on the objectives formulated above are discussed in this section.

a) ***Energy required for cooking should be met:***

The coefficients used here are end-use efficiencies.

$$0.1x_{121} + 0.2x_{131} + 0.4x_{761} + 0.4x_{761N} + 0.45x_{551} \geq 15559;$$

b) ***Energy used for feed preparation should be met***: The coefficients are end-use efficiencies.

$$0.1x_{122} + 0.1x_{222} + 0.2\ (0.0905\ x_{131}) \geq 1483;$$

c) ***Energy required for lighting and appliances should be met***:

The lighting energy requirement in Bhadaure Tamagi could be met by two sources, either by hydro-based electricity or by kerosene. The lighting energy in Chapakot can be met by grid electricity and hydro potential in Chapakot can be used in Bhadaure Tamagi because of the proximity of the site with Bhadaure Tamagi. The constraints for lighting energy (both demand and potential) have been developed on a VDC basis because of localized nature of hydropower installation.

$1.0017\,(x_{6931} + x_{6932}) + 0.45x_{5831} \geq 575;$

$x_{6931} \leq 114/1.0017;$

$x_{6932} \leq 91/1.0017;$

In Chapakot, all lighting/appliances energy is met by grid electricity

$x_{9932} \geq 400/1.0017;$

In Dhikur Pokhari, grid electricity, hydroelectricity, or kerosene could be used for lighting. Almost 87% of the households meet their lighting energy demand by grid electricity; the rest would be supplied with electricity generated by micro hydro plants and kerosene for lighting.

$1.0017\,x_{6933} + 0.45x_{5833} \geq 117;$

$x_{6933} \leq 54/1.0017;$

$x_{9933} \geq 766/1.0017;$

In Kaskikot, all lighting/appliances energy is met by grid electricity

$x_{9934} \geq 794/1.0017;$

In Pumdi Bhumdi, lighting/appliances energy is met by grid electricity

$x_{9935} \geq 196/1.0017;$

In Sarangkot, all lighting/appliances energy could be met by grid electricity

$x_{9936} \geq 635/1.0017;$

d) ***Energy required for heating should be met:***

$x_{124} + x_{224} \geq 2374;$

e) ***Energy used for food processing should be met:*** The coefficients used here are end-use efficiencies.

$0.1x_{125} + 0.1x_{225} + 0.2\ (0.0152)\ x_{131} + 0.4\ (0.0152\ x_{761N}) \geq 237;$

f) ***There is a limit on the use of crop residues as fuel:***

$x_{221} + x_{222} + x_{225} \leq 29870;$

g) ***The fuelwood supply should not exceed the sustainable limit:***

The availability is to be measured in terms of accessible forest area. The accessible fuelwood supply in the watershed is given in Table 6.3, therefore, the constraint is formulated as,

$x_{121} + x_{122} + x_{124} + x_{125} + 1.1102\ \ x_{131} \leq 191746;$

h) ***There is a limit on EFS installation:***

It is assumed that the decision makers set a target of installing 600 EFSs in the watershed. For cooking, food processing, and feed preparation, an EFS would require 16.4 GJ of primary energy.

$x_{131} \leq 9840/1.1102;$

i) ***Kerosene consumption should be reduced:***

Kerosene must be consumed in Bhadaure Tamagi and in parts of Dhikur Pokhari for lighting because there is no electricity available and the hydro potential is not enough to meet all of the demand. Also, wherever there is a fuelwood deficit, if might be wise to promote the use of kerosene for cooking as a short term measure to alleviate forest denudation. However, a restriction should be put on the quantity of kerosene to be consumed in the watershed. A limit of 1,000 GJ is used for the purpose of illustration.

$$x_{551} + x_{5831} + x_{5833} \leq 1000;$$

j) *Existing biogas demand should be met by existing biogas plants*:

$$x_{761} \leq 30;$$

k) *There is a limit on the installation of biogas plants*:

There is a potential to install 143 biogas plants. Therefore, the constraint could be written as,

$$1.0152\ x_{761N} \leq 1072;$$

D.1.3 First Iteration

The following is the formulation for the first iteration to be analysed by the STEP-method. This formulation is based on equation (3.5).

Minimize δ

s.t. $x \in X;$

$$\pi_1 [f_1^* - \{-8.3(x_{121} + x_{122} + x_{124} + x_{125}) - 8.5(1.1102 * x_{131}) -$$

$$26.7(1.0152 * x_{761N}) - 1.0017\ (1.2\ x_{6931} + 1.6x_{6932} + 2.6\ x_{6932}) -$$

$$0.96(x_{551} + x_{5831} + x_{5833}\ )\}] - \delta \leq 0;$$

$\pi_2 [f_2^* - \{-(x_{121} + x_{122} + x_{125} + x_{124} + x_{222} + x_{224} + x_{225} + 1.1102\, x_{131} + x_{551} + x_{5831} +$

$x_{5833} + x_{761} + 1.0152\, x_{761N}) - 1.0017\,(x_{6931} + x_{6932} + x_{6933} + x_{9932} + x_{9933} + x_{9934}$

$+ x_{9935} + x_{9936})\}] - \delta \leq 0;$

$\pi_3 [f_3^* - \{ 7(x_{121} + x_{122} + x_{124} + x_{125}) + 10 * 1.1102\, x_{131} + 15 * 1.0152 x_{761N} +$

$3(x_{551} + x_{5831} + x_{5833}) + 1.0017 * 20\,(x_{6931} + x_{6932}) +$

$1.0017 * 29 x_{6933} \}] - \delta \leq 0;$

D.1.4 Second Iteration

As explained in Section 3.2, when the value of one of the objective functions is changed to search for an improvement over the values of the other objective functions, then the weight to be associated with the chosen objective function should be equal to zero. Therefore, in this case, $\pi_3 = 0$ (the employment objective). The formulation of the problem presented below for this iteration is based on equations (3.5) and (3.6). As shown in equation (3.6), the decision makers can choose either to relax objectives or to set a target and reanalyse the problem. Here, a target of 1,000 person-years of employment is chosen.

Minimize δ

s.t. $x \in X;$

$\pi_1 [f_1^* - \{-8.3(x_{121} + x_{122} + x_{124} + x_{125}) - 8.5(1.1102\, x_{131}) -$

$26.7(1.0152\, x_{761N}) - 1.0017\,(1.2\, x_{6931} + 1.6 x_{6932} + 2.6\, x_{6932}) -$

$$0.96(x_{551} + x_{5831} + x_{5833})\}]-\delta \leq 0;$$

$$\pi_2 [f_2^{*} - \{- (x_{121} + x_{122} + x_{125} + x_{124} + x_{222} + x_{224} + x_{225} + 1.1102\, x_{131} + x_{551} +$$

$$x_{5831} + x_{5833} + x_{761} + 1.0152\, x_{761N}) - 1.0017\, (x_{6931} + x_{6932} + x_{6933} + x_{9932} +$$

$$x_{9933} + x_{9934} + x_{9935} + x_{9936})\}]- \delta \leq 0;$$

$$8.3(x_{121} + x_{122} + x_{124} + x_{125}) + 8.5(1.1102 * x_{131}) +$$

$$26.7(1.0152 * x_{761N}) + 1.0017\, (1.2\, x_{6931} + 1.6 x_{6932} + 2.6\, x_{6932}) +$$

$$0.96(x_{551} + x_{5831} + x_{5833}) \leq f_1^{1};$$

$$(x_{121} + x_{122} + x_{125} + x_{124} + x_{222} + x_{224} + x_{225} + 1.1102\, x_{131} + x_{551} + x_{5831} +$$

$$x_{5833} + x_{761} + 1.0152\, x_{761N} + 1.0017\, (x_{6931} + x_{6932} + x_{6933} + x_{9932} + x_{9933} + x_{9934}$$

$$+ x_{9935} + x_{9936}) \leq f_2^{1};$$

$$7(x_{121} + x_{122} + x_{124} + x_{125}) + 10\, (1.1102\, x_{131}) + 15(1.0152 x_{761N}) +$$

$$3(x_{551} + x_{5831} + x_{5833}) + 20 * 1.0017\, (x_{6931} + x_{6932}) +$$

$$29 * 1.0017\, x_{6933} = 1000,000;$$

D.2 Case 2

In this case, the watershed is divided into six administrative areas and the energy demand and potential for each VDC is analysed separately. There are six VDCs in the watershed. Therefore, $p = 1, 2, \ldots, 6$.

D.2.1 The Objectives

a) ***Minimizing the cost allocation for the program implementation:***

$$\text{Minimize} \sum_{p=1}^{6} \{ 8.3(x_{121p} + x_{122p} + x_{124p} + x_{125p}) + 8.5(1.1102\, x_{131p}) + 26.7(1.0152 x_{761pN}) + 0.96(x_{551p}) \} + 1.0017\,(2.6 x_{6933} + 1.6\, x_{6932} + 1.2\, x_{6931}) + 0.96(x_{5831} + x_{5833});$$

b) ***Minimizing total energy input:***

$$\text{Minimize} \sum_{p=1}^{6} \{ x_{121p} + x_{122p} + x_{125p} + x_{124p} + x_{222p} + x_{224p} + x_{225p} + 1.1102\, x_{131p} + x_{551p} + 1.0152\, x_{761pN} + x_{761p} \} + x_{5831} + x_{5833} + 1.0017(x_{6931} + x_{6932} + x_{6933} + x_{9932} + x_{9933} + x_{9934} + x_{9935} + x_{9936});$$

c) ***Maximize rural employment:***

In the objective function formulated below, employment coefficients are expressed in 1/1000 GJ.

$$\text{Maximize} \sum_{p=1}^{6} \{7(x_{121p} + x_{122p} + x_{124p} + x_{125p}) + 10(1.1102 x_{131p}) + 15(1.0152 x_{761pN}) + 3(x_{551p})\} + 3(x_{5831} + x_{5833}) + 20 * 1.0017(x_{6931} + x_{6932}) + 29 * 1.0017 x_{6933};$$

D.2.2 Constraints Set

a) *Energy demand for cooking should be met:*

$$0.1x_{1211} + 0.2x_{1311} + 0.4x_{7611} + 0.4x_{7611N} + 0.45x_{5511} \geq 2570;$$

$$0.1x_{1212} + 0.2x_{1312} + 0.4x_{7612} + 0.4x_{7612N} + 0.45x_{5512} \geq 1788;$$

$$0.1x_{1213} + 0.2x_{1313} + 0.4x_{7613} + 0.4x_{7613N} + 0.45x_{5513} \geq 3946;$$

$$0.1x_{1214} + 0.2x_{1314} + 0.4x_{7614} + 0.4x_{7614N} + 0.45x_{5514} \geq 3544;$$

$$0.1x_{1215} + 0.2x_{1315} + 0.4x_{7615} + 0.4x_{7615N} + 0.45x_{5515} \geq 877;$$

$$0.1x_{1216} + 0.2x_{1316} + 0.4x_{7616} + 0.4x_{7616N} + 0.45x_{5516} \geq 2834;$$

b) *Energy used for feed preparation should be met:*

$$0.1x_{1221} + 0.1x_{2221} + 0.2(0.095x_{1311}) \geq 245;$$

$$0.1x_{1222} + 0.1x_{2222} + 0.2(0.095x_{1312}) \geq 170;$$

$$0.1x_{1223} + 0.1x_{2223} + 0.2(0.095x_{1313}) \geq 376;$$

$$0.1x_{1224} + 0.1x_{2224} + 0.2(0.095x_{1314}) \geq 338;$$

$$0.1x_{1225} + 0.1x_{2225} + 0.2(0.095x_{1315}) \geq 84;$$

$$0.1x_{1226} + 0.1x_{2226} + 0.2(0.095x_{1316}) \geq 270;$$

c) *Energy required for lighting and appliances should be met:*

As indicated before, in Dhikur Pokhari and Bhadaure Tamagi, the lighting energy deficit would be met by electricity and kerosene. The hydro potential in Chapakot would be used in Bhadaure Tamagi.

$$1.0017\,(x_{6931} + x_{6932}) + 0.45x_{5831} \geq 575;$$

$$x_{6931} \leq 114;$$

$x_{6932} \leq 91;$

In Chapakot, all lighting/appliances energy is met by grid electricity

$x_{9932} \geq 399.3;$

In Dhikur Pokhari, grid electricity, hydro, or kerosene could be used.

$1.0017\, x_{6933} + 0.45x_{5833} \geq 117;$

$x_{6933} \leq 54;$ $\quad$ $x_{9933} \geq 764.7;$

In Kaskikot, all lighting/appliances energy is met by grid electricity

$x_{9934} \geq 792.6;$

In Pumdi Bhumdi, lighting/appliances energy is met by grid electricity

$x_{9935} \geq 195.7;$

In Sarangkot, all lighting/appliances energy could be met by grid electricity

$x_{9936} \geq 633.9;$

d) ***Energy required for heating should be met:***

$x_{1241} + x_{2241} \geq 392;$ $\quad$ $x_{1242} + x_{2242} \geq 273;$

$x_{1243} + x_{2243} \geq 602;$ $\quad$ $x_{1244} + x_{2244} \geq 541;$

$x_{1245} + x_{2245} \geq 134;$ $\quad$ $x_{1246} + x_{2246} \geq 432;$

e) ***Energy used for food processing should be met:***

$0.1x_{1251} + 0.1x_{2251} + 0.0152\, (0.2x_{1311} + 0.4x_{7611N}) \geq 39;$

$0.1x_{1252} + 0.1x_{2252} + 0.0152\, (\, 0.2x_{1312} + 0.4x_{7612N}) \geq 27;$

$0.1x_{1253} + 0.1x_{2253} + 0.0152\, (0.2x_{13153} + 0.4x_{7613N}) \geq 60;$

$0.1x_{1254} + 0.1x_{2254} + 0.0152\, (0.2x_{13154} + 0.4x_{7614N}) \geq 54;$

$0.1x_{1255} + 0.1x_{2255} + 0.0152\ (0.2x_{13155} + 0.4x_{7615N}) \geq 13;$

$0.1x_{1256} + 0.1x_{2256} + 0.0152\ (\ 0.2x_{13156} + 0.4x_{7616N}) \geq 44;$

f) ***There is a limit on the use of crop residues as fuel:***

$x_{2221} + x_{2221} + x_{2251} \leq 3174;$

$x_{2222} + x_{2222} + x_{2252} \leq 4946;$

$x_{2223} + x_{2223} + x_{2253} \leq 6695;$

$x_{2224} + x_{2224} + x_{2254} \leq 8739;$

$x_{2225} + x_{2225} + x_{2255} \leq 400;$

$x_{2226} + x_{2226} + x_{2256} \leq 5916;$

g) ***The fuelwood supply should not exceed the sustainable limit:***

$x_{1211} + {}_{x1221} + x_{1241} + x_{1251} + 1.1102x_{1311} \leq 51683;$

$x_{1212} + x_{1222} + x_{1242} + x_{1252} + 1.1102\ x_{1312} \leq 76654;$

$x_{1213} + x_{1223} + x_{1243} + x_{1253} + 1.1102\ x_{1313} \leq 22790;$

$x_{1214} + x_{1224} + x_{1244} + x_{1254} + 1.1102x_{1314} \leq 13750;$

$x_{1215} + x_{1225} + x_{1245} + x_{1255} + 1.1102x_{1315} \leq 11027;$

$x_{1216} + x_{1226} + x_{1246} + x_{1256} + 1.1102x_{1316} \leq 15842;$

h) ***There is a limit on the installation of EFS (600) in a year:***

As mentioned before, a target of installing 600 EFSs in the watershed has been studied here. The installation could also be limited for each VDC. For example, installation could be planned only in the northern areas of the watershed.

$1.1102\ (x_{1311} + x_{1312} + x_{1313} + x_{1314} + x_{1315} + x_{1316}) \leq 9840;$

i) ***A restriction should be put on kerosene supply*:**

The earlier assumption to restrict the kerosene supply to a level of 1,000 GJ gave an infeasible solution mainly because of the high cooking energy demand in Sarangkot, Dhikur Pokhari, and Kaskikot VDCs. Trial runs indicated that a minimum of about 10,160 GJ (or 280 kl) would be required for a feasible solution. Therefore, 10,160 GJ is set as the upper limit for kerosene supply.

$x_{5513} + x_{5514} + x_{5516} + x_{5831} + x_{5833} \leq 10160;$

j) ***Existing biogas plants should supply energy*:**

$x_{7611} \leq 5;$ $x_{7612} \leq 3;$ $x_{7613} \leq 8;$

$x_{7614} \leq 7;$ $x_{7615} \leq 2;$ $x_{7616} \leq 5;$

k) ***There is a limit on the installation of new biogas plants*:**

The total potential to install 143 biogas plants in different VDCs as shown below. The energy value is based on the consumption for cooking and food processing only.

$1.0152\ x_{7611N} \leq 60;$ $1.0152\ x_{7612N} \leq 420;$ $1.0152\ x_{7613N} \leq 37;$

$1.0152\ x_{7614N} \leq 37;$ $1.0152\ x_{7615N} \leq 210;$ $1.0152\ x_{7616N} \leq 308;$

D.2.3 First Iteration

The formulation of the problem to be analysed by the first iteration is based on equation (3.5). The set of reformulated objectives and constraints for the first iteration of Case 2 is given below.

Minimize δ

s.t. $x \in X;$

$$\pi_1 [f_1^* - \{ - \sum_{p=1}^{6} \{ 8.3(x_{121p} + x_{122p} + x_{124p} + x_{125p}) + 8.5(1.1102\, x_{131p})$$

$$+26.7(1.0152x_{761pN}) + 0.96(x_{551p})\} - 1.0017\,(2.6x_{6933} + 1.6\, x_{6932} +$$

$$1.2\, x_{6931}) - 0.96(x_{5831} + x_{5833})\}] - \delta \leq 0;$$

$$\pi_2 [f_2^* - \{ - \sum_{p=1}^{6} \{ x_{121p} + x_{122p} + x_{125p} + x_{124p} + x_{222p} + x_{224p} + x_{225p} +$$

$$1.1102\ x_{131p} + x_{551p} + 1.0152\, x_{761pN} + x_{761p} \} -$$

$$x_{5831} - x_{5833} - 1.0017(x_{6931} + x_{6932} + x_{6933} + x_{9932} +$$

$$x_{9933} + x_{9934} + x_{9935} + x_{9936})\}] - \delta \leq 0;$$

$$\pi_3 [f_3^* - \{ \sum_{p=1}^{6} \{ 7(x_{121p} + x_{122p} + x_{124p} + x_{125p}) + 10(1.1102x_{131p}) +$$

$$15(1.0152x_{761pN}) + 3(x_{551p}) \} + 3(x_{5831} + x_{5833}) +$$

$$20 * 1.0017\,(x_{6931} + x_{6932}) + 29 * 1.0017x_{6933} \}] - \delta \leq 0;$$

D.2.4 Second Iteration

In this iteration, the problem is reformulated by applying equations (3.5) and (3.6). The weight on the third objective is set to zero because it is assumed that the decision makers have decided to set different employment targets for the analysis. The formulation for the employment target of 900 person-years is given below.

Minimize δ

s.t. $x \in X;$

$$\pi_1 [f_1^* - \{ - \sum_{p=1}^{6} \{ 8.3(x_{121p} + x_{122p} + x_{124p} + x_{125p}) + 8.5(1.1102\, x_{131p}) + 26.7(1.0152 x_{761pN}) + 0.96(x_{551p})\} - 1.0017\,(2.6 x_{6933} + 1.6\, x_{6932} + 1.2\, x_{6931}) - 0.96(x_{5831} + x_{5833})\}] - \delta \leq 0;$$

$$\pi_2 [f_2^* - \{ - \sum_{p=1}^{6} \{ x_{121p} + x_{122p} + x_{125p} + x_{124p} + x_{222p} + x_{224p} + x_{225p} + 1.1102\, x_{131p} + x_{551p} + 1.0152\, x_{761pN} + x_{761p} \} - x_{5831} - x_{5833} - 1.0017(x_{6931} + x_{6932} + x_{6933} + x_{9932} + x_{9933} + x_{9934} + x_{9935} + x_{9936})\}] - \delta \leq 0;$$

$$\sum_{p=1}^{6} \{ 8.3(x_{121p} + x_{122p} + x_{124p} + x_{125p}) + 8.5(1.1102\, x_{131p}) + 26.7(1.0152 x_{761pN}) + 0.96(x_{551p})\} + 1.0017\,(2.6 x_{6933} + 1.6\, x_{6932} + 1.2\, x_{6931}) + 0.96(x_{5831} + x_{5833}) \leq f_1^1;$$

$$\sum_{p=1}^{6} \{ x_{121p} + x_{122p} + x_{125p} + x_{124p} + x_{222p} + x_{224p} + x_{225p} + 1.1102\, x_{131p} + x_{551p} + 1.0152\, x_{761pN} + x_{761p} \} + x_{5831} + x_{5833} + 1.0017(x_{6931} + x_{6932} + x_{6933} + x_{9932} + x_{9933} + x_{9934} + x_{9935} + x_{9936}) \leq f_2^1;$$

$$\sum_{p=1}^{6} \{7(x_{121p} + x_{122p} + x_{124p} + x_{125p}) + 10(1.1102 x_{131p}) + 15(1.0152 x_{761pN}) + 3(x_{551p}) \} + 3(x_{5831} + x_{5833}) + 1.0017\,\{20(x_{6931} + x_{6932}) + 29 x_{6933}\} = 900{,}000;$$

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