A Systems Approach for Rural Energy Intervention Design in India: Integrating Women, Resources, Technologies, and Processes

by

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Abstract

One of the greatest challenges facing a developing country such as India is how to meet the domestic energy needs of a substantial and growing rural population in an ecologically sustainable manner. Over the past three decades, numerous piecemeal attempts, such as Improved Cookstove Programmes, Biogas Development, and Social Forestry, have been made in the rural areas as a panacea to combat the varied and combined aspects of the rural energy crisis: the deleterious effects of inefficient combustion technologies, indoor smoke, deforestation, and drudgery for women. These efforts have had limited success primarily because they failed to consider the felt needs of the intended rural beneficiaries and failed to recognise the interconnectedness of the multifarious aspects of the rural energy problem.

Based on the premise that the rural energy crisis must be understood as a whole system problem, a systems approach to planning and designing rural energy interventions, emphasising the full participation of rural women - the primary users of the domestic energy technologies - is proposed. System modelling is an integral element of this systems approach. Accordingly, as a key component of the proposed intervention design methodology, a mathematical model of the domestic cooking energy system is developed. The purpose of this model is to allow policy planners to better understand the structure and function of the domestic energy system and to investigate the potential impacts on this system of various renewable energy technology interventions.

A conceptual model of the domestic rural energy system is first devised. This abstraction establishes the fundamental interactions among the system's four basic components: resources, technologies, tasks, and people. This model is then translated into a mass-energy mathematical model and several new components are created to specifically allow the incorporation of the household decisions. In the model, the various components, such as the different stoves, buffaloes, and the agricultural fields, are represented as material transformation processes; the inputs to the model are environmental resources, such as fuelwood; and the outputs of the model are cooking demands or the kcals of energy required to meet the daily cooking demands of the household, disaggragated by cooking task. The utility of the model for understanding both the domestic cooking energy scenario and the impact of alternative renewable energy interventions for one household is presented in a detailed example, based on field data collected in India. The extension of the model to village level energy intervention planning also is demonstrated through a detailed example investigating the impact on village level resource consumption of four different cooking energy scenarios. Finally, the results of a real world intervention design exercise to introduce the use of crop residue briquettes as a fuel in the place of traditional dung cakes, conducted in the village of Gari Natthe Khan, Haryana, are given. This latter example illustrates how the systems approach for rural energy intervention design may actually be used by an intervention agency, such as a local non-governmental organisation.

The model demonstrates a very effective tool for understanding the complex structure and interactions which comprise the rural domestic cooking energy system. The results also clearly indicate the natural resource savings, at both the household and village level, which may be achieved by the adoption of renewable energy technologies such as improved cookstoves (chulhas) and biogas plants. Further, the success of the crop residue briquetting intervention activity in Gari Natthe Khan, designed following the systems approach presented here, illustrates the potential for rural energy intervention design when a holistic and women-centred approach is taken.

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Chapter 1

Introduction

In developing countries such as India, energy is a critical input to development, since all of the activities of central priority - poverty alleviation, employment creation, and social integration - require energy in one form or another. The issue of energy availability, therefore, is essential to address India's pressing development concerns.

In the rural areas of India, the need for energy for development is intimately connected with the predominant role which energy plays in the domestic system. Specifically, energy for cooking and lighting is a basic necessity which accounts for up to 90% of the total domestic energy consumed, and with a growing rural population of already over 600 million represents an immense energy demand. The majority of this energy requirement is met by non-commercial, locally collected biofuels consisting primarily of wood, crop residues, and dung cakes. These fuels are burnt in mud stoves that have low efficiencies, and in kitchens with inadequate ventilation. The traditional stoves and cooking practices have evolved locally over the centuries, and hence have features that are valued by the rural women. As the use of these biofuels continues, however, in conjunction with a fast deteriorating biomass resource base and the inability of people to shift to commercial fuels on account of low purchasing power and limited availability, the scarcity of these resources is becoming increasingly severe.

To meet the demand for energy, both for local cooking needs and economic development in a sustainable manner, renewable energy technologies will have to be the dominant power source. This will require the creation and expansion of efficient, affordable, reliable, and sustainable energy systems and large-scale dissemination of renewable energy technologies. The term 'sustainable development' is used in the sense defined by the World Commission on Environment and Development, referring to the process by which humanity can "ensure that it meets the needs of the present without comprimising the ability of future generations to meet their own needs" [97]. In this context, sustainable energy systems are defined as alternatives which are both financially feasible for the user and based on viable, sustainable fuels.

Women have a key role to play in this context. In rural India, women are the managers of the domestic energy systems; they play the roles of producer, processor, trader, and user of the biomass resources. In performing their tasks, women make decisions about which resources to use and how to use them. Consequently, the women are affected by tradition, resource availability, accessibility to technology and income disposability. These issues have direct implications in the technology choices made and the environmental impacts produced. Therefore, the enhancement of women's capabilities is a key to guarantee the adoption of new energy technologies, to improve efficiency in resource use, and to ensure the establishment and continuity of sustainable energy systems.

In response to this need for new energy options, various renewable energy technologies have been disseminated in the rural areas of India over the past decade with the aim either to reduce the demand for energy or increase the supply of local biomass resources. While the largest of these efforts have been co-ordinated at the national level to attempt large scale dissemination, at the local level the various intervention activities have been realised as disjointed and piecemeal projects. Consequently, the combined impact on the rural energy situation of these various individual development attempts remains insignificant. While genuine success and progress have been made in some areas, by far the vast majority of the rural people in India continue to struggle in their day-to-day existence.

While there are numerous reasons for the failure of the past rural energy intervention programmes, two issues are most predominant. The first is the lack of an integrated approach both for understanding the rural energy problem and for co-ordinating the various technology dissemination efforts. The second is the combined lack of genuine participation for the local inhabitants with a complete disregard for the critical and central role women play in the rural energy system. For genuine progress to be made in ameliorating the rural energy crisis, researchers must recognise not only the critical role which energy plays in overall development but also the interconnectedness of the entire rural energy system and the integral role that the local people should have in finding solutions to their energy problems.

The underlying premise of this thesis is that development efforts in the rural energy system can be made more effective by adopting a holistic systems approach for the design and implementation of interventions. Furthermore, intervention design and dissemination can be facilitated by involving local women in a decisive role in all stages of the project cycle. The aim of this thesis then is twofold. The first is to develop, based on well established principles of systems theory, an integrated systems approach to rural energy intervention design. The second is to develop and implement a comprehensive mathematical model of the rural energy system as a useful tool for understanding the structure of the system, investigating development options, and assessing the impact on the biomass resource base of various cooking energy technology development choices.

In Chapter 2, a detailed discussion of the background to the rural Indian energy crisis is given. A description of the current rural energy scenario is first presented, highlighting the contrasts between the rural and urban energy situations. The role of women in the domestic energy system is next examined, emphasising her sphere of production, her role as producer, processor, and user of biomass resources and cooking technologies, the significant impact on her daily activities of the severe shortage of biomass, and her decision-making responsibilities. Because the fuelwood crisis lies at the heart of the rural energy crisis, Chapter 2 also examines it in greater detail. Specifically, a conceptual framework for understanding the fuelwood crisis as a problem of choice, and for developing solution alternatives, is presented. Chapter 2 closes with a discussion of several of the largest Government of India sponsored intervention programmes, highlighting the key reasons for their failure to impact on the problems which they sought to address and the barriers to women's participation in these programmes. Drawing on the root causes for the failure of these past interventions, Chapter 3 presents the case for why a systems approach for energy intervention design in the rural domestic energy system is necessary to genuinely address the rural energy crisis. A description of what constitutes a systems approach is first given, with some basic definitions from system's theory, and then the actual structure of the system design methodology is presented. This chapter also includes a discussion of the need for modelling the rural energy system, to understand the system's complex structure and function. Past modelling approaches are described and the requirements of the new model developed in this thesis given.

In Chapter 4, the background on mass-energy theory is presented. Because the fundamental concepts upon which mass-energy theory is based are rooted in the Graph Theoretic Method (GTM), the basic terminology and concepts from GTM are first given. This is followed by a detailed discussion of the basics of mass-energy theory in general. The chapter closes with a simple two process mass-energy example, which demonstrates the use of mass-energy models for studying environmental systems. Chapter 5 discusses the application of mass-energy modelling methods to rural energy systems. In order to capture the decision-making structure in the household, which is a key component of the system, four new decision components are developed: decision joiners and splitters, 2-decision demand processes, and weighted decision material transformation processes. A discussion of the mathematical structure of four new decision components is first presented. Chapter 5 concludes with a simple example of a mass-energy model of the domestic cooking energy system; the complete model formulation and equation derivation for the buffalo subsystem is then given. In Chapter 6, the creation of the complete General Household Mass-Energy model is presented in three parts. First, the definition of the conceptual model is given. Second, the mass-energy model, divided into two subsystems, the General Household Model Subsystem and the Agricultural Subsystem, is presented. For these two subsystems, each component is described and the defining parameters, variables, and equations are given. Finally, a detailed example of the application of the complete model to a study household in Dhanawas, Haryana is given. In the example, a detailed household energy scenario is outlined and the model results for this baseline scenario and two intervention alternatives are presented and discussed. In Chapter 7, the application of the model to village level energy intervention planning is presented. Starting with a discussion of the various policy alternatives outlined in Chapter 2 for addressing the fuelwood crisis as a problem of choice, one alternative is selected for investigation. For a village composition typical of Haryana state, the options of moving down or up the energy ladder or switching to alternative renewable energy technologies, when faced with a shortage of safe and feasible fuelwood supplies, are investigated. Specifically, the model results are interpreted in relation to how they could guide rural energy policy planning. Finally, in Chapter 8, a real world example of the use of the systems approach for rural energy intervention design in a village, Gari Natthe Khan, in Haryana state is discussed. Chapter 9 presents the conclusions of the thesis, outlines the limitations of the current model and presents avenues and directions for future work.

Chapter 2

Background on the Rural Energy Crisis

2.1 The Rural Energy Scenario in India

India is a vast country of stark contrasts: harsh deserts vs. lush tropical forests, snow-capped mountains vs. flat arid plains, wealth vs. poverty, ancient vs. modern, and rural vs. urban. Further, each state has different languages, cultures, customs, and traditions. Despite the regional diversity, however, India is becoming increasingly polarised into two separate 'nations': the wealthy, urban, industrialised centre, and the poor, rural, traditional periphery. Indeed, nation-wide the rural areas may be generally characterised by high population ratios and growth rates, inadequate infrastructure development, lack of essential social amenities, low levels of income, concentration of poverty, significant socio-economic disparities relative to urban areas, rural - urban migration for employment, a scarcity of energy to meet basic needs and for economic development, and a deteriorating environmental base due to increasing pressures on available natural resources [79].

The Indian dichotomy is perhaps best represented by the differences in the energy scenarios typifying the urban and rural communities. The two greatest consumers of urban energy - industry and the transport sector - have a high purchasing power and the supply system is organised, commercial in nature, and based on fossil fuels. This group, however, constitutes only 26% of the Indian population. Conversely, the greatest consumer of rural energy - the domestic sector with cooking as the major end use of energy - has a very low purchasing power and the supply system is informal, non-commercial in nature and based on biomass fuels (biofuels). According to a NCAER survey report published in 1985, over 90% of the energy needs of the rural domestic sector in India are met by locally available, predominantly gathered biofuels consisting primarily of wood (56%), crop residues (16%), and dung cakes (21%) [67]. As the use of these biofuels continues, in conjunction with other external causes of deforestation, desertification and environmental degradation, the scarcity of these resources, particularly fuelwood, is becoming increasingly severe.

Additional strain on the local biomass resources also arises from the poor penetration of commercial fuels into the rural areas. Indeed, in India neither rural electrification nor kerosene nor LPG supplied at considerable subsidies have been able to increase the accessibility of commercial fuels to rural people. Currently, 85% of the villages are electrified (via grid connection). However, only 30% of the households are actually connected, and even then supply is often very sporadic with some areas being without electricity for several days at a time. Kerosene accounts for only 7% of the rural energy consumption [67] and this is predominantly for lighting as opposed to cooking. LPG, with a Rs 71 (Rs 24 = 1 $ Cdn, 1996 prices) government subsidy for every 14.2 Kg cylinder sold at the retail rate of Rs 105 [80] accounts for less than 4% of the rural energy consumption. As three quarters (74%) of the Indian population lives in the rural areas, the issues of sustainable supply and demand management of these biomass resources are becoming increasingly critical. Indeed, India is facing a severe fuelwood crisis which has been termed as no less than the 'second energy crisis' [40].

Within the rural energy system, women are primarily responsible for managing the domestic energy requirements at the household level. Because the predominant sources of fuel are derived from biomass resources, women have a very intrinsic and symbiotic relationship with the local natural resource system. As such, the impact of biomass scarcity has had the most severe and far reaching implications for women; so much so that the rural energy crisis can arguably be viewed as a 'crisis of women's time'. Thus, the 'second energy crisis' is not only a fuelwood crisis, but also a critical link in the myriad of gender inequalities facing rural Indian women. Although this reason alone makes it an important area of study, when considered together with the 600 million strong and growing rural population and the very poor penetration of commercial fuels into the rural areas, it may be viewed as one of the most pressing problems facing India today.

Before examining some of the past attempts by the Indian government to alleviate this crisis, we first need to understand the important role of women in the rural energy system and also attempt a more in-depth analysis of the nature of the fuelwood crisis. Having an understanding of the complex structure of the fuelwood crisis will then provide a starting point for investigating possible solution avenues.

2.2 The Role of Women in Rural India

Historically, the critical dimension that the concept of distinct gender roles for men and women contributes to the understanding of the dynamics of the rural energy system has been either misinterpreted or entirely overlooked. Only in relatively recent years have gender and gender inequalities risen to the forefront of issues of concern to rural development professionals. Indeed, since the mid-1980's the importance of gender issues in development has been increasingly recognised and has paved the way for the new paradigm of Rapid and Participatory Rural Appraisal techniques which are often aimed specifically at facilitating the involvement of women in the rural development process [11, 21, 22, 30, 31, 39]. While an in-depth analysis of gender issues in India is beyond the scope of this work, an understanding the role of women in rural India and specifically in the rural energy system is critical for understanding the rural energy crisis. The fundamental unit of Indian society is the family. Consequently, we begin with an examination of the concept of the Indian household.

2.2.1 The Concept of the Household

The prevalent model of the household in rural India is a kin-based social unit working together in one production system, with a male head who acts as the single farm decision maker and who controls the allocation of all family resources [36, 44, 15, 95]. This model is incomplete and often incorrect. For example, considering a household to constitute those who eat from the same cooking pot fails to capture the household whose livelihood strategy involves sending some members to urban areas to work as wage labours [36]. Perhaps more importantly, 25 - 33 % of all rural households world-wide are headed by women either *de jure* or *de facto* [44]. Another 10 % are organised pologamously. In these households women are the producers and decision makers in their own right. Furthermore, in the majority of rural

Indian households there is more than one production system: a male production system, a female, and a joint, and men and women may have conflicting interests over the use of household resources in each of these systems. Consequently, adhering to a *unitary household model* [96] for policy intervention and development may mean that some household members actually end up worse off. Conversely, a *collective household model* [96], in which resources are not necessarily pooled and the household acts as a collective, with members having their own preferences and decisions reflecting the relative bargaining power of household members of the collective, more adequately represents the reality of the rural Indian home.

2.2.2 The Sphere of Women and the Sphere of Men

As the collective household model indicates, women and men in rural India often work in different production spheres. The extent of the segregation in all facets of their daily lives can also be enormous. Anees Jung [50] and Elisabeth Bumiller [18] both present indepth analyses of the journey an Indian woman follows through her life. Indeed, Jung paints a vivid picture of the sharp delineation along gender lines of the distinct roles of men and women in rural India:

> A cart is parked on a dreary desert track. It rests on two massive Dunlop tyres and is attached to a camel. A man and a woman are seated in it, across from each other. They are silent. They are husband and wife, ... 'Yes she is my wife,' he nods in a matter-of-fact manner. In his tone there is contentment that boarders on smugness. She is his wife, not his better half. While he talks, she stays silent...He talks about his land, his harvest of mustard, wheat and corn, his animals. These are the things that are integral to his life and work. Everything else can wait. ... Do they spend time together? He laughs. 'Where is the time to spend with her? She is busy. I am busy.' ... This is a twentieth century portrait of a man and wife in rural India. All that has changed in the frame are the wheels of his vehicle. They are no longer made of wood or crafted by hand. ... The farmer has changed his wheels but not the culture of his mind. He is willing to learn about tractors and pumps, fertilisers and cross-bred cows. These are good for his land, his harvest, his well-being. Does he connect these with the well-being of his family? Not directly. If his milching cow or his prized bull is ill, he will rush it to the veterinarian. But not his child who may be victim of chronic diarrhoea. ... His wife, to him is a mere tool, necessary to keep a unit complete and further a generation. He has no room for her. She finds room for herself in her motherhood [50].

Men and women in rural India exist in two separate spheres, which overlap to varying degrees from one region of the country to another depending on factors such as the ethnic group, class, caste, and household income. Indeed the very meaning of male and female in India is closely tied to the respective spheres of existence. The woman's sphere is associated with *inside* the home and courtyard, where she cares for her family. Conversely, the male sphere is *outside*, in the fields and bazaars where livelihoods are earned and economic and political power wielded [95]. Once again, the actual definition of what constitutes inside, the precise boundaries of a women's sphere, varies according to economic status, caste, community social norms, and a woman's age.

In terms of daily work roles, the sphere of the male encompasses the cash economy and pubic life and his daily routine consists of income generation activities: wage labour, crafts, cash cropping, or raising livestock. From his activities he earns the primary cash income of the household, which he spends as he deems appropriate, often on liquor, cigarettes and other treats for himself [18, 44, 94]. The male and female spheres or production systems overlap where there is joint production of cash or food crops or other income generating activities.

The sphere of the woman is limited to the household and children. The tasks which comprise a woman's day revolve around the subsistence economy, family, food production and household maintenance. The women's activities, while essential to family survival and welfare, are typically unpaid, despite the fact that they may make a substantial contribution to the family income [20]. Because women usually devote their earnings and output entirely to the well-being of the family, women's production and income are of particular importance to the welfare and development future of the household [44].

Woman's work may be divided into: family agriculture work - the production of food and cash crops either in her husband's fields or within the confines of a home garden, assisting her husband in the production of his cash crops, husbandry of small livestock, fish, or poultry, gathering and nurturing of wild plants, and planting and tending trees for household use; household work - bearing and raising children, cooking, cleaning, nursing the sick, repairing the house, fetching water, collecting fuel, hiring and supervising wage labour; and, income earning work - wage labouring in local fields [20, 36, 44]. An ILO study of five Indian villages found that, on average, a woman spends 3.9 hours a day on agricultural work, 4.0 on non-agricultural work, 4.8 hours on fuel collection and cooking, and 0.9 hours on other activities [20]. The two most labour intensive activities in a woman's day, cooking and fuel collection, are directly related to the domestic energy system.

Cooking and Fuel Gathering

Cooking is one of the central activities performed by women in rural India. It constitutes up to 34 % of a woman's daily workload [20]. In some seriously deforested regions, women will spend an average of 3 to 4 hours on fuel collection, another 3.5 to 4 hours cooking meals, and have hardly more than two hours of leisure time [93]. While in some areas men may help with the fuel collection in terms of cutting down trees and chopping logs, the procurement, production, processing, and use of the three most common fuels in rural India (fuelwood, crop residues, dung cakes) are predominantly within the sphere of women's activities.

Thus, women are responsible for the management of the domestic energy system and through this responsibility women are directly involved with the use and management of natural resources: soil, water, forests. Consequently, when these natural resources are threatened by deforestation and environmental degradation, women are the most severely affected members of the household; it becomes increasingly difficult for women to provide for the basic needs of their family [20].

2.2.3 The Effects of Deforestation on Rural Women

As deforestation and desertification increase, the sphere of women's work is influenced on several different fronts. As erosion, salinisation and other soil deterioration increases, the most fertile land is allocated to the men's cash crops. Women are then forced to use increasingly marginal and fragile soils for food production which require increased labour inputs yet yield decreased productivity. When the agricultural land is degraded to the extent that it is no longer economically feasible to farm, the men are often forced to leave the household in search of seasonal work on distant large farms or in the urban areas. Women are then responsible for *all* of the household's agricultural activities.

As the quality and quantity of biomass resources decreases due to deforestation and environmental degradation, women must devote more time and effort to fuel and water collection. Biomass shortages are reflected in women having to walk longer distances to collect fuelwood, switching to inferior fuels like twigs, bushes, roots and weeds, purchasing fuel, and even changing food and cooking habits to adjust to the reduced fuel availability. For the women, these adaptations and coping strategies have resulted in increased drudgery, smoke-filled kitchens causing discomfort, lung, eye, and throat disorders, and a lowering of nutrition levels in the family's diet. Specifically, case studies in Gujarat villages showed that women have to rely increasingly on roots of trees, shrubs and grasses, which take longer to collect due to the greater quantity needed for daily cooking because of their lower calorific value, do not provide continuous heat, need to be constantly tended, and also increase cooking time [66]. This latter result translates into increased exposure time for women to smoke-filled kitchen atmospheres. Batliwala [10] has pointed out that in order to cope with reduced fuel availability, fewer meals are cooked in a day and dietary changes are made to include cereals that require less cooking but are also less nutritious.

In many rural areas, women were once able to combine fuel collection with other activities, such as herb gathering on their way back from the field [20]. The increased workload caused by fuel scarcity often means that women no longer have time for collecting minor wild forest and field products which traditionally supplemented the family's nutrition and incomes, i.e. through processing of forest products for sale. Additionally, women may now have less time for alternative income generating activities. In the end women often have little choice but to work more, cut down on the family living standard, and to try to squeeze more output and income from the degraded land, which contributes to the vicious cycle of environmental degradation [20].

The nature of the choices a woman must make in the face of deforestation and environmental degradation is significantly affected by the decision-making structure in the household. In the majority of the rural Indian households, best typified by the collective household model, men and women are responsible independently for decisions made in their individual spheres and women *may* be consulted in decisions concerning joint activities.

2.2.4 Decision Making in the Household

The decisions to procure, allocate, and use resources within the household are not only made reflecting market rates of return but they also mirror the relative bargaining power of different household members [96]. Men and women often take decisions within each of their spheres of influence independently, despite the fact that they are competing for the same resources and thus the consequences of the decisions will affect other members of the household. For this reason, men and women are often in conflict when it comes to resource use in the household. Indeed, the cause of many of the gender inequalities in rural India are intimately linked to the intrahousehold decision-making process [96]. Thus, understanding the nature of decisions made in the household is essential for eliminating gender inequalities.

The Male Decision-Making Sphere

In rural India the decisions made by the males of the household are typically of a financial nature. The types of cash crops to grow; the procurement of seeds, fertiliser, and irrigation sources (installation of electric or diesel tube wells); the number and composition of livestock to be reared; the selection of construction materials for the kitchen walls and roof; the purchase of kerosene, LPG, or fuelwood; the purchase of renewable energy technologies such as solar lamps and ovens and biogas plants; and, the type of cooking device to be used in the home are all decisions made by men. In the case of the latter example, device choice, the decision is made by the men only when there is a direct monetary purchase cost. If the stove is constructed for 'free' by the woman then the decision rests within her domain. In some households, women may be consulted, but not necessarily, and ultimately all decisions of a financial nature rest with the male head of the home.

The Female Decision-Making Sphere

In contrast, the decision-making responsibilities of the women lie within the domain of the management of resources within the home and kitchen. Women are responsible for all agricultural decisions relating to her own fields or home garden; all decisions regarding the day-to-day running of the household, and specifically relating to the energy system; all decisions concerning where to place the chulha and its construction; which fuelwood species to use; where to procure it from; and how to best chop and store it. When fuelwood is no longer available, the woman decides which alternative fuels to use and from which sources.

The amount of influence a woman may have on the decisions taken by her husband will often depend on the economic status of the household. There is often an inverse relationship between a women's status in the community and her status within the decision-making structure of the household [95]. At one end of the spectrum is the female head of her own household, who is economically vulnerable and has low status in the community but has full say in the allocation of her family's resources. At the other end is the wife of a large land owner who is not required (or often permitted) to work outside of the home and enjoys high status in the larger community, but since she contributes little to the family income has little or no input into the decision-making process in the household. Generally in poorer and lower caste families, where women are required to work as wage labours for family survival, the women has the greatest input into household decision making. Conversely, in wealthy, upper caste families, where it is considered a status symbol for the women not to have to work, the women are rarely consulted in household decisions.

The delineation of decision-making activities by gender is extremely important when innovations are to be introduced into the domestic energy system. Although women are the potential users of biogas plants and stoves, solar ovens, and other cooking innovations, and therefore are in the best position to assess the advantages and disadvantages, it is the men who handle the household cash and make the decisions on how it is spent. Because of their different work spheres, the men and women of the household often perceive the necessity for the new innovations very differently.

To summarise, the role of women in the domestic energy system is best defined both by her sphere of work, production, or influence and by her role in the decision-making process in the household. We have now examined the 'outer' two layers of the rural energy crisis. At the centre of the crisis, with its dire consequences for rural women, is the fuelwood crisis. In order to genuinely understand the structure of the rural energy crisis and its impact on women and to establish a starting point for problem solution, the fuelwood crisis must be investigated in greater detail.

2.3 A Framework for Understanding The Fuelwood Crisis

When research into the rural energy crisis first began, a direct cause-and-effect link between deforestation and fuelwood consumption by local rural inhabitants was assumed. This key assumption was not based on appropriate evidence. Instead, starting with data on global deforestation rates and then extrapolating existing trends in population growth, deforestation rates, and afforestation efforts, researchers assumed a link between deforestation and the high rural populace inhabiting deforested regions [62]. Furthermore, 'deforestation' was incorrectly used in a generic sense to imply fuelwood scarcity. There is, however, no one root cause for deforestation and desertification in India. Although direct causal links have yet to be clearly established, pressure from population growth, the need for increased agricultural land and shifting agricultural practices, the expansion of commercial logging, and rural fuelwood collection have all contributed to the depletion of the forest resource base [89, 9]. Indeed, deforestation problems are often location specific, with the exact set of causes differing from place to place and consequently the best remedial approach will also vary regionally. Deforestation and the fuelwood crisis is therefore a much more complex issue than was originally understood. Consequently, the way in which the fuelwood crisis is defined and the underlying problems identified have important consequences for energy policy. A linear problem-solution frame of thinking is inadequate. Therefore, as a basis for the study of the rural energy crisis, a complete conceptual framework within which to comprehend and examine the fuelwood crisis is required. Fortunately, an excellent conceptual framework has been proposed and developed by Pearson and Stevens [75]. This frameowork for understanding the fuelwood crisis is selected without undertaking an extensive review of alternative policy frameworks. In doing so, this is not intended to suggest that this is the only or most valid approach to understanding the fuelwood crisis. However, the framework proposed by Pearson and Stevens is discussed here because it provides a very clear and easily digestible approach for studying the fuelwood crisis.

2.3.1 The Fuelwood Crisis as a Problem of Choice

Pearson and Stevens categorise the woodfuel problem as a ***problem of choice*** which arises because there exist unlimited wants to consume in a world of scarce resources (unlimited wants, in the sense that, regardless of whether a demand for energy is being met in a sustainable or unsustainable fashion, the demand for energy to meet basic needs is persistent over time). In this context, a shortage of a given resource does not necessarily constitute a crisis. Different decision-making bodies need to choose which of their wants to satisfy and which to frustrate. A crisis emerges as a consequence of these choices and from changes over time in both wants and resources [75].

In order to understand the nature of the woodfuel crisis in India, its place within a wider context of related issues must first be clear. The fuelwood problem is not an isolated problem; it is intimately connected with the myriad of other issues facing the nation. Specifically, the woodfuel crisis is a subset of the larger energy crisis which is itself a subset of India's overall development problems [75]. This overall context is important to avoid the trap of 'energy fundamentalism' [75]. Thus, extending Pearson's and Stevens' concept of problem of choice to this wider context, an energy problem or crisis may be conceptualised as a choice between energy shortages on one hand, with their attendant loss of production or comfort, versus the sacrifices which must be made in other sectors to overcome an energy shortage, i.e. reducing spending on health care or education in order to spend on energy. The general development problem emerges because the gaps between wants and resources in numerous sectors are so wide that choices become severely constrained. In these terms, the woodfuel crisis is an issue of the demand for woodfuel, predominantly for cooking, exceeding the available supply of safe and/or feasible wood.

Safe and Feasible Wood Resources

The concept of safe and feasible wood resources is central to Pearson and Stevens' description of the fuelwood crisis. Safe wood is wood used in a sustainable manner which also does not result in environmental degradation. Feasible wood either requires only some manageable portion of a household's budget for purchase or requires only a physically feasible amount of time and effort for collection. The concepts of safety and feasibility are intimately linked in two specific ways as depicted in the Figures 2.1 and 2.2 below. In Figure 2.1, where fuelwood is collected, as the supply of local, safe wood disappears women are forced to seek safe wood supplies at an increasingly further distance from the home, which results in an increase in collection time and effort until these alternate supplies become infeasible, forcing the women to turn to using unsafe wood. The second case is depicted in Figure 2.2. In this case, where fuelwood is purchased, a decrease in the supply of safe wood would result in an increase in the unit price, forcing the household to allocate a larger portion of its budget to fuel purchase. As the feasibility of purchasing wood decreases, the family is forced to turn to using unsafe wood.

If a safe and feasible wood supply is available to a household, then it has the ***choice*** to either use the supply or not. The fuelwood crisis emerges when the demand for safe and feasible wood exceeds the supply. The extent of the supply vs. demand gap will vary enormously from region to region in the country, depending on two interlinking causes for the rise in the crisis: 1) excessive demand for fuelwood and 2) shortage of safe, feasible wood [75]. The two most significant causes of excessive demand for fuelwood are (i) population growth and (ii) the relative price of wood (too low) and commercial energy (too high). Fuelwood is considered to be collected at a 'zero cost' to the user as rural households do not consider either women's time to collect the wood or the environmental damage caused by fuelwood extraction to be costs associated with the use. Even with subsidies, commercial energy is often far beyond the financial reach of most rural households.

When a crisis situation emerges, the household is faced with the necessity to take one or several of a number of different *choices* as described by Pearson and Stevens.

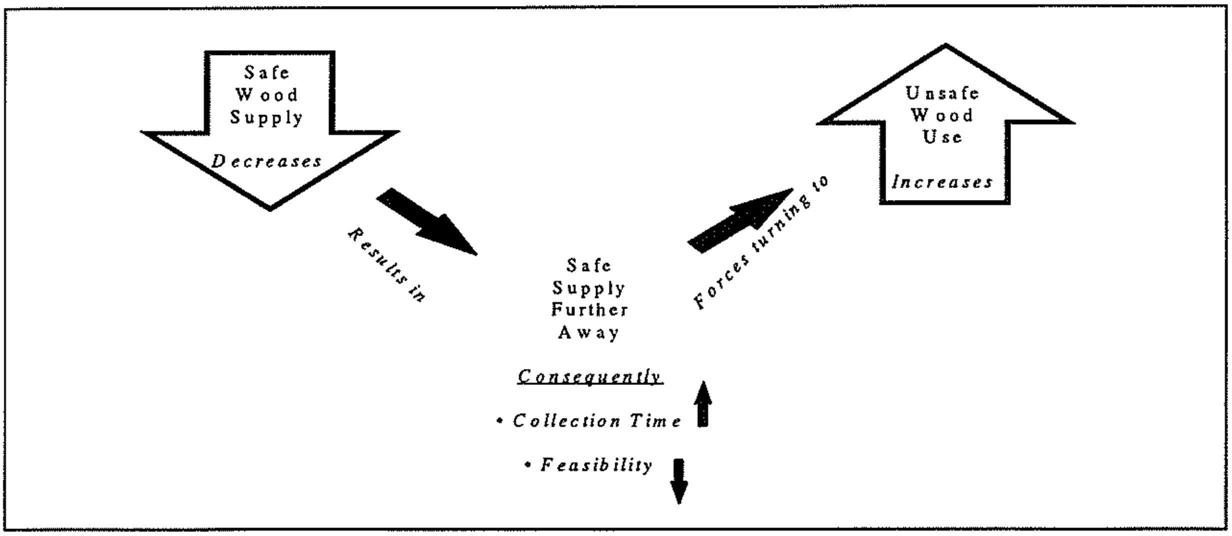


Figure 2.1 - Safe and Feasible Wood Linkages - Fuelwood Collected

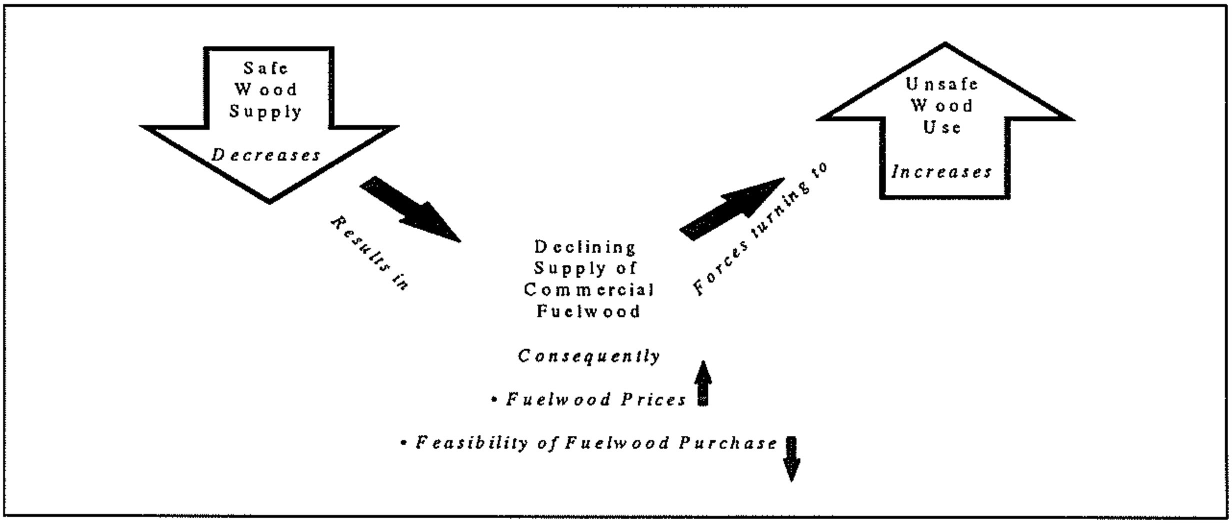


Figure 2.2 - Safe and Feasible Wood Linkages - Fuelwood Purchases

Choice 1 - Turn to Unsafe Wood

When the shortage of safe wood reaches a critical level, the household may decide to use locally available unsafe wood, impacting on deforestation. Because the rural women generally collect twigs and branches as opposed to cutting down trees, however, deforestation is not directly or substantially caused by fuelwood collection. Land clearing for agriculture, commercial logging beyond regeneration rates, and overgrazing are believed to be more significant causes. As these latter actions turn safe wood into unsafe wood, which women may choose to collect, the deforestation process and the many deleterious effects of deforestation, such as soil erosion, siltation, and desertification, are aggravated.

Choice 2 - Fuel Substitution

There are three broad options for fuel substitution: downgrading to a less preferred fuel, upgrading to a commercial fuel, or creating a new safe, feasible fuelwood supply. The first two options deal with moving down or up the 'energy ladder' [9] in which the 'rungs' are represented by different types of fuel starting at the bottom rung with the least preferred grasses and roots and moving up sequentially to crop residues and dung, to fuelwood, to charcoal, to kerosene, to LPG or natural gas, and finally to electricity as the most preferred fuel for cooking.

Option 1

The choice to downgrade from fuelwood to less preferred crop residues and cow dung implies that the household's wants are being less well satisfied. Additionally, the use of animal wastes and crop residues increases the deprivation to soils of valuable nutrients and organic conditioning material. Downgrading fuels represents problems of *fuel poverty and equity* [75], the poor are becoming poorer. Additionally, agriculture production *efficiency* [75] problems arise due to the loss of soil fertility.

Option 2

The second option is for households to move up the energy ladder to commercial fuels. If a household did not choose commercial fuels previously, however, it was likely because it could not afford them. For the vast majority of the poor people in rural India, biofuels are the only source of energy within their financial reach. Even when heavily subsidised, commercial fuels such as kerosene, electricity, and bottled gas are still much too expensive for a poor family in comparison to 'free' biofuels [40]. Additionally, in order to use the commercial fuels, not only must they be purchased, but also the stoves which are fuelled by them must be bought, as they cannot be made from local materials. This combined expense is generally far too great for the majority of families in rural India. Thus, moving up the energy ladder poses additional problems of *fuel poverty and equity*.

Option 3

The third option is to create new supplies of safe, feasible wood through reforestation or social forestry programs, improved stove programmes, or other alternative renewable energy technologies such as solar cookstoves or biogas plants. The first alternative would directly provide a new supply of safe and feasible wood and can provide an *efficient* means of using a resource in a sustainable manner. The latter two alternatives would serve to reduce the demand for unsafe wood. Problems of *poverty and equity* may arise, however, if the new technologies are inaccessible to the poorest people.

Choice 3 - Do Nothing and Accept Shortage

The third choice available to rural households is to accept the shortage of safe wood and to adjust their lifestyle to accommodate the shortage. This choice, however, would result in increased *fuel poverty*, as the household would have less light, less warmth, eat fewer meals (perhaps only cooking one meal per day) or eat less well cooked foods. Notably, this option may be involuntary, as in the case of legislation restricting access to unsafe wood or to alternate sources of safe, feasible wood.

After identifying the fuelwood crisis in terms of choices, the next stage in Pearson and Stevens' analysis is to examine how policy can impinge on these choices. The authors believe that the definition of the nature of a policy problem influences the selection of both objectives and instruments of policy formulation. They then identify three different approaches for specifying the nature of the woodfuel crisis and the types of policy options associated with each. As was highlighted above in the description of each of the options for fuelwood use, the fuelwood choices can lead to problems which can be generally classified as ***problems of efficiency, fuel poverty,*** and/or ***equity***. For each of these types of problems, policy options may be devised.

Approach # 1 - Efficiency Problem

This approach views the fuelwood crisis as a consequence of deforestation and resource degradation from inappropriate use of an environmental resource [75]. In this version of the fuelwood crisis, the consumption of wood is too high and its cost too low, reflecting the uninternalised costs of environmental externalities. Pearson and Stevens consider these problems to require *efficiency-based policies,* designed to internalise the externalities. Specifically, the authors suggest three policy options: (i) taxation of wood to raise its price; (ii) regulations to control consumption; and (iii) redefinition of property rights.

Approach # 2 - Fuel Poverty Problems

The second approach is to view the fuelwood crisis as one of fuel poverty, marked by the inability of the poorer groups of rural villagers to obtain adequate supplies of fuel at appropriate prices [75]. The authors suggest that fuel poverty problems require policies which focus on equity and the elimination of poverty and the meeting of basic needs. Three specific policy options are suggested: (i) raise incomes directly; (ii) increase the supply of safe, feasible wood; and (iii) decrease the demand for wood.

Approach # 3 - Gender Inequity Problems

The third approach views the fuelwood crisis as a gender issue. As mentioned earlier, women are usually responsible for the procurement and processing of fuel as well as for cooking. If less time could be dedicated to these activities, women would have more time to earn money and purchase better stoves or commercial fuels. Policy options would then focus on time saving options for women and increased employment opportunities.

Pearson and Stevens have provided an excellent conceptual framework for understanding the various complex issues which constitute the fuelwood crisis. Framing the crisis as a problem of choice facilitates understanding and classifying the options available to rural women and men. Moreover, specifying the nature of the fuelwood crisis as either problems of efficiency or fuel poverty and equity among different economic classes and castes helps to identify concrete avenues for policy investigation. Given our understanding of the differing roles of men and women in the rural energy system, however, we believe that the fuelwood crisis is *at the same time* always a problem of gender inequality. More specifically, the number of choices realistically available to a woman is limited by her level of influence in the various decision-making spheres in the household.

Most importantly, Pearson and Stevens remark that the efficiency, poverty, and equity aspects of the fuelwood crisis are not easily separable. For example, current environmental degradation is likely to have long-term implications for poverty and inequality with the poor, particularly women, facing the most serious impacts. Consequently, policies aimed at addressing efficiency issues could serve to worsen poverty problems. Thus, policy options which are too narrowly focused are likely to be ineffectual and may even exacerbate the fuelwood problem, especially for rural women. What Pearson and Stevens do not discuss is a methodology for developing and investigating solutions and policy options. Given the complex nature of the fuelwood crisis, how then do we devise the best mix of policy options? We require an approach and a set of tools for effective policy formulation. With this in mind we next examine the past attempts by the Indian government to address the fuelwood crisis and the reasons for their failures. Understanding what has been lacking in past intervention attempts will help to identify possible solution approaches.

2.4 Past Government Intervention Initiatives

Since 1980 the Government of India has made a concerted effort to address the rural energy problem through the promotion and dissemination of renewable and efficient energy systems [47]. Most notable among these programmes are the National Programme on Improved Chulhas (NPIC), the National Project on Biogas Development (NPBD), and Social Forestry. Additional initiatives have been undertaken at the village level in the form of Urjagrams (self sufficient energy villages) and at the block level as the Integrated Rural Energy Programme (IREP).

2.4.1 National Programme on Improved Chulhas

The National Programme on Improved Chulhas (NPIC) has been a regular project integrated into the Ministry of Non-Conventional Energy Sources' (MNES - formally the Department of Non-Conventional Energy Sources - DNES) Five Year Plans since 1983. The primary aims of the project were increased fuel efficiency and fuel savings, with secondary aims of saving women's time, decreasing the drudgery from fuel collection, and decreasing the exposure rates of women and children to the serious health hazards of indoor smoke. Officially, the project was intended to be designed by and for women and to train local women as 'chulha masons', thereby providing a source of local employment [85]. The cost of the materials for the chulhas was fully subsidised by the government and beneficiaries had to pay between 25-50% of the cost of an approved portable model. For each year of the project, daunting targets were set, 1000's of training courses were to be held and up to 4 lakhs (1 lakh = 100 000) of chulhas were to be built. To date, around 19 million stoves have been installed under NPIC. The functionality rates reported by different evaluation studies, however, have been very discouraging. For example, the NCAER evaluation survey of NPIC reported that 55.6% of chulhas surveyed were functional and in use , 4.7% were functional but not in use, and 39.7% were non-functional.

2.4.2 National Project on Biogas Development

In 1981-82 the DNES launched the National Project on Biogas Development (NPBD). In order to incorporate region specific factors and to encourage entrepreneurs and non-governmental organisations (NGO's) to participate, the NPBD was implemented as a multi-model, multi-agency, nation-wide, mass dissemination project. The DNES, which in 1992 was upgraded to the MNES, is responsible for providing funding and administrative support for the NPBD. The main goals of the project, in addition to ameliorating national fuelwood savings, are to provide cooking energy in a clean, non-polluting form; produce enriched manure to supplement the use of chemical fertilisers; improve the quality of life of rural women; and, improve sanitation and hygiene. In terms of the number of plants installed, the NPBD is considered by MNES to be a success, as by December 1993 nearly 1.85 million biogas plants had been installed in different parts of the country [80]. In terms of the actual number of functioning plants, however, the success of the NPBD is questionable. The national functionality rate of only 66% indicates that a significant number of plants (34%) were either never commissioned or failed shortly after commissioning and were never repaired.

2.4.3 Social Forestry

There has been no 'national programme or project' for social forestry in India. Thousands of small forestry projects, e.g. reforestation efforts, community woodlots, or agro-forestry programmes, have been undertaken in the rural areas, initiated either by the state forest department or NGO's with varying levels of participation by the local inhabitants. Consequently, it is difficult to assess the overall success or failure of these projects. One assessment by the Tata Energy Research Institute of a state government run social forestry project in a collection of villages near Jodhpur, Rajasthan indicated that conflicting objectives with those of the state forest department caused most of the villagers to treat the government tree plantations with hostility. The overall impact of such projects on the fuelwood crisis has been minimal.

2.5 Reasons for the Failure of Past Interventions

Over the past decade, a vast amount of literature has been written in an attempt to clarify and understand the reasons for the failure of rural energy technology dissemination programmes, especially ICS dissemination. Excellent critical assessments of international cookstoves programmes are presented in Agarwal [2, 3, 4], Manibog [62], Foley, Moss, and Timberlake [35], Gas [38], Ahuja [6], Barnes et. al [9], and Subramaniam [90]. Additionally, Sarin [85], Joshi [46], Ramakrishna [77], Ghandhi, Patel, and George [37], Mittal [64], Sadaphal et. al. [84], Cherail [26], and Kammen [51], provide specific analyses of the Indian NPIC. Additionally, the proceedings from the first and second International Workshops on Wood Stove Dissemination [29, 19] and Islam [43], and Kammen [52] provide both excellent details on wood-stove dissemination theories and on the physics of the actual cookstoves. The NPBD is reviewed in Ramana [78]. Problems with implementation strategies for biogas plants are examined in Dutta et. al [32], and Kishore et. al. [54, 55, 56]. Parikh and Parikh [72], Kandpal, Joshi, and Sinha [53], and Bhatt [12] discuss the socio-economic logistics of family-sized biogas plants, while Agrawal [5] examines the prospects for community biogas plants. Chaudhary [25] examines the specific impact of the adoption of biogas technology on the lives of rural women. Finally, Dutta et. al [33] present an excellent assessment of the impact of the biogas technology in Gujarat state. These past intervention initiatives have tended to primarily concentrate on one aspect of environmental conservation, demonstration of renewable energy technologies, or improvement of quality of life. Furthermore, these energy sector interventions have been at a national scale; there has been no regional or problem area focus [47] and the nature of the targets has been such that the aggregate impact on the rural energy use pattern has been negligible.

The cookstove programmes have been generally judged unsuccessful due to a variety of reasons which may be classified as: (i) technical, economic, and socio-cultural difficulties inherent to the stove technology itself, and (ii) serious inadequacies in the dissemination program formulation and implementation [62, 2, 35]. A similar set of shortcomings with the biogas implementation programmes may also be identified. In order to comprehend the barriers to successful adoption of the new cooking innovations, the benefits of the traditional cookstoves they are aiming to replace must be clear.

Benefits of Traditional Cookstoves

Traditional cooking stoves come in a bewildering variety of designs and materials. Over the centuries, they have evolved to suit local foods, diets, and lifestyles, such that almost every Indian village may be said to possess its own unique design. Nevertheless, the traditional cookstoves may be classified into one of three categories: open fires, portable stoves, and fixed stoves. An open fire may be built anywhere, no special materials or skills are required for its construction, and it may be moved easily and as often as desired. Traditional mud cookstoves (TMC) are constructed out of locally available materials by their users and have very simple designs. Both an open fire and TMC may be used to burn different kinds of fuels. This can be very important if fuel availability and use changes on a seasonal basis. Different sizes and shapes of fuels are easily accommodated by an open fire and also by many TMCs. The power output of the traditional stoves can be varied to perform different cooking tasks: baking, frying, boiling, simmering. The size and temperature of the fire is regulated by modifying the rate at which fuel is added. The pot holes of the TMC are made to fit the pots available to the household. Finally, because biofuels require frequent tending, TMC provide visual feedback to the cook, allowing her to perform other tasks at the same time as cooking [6, 35].

Aside from being used for cooking, traditional stoves also perform a number of other tasks not directly associated with cooking. The stove may be a source of domestic lighting and heating. The smoke and heat are often used for curing meats and preserving grains and other foodstuffs stored in the kitchen. The smoke is also very useful for keeping insects away, including out of the roof of the dwelling thereby aiding to preserve the thatch.

Technical Problems

In the early years of the NPIC, the overriding objective of the programme was increased fuel efficiency and fuel savings. Consequently, the early designs were developed and tested in the laboratory with the emphasis on smokelessness and efficiency. Unfortunately, significant differences arose between the performance of the stoves in the carefully controlled lab setting vs. in the field; in practice many of the 'improved' stoves actually consumed the same amount or more fuel than the traditional stoves. As Manibog [62] notes, there existed significant disagreements on both the concept and measurement of efficiency within the international cookstove research community and Barnes et. al. [9] confirm that the issue is still contentious today. Other technical problems arose in the selection of construction material: conflict between optimising for the technical requirements vs. socio-cultural acceptability; and local availability of material. Many of the designs with the best lab performance were complex, with a chimney, damper, and firedoor which needed to be constructed to precise specifications by trained masons. Additionally, the stoves were usually optimised for use with one cooking fuel and required specific cooking techniques and utensils for optimal use. As a result of these factors, a significant number of the stoves were poorly constructed and improperly used by women who were not trained in their use.

In the case of the biogas technology, the first workable plant design - the floating drum biogas plant - was developed in the 1950's and since that time other models have evolved and the technology has been tested, refined, and proven reliable. Consequently, there have been few actual technical barriers to the adoption of the biogas technology. The economic and socio-cultural problems in conjunction with poor construction and user training have presented much more significant barriers to widespread biogas adoption.

Economic Problems

The economic barrier presented to efforts to diffuse rural energy interventions stems from the fact that both the fuels used in the home and the devices for cooking are generally procured at a zero monetary cost to the user. Stoves are generally made from locally available materials (mud, clay, sand, home-made bricks and stones) by the women and the labour required for fuel collection and cooking is unpaid. Thus, many rural families are often unwilling and/or unable to invest in the new technology. One of the biggest impediments to the acceptance of ICS is their increased cost. Unfortunately, there is a direct relationship between stoves with excellent fuel efficiency and much higher costs [62]. The stove costs are high because many of the ICS are made from imported materials and by trained masons, who must be paid for their labour. There are also indirect costs involved with the purchase of a new cooking innovation; for example, often new cooking utensils are needed. Finally, the predominantly non-financial benefits from the ICS technology (savings in a free fuel, women's time, and the absence of smoke in the kitchen) are not viewed by rural men as sufficient to offset the cost of purchasing the new technology.

In the case of biogas plants, a significant initial investment is required to purchase and install the plant. Additionally, the household must own both sufficient land on which to install the plant and cattle to provide an adequate quantity of dung to fuel the plant. Finally, the numerous benefits of biogas: providing a clean, non-polluting form of cooking energy, improving the quality of life of women, improving sanitation and hygiene, and providing an enriched manure to replace chemical fertilisers, especially those related to "making a woman's life easier", are often not considered to be significant enough by men to justify the cost.

Socio-cultural Problems

In the case of the ICS dissemination programmes, one of the greatest barriers to user acceptance was the lack of understanding by professionals of the multi-purpose use which stoves have in rural homes. Earlier, the numerous benefits of traditional cookstoves were highlighted. Additionally, preferences for traditional cooking methods and for the tastes of foods cooked in traditional ways translated into decreased acceptance of the new stoves. In terms of biogas plants and stoves, many of the rural people held inaccurate beliefs as to the amount of time and labour involved in feeding the plants, the smell of the slurry, and the safety of cooking on gas derived from dung.

In some castes, taboos with regard to handling the dung served as an effective barrier to biogas adoption. Another significant socio-cultural barrier to ICS and biogas adoption was the financial decision-making structure in the household, as discussed earlier. The women who would be aware of the benefits of and need for the new technologies were ***not*** responsible for the decision to purchase the innovations. In the both cases, the promoters of the new innovations failed to consider the socio-cultural setting into which they were introducing the new technologies. The lack of understanding of the rural customs, beliefs, traditions, and taboos, in conjunction with the lack of consideration of the user's needs and preferences for cooking fuels and stoves, meant that the promoters had no determinants of user acceptance.

Program Inadequacies

Compounding the technical, economic, and social problems with the rural energy technologies themselves were the significant inadequacies in the planning and implementation of the actual dissemination projects. Although in recent years the focus has been shifting, originally the predominant focus of both the NPIC and NPBD was on meeting quotas for stove/biogas plant installation. Consequently, the quality of construction was often vastly compromised; little or no user training for use and maintenance of the technologies was given; and, no follow-up was provided. Not only was there little or no training given to the users of the ICSs but also, the training given to the women who were to make a living constructing improved stoves was inadequate [85]. Often the women would have the chance to construct only one stove during the training session and then be considered 'experts'. Because of the low level of education among the rural women, most did not understand the basic physical principles of efficient combustion, so they did not grasp the need for sound construction.

Perhaps the greatest short coming of the NPIC was the complete lack of attention given to the ***needs*** of the users - the rural women. Because the stoves were designed and tested in a laboratory and then disseminated en masse with no options for user adaptation, they were sorely mismatched to the needs of the users. The ICS's often required larger pieces of wood and different size pots than were locally available. The women were required to change their cooking technique to use the new technology and the new stoves, with their flues and dampers, were often complicated to operate. Because the new stoves did not fit into their lifestyles and traditions many women simply stopped using them. As Gill [38] notes, *the failure of the early ICS programmes may be principally attributed to the fact that the priorities of the villagers were different from those of the stove promoters.* Generally, it was assumed that the acceptance of the new technologies by the intended beneficiaries would 'naturally' occur, given the 'obviously' superior performance of the improved cookstoves and biogas plants/stoves over their conventional counterparts. In reality, however, because the new technologies were so poorly matched to their needs, the intended users either simply discarded or discontinued to use them after they fell into disrepair.

A second key negative feature of the ICS dissemination program was the startling lack of consistent monitoring, evaluation, and/or follow-up. NPIC was primarily aimed at achieving stove dissemination targets. Once the stoves were installed into the rural households, the project planners or stove masons rarely returned. Consequently, very little information was ever gathered to assess the actual performance of the stoves in the field. The lack of follow-up to the programme meant that once the approximate two year lifespan of a stove expired, rural women were forced to return to traditional cooking methods.

Similar to NPIC, the NPBD was, and still is to a great extent, focused on achieving installation targets as opposed to long term use and maintenance of the technology. Consequently, the main problems with the biogas plants appear to be structural defects resulting from poor quality construction and improper usage of the plants as a result of inadequate training for users on the use and maintenance of the device. A significant number of plants in India are so poorly constructed that they are either never commissioned or fail shortly thereafter. Since virtually no user training on the use and maintenance of the plant is provided and there is no programme for follow-up by the masons, many simple problems permanently cripple the plant operation.

Finally, and perhaps most significantly, many of the problems and failures of past interventions are directly attributable to the lack of genuine participation by rural women. In the current structure of both the NPIC and the NPBD, women play the role of beneficiaries or final users of the innovation. Even in intervention experiences in which there have been efforts at seeking women's participation, their involvement is usually restricted to those of 'data sources'.

2.5.1 Barriers to Women's Participation

A number of factors form barriers to the effective participation of women in rural energy intervention programmes, the most significant of which are economic and social. Such factors can be broadly classified as arising from the following constraints [65, 95]:

- economic impediments
- traditional decision-making roles in the society
- educational constraints
- ideological barriers in extension services

Economic Constraints

As was identified earlier, the majority of activities within women's productive sphere are of a subsistence nature and within the informal economy. Women are rarely paid for their daily labour and when they are it is often at rates up to 50% less than men receive for identical activities. Consequently, women rarely have access to disposable cash incomes with which to purchase new innovations. Additionally, women are often denied access to institutional credit; often loans are only given to men, since women are denied the right to own land they lack collateral to guarantee loans. Furthermore, because the household decision-making structure places all monetary decisions and control in the hands of men, women are often denied access to benefits of rural energy interventions. This phenomenon is reflected in interventions in the domestic cooking system where men have to be convinced to undertake even the smallest expenditure for the kitchen.

Restrictions on Decision Making Outside of the Household

Earlier in this chapter, the decision-making roles of men and women within the household were discussed. Because of cultural and social norms in rural India, women generally do not have the opportunity to undertake decision-making roles or responsibilities in the public sphere, such as being involved in the local Panchayat (village council). Thus, often no formal mechanisms exist for publicly voicing or debating the concerns of women. Consequently, ' women's issues' are often not seen as being as important as 'men's issues' because they are not publicly discussed. Because women lack a formal voice in the community, rural energy development projects are often formulated with objectives or implementation schemes which are in direct conflict with their desires or capabilities. For example, a village social forestry project may be realised as a single species, cash crop tree plantation, as preferred by the men, as opposed to a multi-canopy, multi-use community forest which would be preferred by the women. Additionally, the project planners, working only with the village men, may assume that the women will be able to tend and water the plantation, ignoring or being unaware of the already backbreaking daily workload the women face.

Educational Barriers and Constraints

Women's restricted access to education, training, and information may also be attributed to the cultural and social norms in rural Indian society. From a young age, rural women receive much less education and training than men, because of women's low social status in Indian society [98]. More than three-fourths of Indian women are illiterate - twice the proportion of illiterates among men - and fully ninety percent of rural women workers are unskilled [95]. Consequently, women seldom have access to information on new innovations. For example, in many instances the programmes both for training masons in the construction of improved chulhas and for general chulha use and maintenance are aimed exclusively at men. This occurs despite the fact that the use of the technology falls firmly within the sphere of women's work.

Ideological Barriers in Extension Services

The information barrier problem often is compounded because of the ideological biases of predominantly male extension workers, which work against direct consultation with rural women. As a result of their role as managers of domestic energy systems women are most familiar with household fuel supply problems as well as the needs and preferences of their families and have an indepth knowledge of the immediate environment and energy systems. Since the extension workers interact primarily with men, this source of indigenous knowledge remains untapped. Worse still, technologies and innovations which are actually targeted for women are based on perceptions and preferences of men. It is not surprising then, that women are reluctant to adopt stoves and participate in programmes that they have had little input in designing.

Chapter 3

A Systems Approach for Rural Energy Intervention Design

The preceding chapter presented the background to a number of very critical issues in the rural energy system. The description of the rural energy scenario illustrated the nature and severity of the rural energy crisis, and the description of the male and female productive and decision-making spheres illustrated the distinctive role of women in the domestic energy system. The indepth study of the fuelwood crisis provided both a conceptual structure to understand the crisis and to guide fuelwood policy formulation, and illustrated the need for concrete methodologies for generating energy policy within the complex rural energy system. Additionally, the examination of past intervention initiatives emphasised the problems encountered by researchers attempting to disseminate renewable energy technologies and investigated the technical, economic, and socio-cultural factors responsible for the failure of the past programmes. These factors can be generalised into two key issues predominantly responsible for the downfall of previous renewable energy technology dissemination efforts:

i. project teams failed to establish, understand, or consider the needs of the rural women and therefore the new technologies were poorly matched to the users' felt or perceived needs. This issue is symptomatic of a larger problem. Project teams failed: to identify women as the principal decision makers in the domestic energy system, to understand the impact which their decisions have on the structure of the system, and to include women as full participants in all stages of the intervention design and dissemination process; and

ii. the rural energy problem was not examined from a system's perspective: the role which different cooking devices and other renewable energy technologies play in the complex cooking energy system was not understood - one household may have several different cooking devices, use different fuels in each, and perform specific cooking tasks on each stove - and, variations in cooking habits, traditions and techniques were not considered.

The fundamental problem underlying the renewable energy technology research and dissemination, which would account for the widespread failure of initiatives such as the ICS and biogas projects, lies in the prevailing conceptual framework and the problem solving method used in the field. Historically, the dominant conceptual framework has been completely inadequate to deal with the scope of the problems presented by the field; it has been too simplistic, one dimensional and linear. Problems such as ICS research and dissemination cannot be considered in isolation from the other issues which constitute the entire domain of rural energy. Indeed, because the problem the field is attempting to address (i.e. reducing fuelwood demand via improving stove efficiencies) is but one dimension interconnected or interwoven into the myriad of other issues which constitute the whole 'rural energy problem', to examine it in isolation is to take far too narrow a point of view. As Bardwell [8] comments, at least 90% of problem solving is generally spent: solving the wrong problem, stating the problem so that it cannot be solved, solving a solution, stating the problem too generally, or trying to get agreement on the solution before there is agreement on the problem. Many of these 'problems' with problem solving can be remedied when a comprehensive, well-founded framework is used to organise the problem solving activity. The most expedient conceptual framework in which to conceive the rural energy crisis is that embodied in the systems approach.

3.1 Why Use a Systems Approach?

The need for a comprehensive 'systems approach' for cooking energy technology development and dissemination and rural energy planning in general has been promogulated for at least the last ten years. In writing on the assessment and monitoring of stove programmes Joseph [45] states that the failure of early ICS dissemination projects is overwhelmingly due to the project directors' lack of understanding of what is involved in developing a product as part of a system. He stresses the need for using a systems design approach for ICS development and dissemination. Conway [30, 31] uses the concepts of systems theory as a basis for his agroecosystem analysis and Nystrom [71] champions the use of a systems analysis approach in her work studying kitchen design in Hanoi, Vietnam. Additionally, Chambers[23] in his 1993 work challenging the dominant approaches characterising rural development, argues for the need of a systems approach to rural development in general. Bormann, Smith, and Bormann [16] also emphasise the need for using a comprehensive systems approach for modelling in the rural energy system. Very little work has been presented to date, however, which actually outlines what constitutes a systems approach to energy intervention design. Before presenting a description of the systems approach - both a contextual framework for examining the complex cooking energy system as well as a methodology for rural energy design based on well established principles of systems theory - the important basic concepts and definitions of systems theory are presented.

3.2 Fundamental Systems Concepts

Within the realm of systems theory, there are a number of fundamental concepts and definitions. The definitions presented here are drawn from the work of Athey [7]. A ***system*** is a set of parts which are co-ordinated and work together to accomplish a set of goals or achieve an overall objective. The parts are more specifically known as ***components*** and these components are the primary elements which comprise a system. Components are not limited to physical objects, rather they may be people, machines, money, concepts, processes, feelings or beliefs. A system is delineated by a ***system boundary*** which comprises the set of components which can be directly influenced or controlled in the design of the system. In this way a system boundary is not a physical boundary, rather it is a mental construct which abstractly encircles the components. The boundary separates the system from the ***environment*** which includes all of those factors which have an influence on the effectiveness of a system but which are not controllable by the system. *Hierarchy* is a fundamental systems concepts, as Churchman notes, " the system is always embedded in a larger system" [28]. In this way, the components which comprise a system may themselves be systems and are thus called *subsystems*. In turn, the system in question may itself be part of a larger, more encompassing system, called a *suprasystem*. A very important aspect of a system is its *structure*, which depicts the relationship between the components, including their organisation, interconnections, and interactions. *Systems Design* is then concerned with determining the system structure comprising the most appropriate selection of components which best meets the overall objectives of the system. The individual or body which has ultimate control over the system design, or who has authority to change the system in accordance with the results of a detailed study of the system, is the Chief Decision Maker (CDM). The *objectives* of the system are then the goals which the CDM desires or should desire the system to achieve. Differing from objectives is the system's *purpose*, which is determined by the system's relationship with the environment. As Athey [7] remarks, a system can have many purposes, which of the purposes is emphasised and how the system goes about satisfying that purpose is dependant on the system objective. Of course, no system can be designed so as to be able to satisfy its multiple, conflicting objectives and purposes equally well, thus *system trade-offs* must be made. Finally, a *systems diagram* is a diagrammatic tool used to illustrate the system and its major parts. The system diagram depicts the interrelationships between the system boundary, the environment, the subsystems and the components. Figure 3.1 below illustrates a general system diagram, including the key elements from the system description.

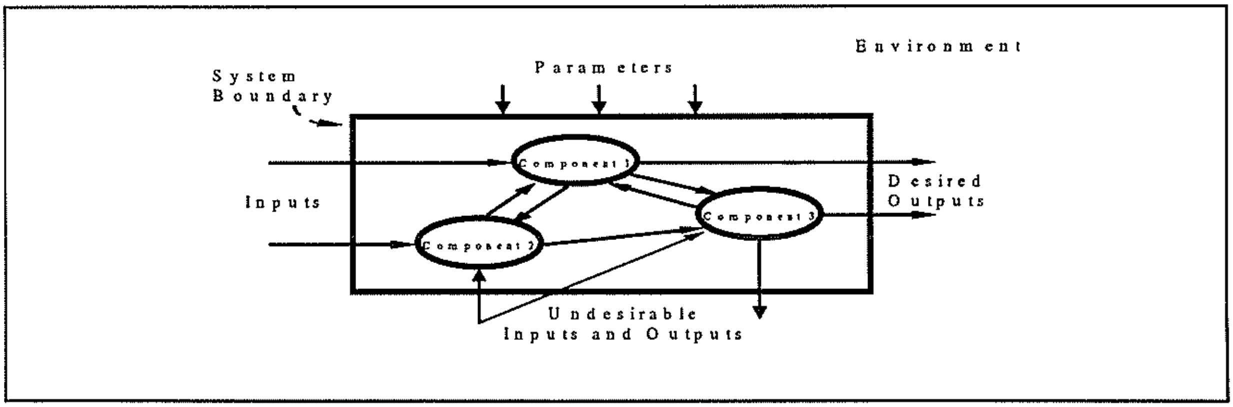


Figure 3.1 - Basic System Components

3.2.1 The Systems Approach

Simply defined, the systems approach is a generalised methodology which provides a blueprint for the creation of solutions to a wide variety of problems, or a general problem solving tool. What sets the systems approach apart from other problem solving methods is that it is much more than a simple step-by-step recipe for problem solving. The systems approach is unique in that the methodology adopts the view that problems cannot be examined in isolation, but rather they need to be seen in relation to the underlying *systems* of which they are part [7]. Most fundamentally, a systems approach is a *thinking process*, it presents a comprehensive and logical framework in which to think about *systems* - their components and interactions - and to conceptualise *systems problems*, in addition to solving them. In a systems approach, individual problems are not emphasised, rather attention is focused on solving *systems problems* and understanding the *whole system performance.* Furthermore, the systems approach is an iterative procedure which gradually encompasses the total problem-solving cycle as a methodical way of covering more and more details, while always retaining an overview of the system.

The systems approach has emerged from general problem solving methods. Starting in 1896, Helmholtz proposed three stages of problem solving: *preparation* - seeing what the problem is, *incubation* - preparing conditions for the development of eventual solutions, and *illumination* - the actual bringing forth of a solution. In 1937, Dewey expanded these to four steps, and in 1957 Osborne further refined the stages to seven steps. In the 1960's authors such as Hitch, Quade, and Churchman developed the seven steps to the systems analysis approach. Finally, with the work of authors such as Athey [7], Roe et. al. [82], Ackoff [1], and Checkland [27] in the 1970's, the systems approach emerged as a methodology which encompasses both the aspects of systems analysis and decision making. The eleven steps which comprise the systems design methodology for problem solving are depicted in Figure 3.2 (adapted from [82]) and described below. There are three key characteristics to bear in mind when considering these eleven phases: (i) this is a circular approach, when the eleventh stage is reached one is returned to the first stage where either a new defect in the environment is identified, or the process may be revisited for an n th iteration; (ii) at each step and between steps there is a constant flow of information; and (iii) at any stage it is acceptable revisit previous stages to modify or clarify earlier decisions.

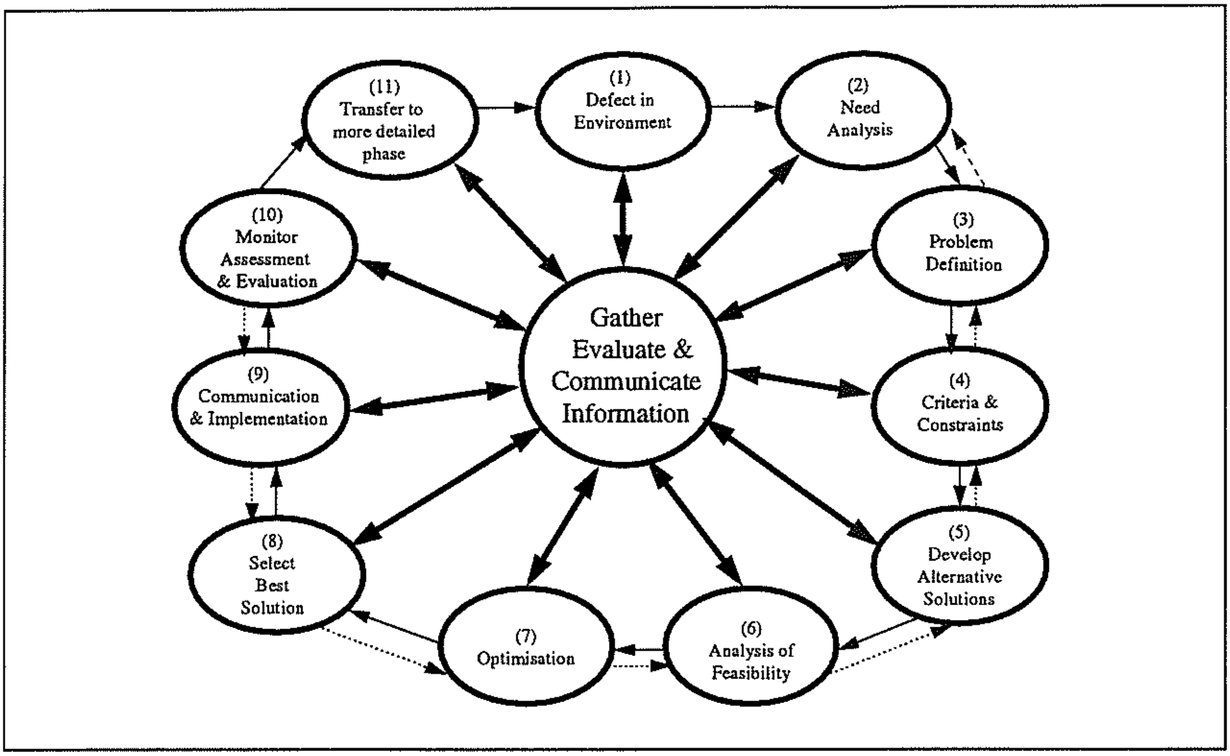


Figure 3.2 - The Stages of the Systems Approach

3.2.2 A Systems Approach for Intervention Design

The eleven steps of the systems approach may be broadly categorised into four different phases: (i) Problem Formulation - Steps 1 - 4, (ii) Alternative Solution Generation - Step 5, (iii) Selection of Best Solution - Steps 6 - 8, and (iv) Implementation, Assessment, and Evaluation - Steps 9 - 11. The problem formulation phase is a critical first step, if the problem to be solved is inadequately formulated then the devised and implemented solutions will likely be inappropriate. When generating alternative solutions, criticism and evaluation of ideas should be minimal and seemingly 'crazy or fanciful' solutions should not be automatically discounted as they may provide the seed for a very innovative and useful solution. In order to select the best solution, a number of iterations between steps 6 to 8 may be required before a satisfactory solution is found. Finally, the importance of assessment and monitoring must be stressed; it is not sufficient to simply 'implement a solution and run' with no thought to the impact or success of the new innovation. Ensuring that an innovation is being used properly, or understanding the reasons for adapting the innovation can provide crucial information for future problem solving ventures.

Problem Formulation

(i) Identification of a Defect or Lack in the Environment. Before the "defect" can be investigated, the very first step of the Systems Approach is to identify the stakeholders or "players" in the system of interest. At this initial stage of the problem solving cycle, the scope has not been established and the field of study should be left open. Thus, the defect describes the problem to be investigated in very general terms, illustrating the nature of the deviation between what is expected and what actually is. Encompassed in this phase is the identification and description of the system to be studied. The system definition cannot possibly include every aspect of the actual system, and in this sense it is an abstraction or model. The model can take on many different forms, from completely conceptual to quantitative and mathematical, depending on the nature of the system under study and the needs of the designer. The model is useful not only for developing a clearer understanding of the key system relationships and understanding how the system functions, but also for searching for and testing various solution hypotheses. To be able to explain why new solutions are superior to the current one, the model is used to gain a complete understanding of the system performance, in terms of benchmarks on cost, accuracy, and reliability etc.

(ii) Need Assessment. The goal of the need assessment is to establish the characteristics of the need. This comprises identifying: *type of need* - whether it is physical or non-physical and whether it is a need for a product, service, or a combination of the two; *extent of the need* - answer questions such as who, when, where, how many/much are effected by the problem; *level of current satisfaction of the need* - does any product or service currently exist which attempts to address this need? Several tools are used to conduct this aspect of the needs assessment. A literature search of secondary background information is used to elucidate the three aforementioned aspects of the need. A market survey is used to investigate the needs and desires of the users with relation to the identified defect. A competition analysis is used to appraise the current competitive solutions to the design problem and to identify how much could be gained by a new solution, as opposed to establishing ways of improving a current solution.

(iii) Problem Definition. Based on the information learned from the needs assessment, this third phase consists of the preparation of a detailed specification of the requirements for the problem solution.

The problem statement must clarify the major restraints upon the solution, the availability of resources, the objectives, and the difficulties which must be overcome. The problem definition takes the form of a concise statement which precisely defines the problem being addressed.

(iv) Criteria & Constraints. The fourth phase is a sub-phase of the problem definition. The criteria and constraints, which provide the quantitative restrictions on the problem solution, comprise a set of performance benchmarks against which alternative solutions may be judged. Criteria are general specifications defining what the solution 'should or might' contain. Constraints, on the other hand, define specific limits or values which the solution is required to meet or fulfil.

Alternative Solution Generation

(v) Generation of Alternative Solutions. Until this point the problem definition should have been sufficiently broad such that a wide range of solutions is still possible. Several tools available for generating alternative solutions are [7]: *examine the existing solution* - the model of the system is used to establish system performance benchmarks, and these can give clues to new solutions by illuminating major weaknesses or disadvantages of the current solution; *modify existing solutions* - examine existing solutions to determine if any may be modified to overcome or minimise negative aspects of the present solution; *pre-packaged / off-the-shelf solutions* - determine if a good solution already exists and simply has to be applied to this problem situation; *start from scratch* - use brainstorming to look for an idealised solution, i.e. if no restrictions were imposed and anything could be done, then add criteria and constraints.

Selection of Best Solution

(vi) Feasibility. Each alternative solution is examined against the criteria and constraints, using an a priori established weighting scheme, performance chart, or evaluation matrix etc. The solutions are ranked in order of feasibility and are screened such that the overall feasible solution alternatives are limited to between 2-5 [7]. Several filters and iterations may be needed to establish the feasibility. At this phase, close interaction and discussions with the stakeholders are essential to ensure that the solutions being investigated are indeed considered to be feasible, compatible with the stakeholders' environment, and congruous with the stakeholders' felt needs.

(vii) Optimisation. For each of the alternative solutions, the criteria and constraints which the solution does not fulfil are examined to determine if the solution may be altered in some way so as to meet them. Different techniques, such as linear programming or multi-criteria decision making, may be used with the model to expedite optimisation. Additionally, demonstration models of the proposed solutions may be constructed and tested in the field by the users and, through these field trials, the solution options may be further refined and optimised to suit the needs of the users.

(viii) Selection of Best Solution. The best solution is chosen, in conjunction with the stakeholders considering the results of the field trials, and based on the criteria and constraints established from the felt needs of the users. A number of iterations between the feasibility and optimisation stages may be required until a satisfactory solution is derived.

Implementation, Assessment and Evaluation

(ix) Communication & Implementation. The key to implementation is acceptance and several different acceptance groups will exist - designers/analysts, decision makers, and users. A number of factors will affect the acceptance of the new solution by the various groups [7]: *pressure* or urgency for a new solution to the problem; *relative advantage* or how much greater total value the new solution has over the current one; *goal congruence* or the degree to which the new solution furthers the goals of the affected groups; and *behavioural changes* or the amount and type of behavioural change the new solution will require. These factors are discussed in greater detail in Chapter 8, as part of the Intervention Design Process. Appropriate communication techniques will have to be used to explain and 'sell' the new solution to each acceptance group, and failure to communicate to a group could result in failure of acceptance of the new solution.

(x) Establishment of Performance Standards, Monitoring & Evaluation. To ensure that the new solution is meeting the desired objectives, standards for the performance must be established and a monitoring program must be put in place to ensure that the standards are indeed being met. Additionally, the introduction of a new innovation into a system will elicit consequences or changes that occur to an individual or a social system as a result of the adoption or rejection of an innovation [83]. The consequences of an innovation are often overlooked. Either it is assumed that only positive changes will occur as a result of innovation adoption or the consequences are difficult to measure and quantify. In reality, however, the changes brought about by the adoption of an innovation are very significant and the

way the adopter perceives these changes will strongly affect their decision to continue to use the innovation. The consequences of an innovation may be classified as: *desirable* vs *undesirable; direct* vs *indirect;* and *anticipated* vs *unanticipated.* In order to assess the impact of the consequences of the implementation of the chosen problem solution, an impact assessment should be conducted. The aim of such an assessment is twofold, first to establish the aforementioned changes brought about in the lives of the stakeholders by the adoption of the solution and second to assess the implementation agencies' performance over the course of the problem cycle. The results of the impact assessment can be used in several ways and determine the nature of the final step in the design cycle.

(xi) Transfer to a More Detailed Phase. At this point either a new defect may be defined or the cycle may be revisited to further refine the proposed solution, depending on the results of the impact assessment. The assessment may uncover problems which still exist or which are not adequately addressed by the chosen solution, this would trigger the start of a new design cycle or a 'transfer to a more detailed phase' in which the problem is once again examined in light of the new problem information learned from the impact assessment. A new problem may have either been created by the introduction of the first solution or a different problem may surface as now having a priority for the stakeholders, and a new problem cycle may be undertaken to investigate this new problem (illustrating how this is a cyclical and ongoing process). Finally, the impact assessment can provide information useful to the implementation agency on how to improve its approach or various techniques used during the entire course of the problem solving cycle.

3.3 Why Model the Rural Domestic Energy System?

An integral element of the first phase of the systems approach is the specification of the system to be studied. A useful system description cannot possibly include every aspect of the real system and in this sense it is an abstraction of reality or a model. A model is one of the most effective tools available to systems theorists and it can be used in several different ways, depending on the nature of the problem at hand. The user of a model must always bear in mind, however, that a model is only an abstraction of reality and therefore any information derived from the model must always be judged in terms of the real world. When dealing with complex systems, a model is very useful for gaining insights into and understanding the multifarious relationships which form the system. Such an understanding can be useful for organising ideas in relation to integration with higher levels in the system hierarchy. A model allows users to experiment with and analyse different possible intricate system structures. In this way, a user may then generate both a range of alternative system objectives or options and a set of indicators - technical, non-technical, and economic - by which to evaluate each of these options. The model can then be used to perform a sensitivity analysis to discover which indicators have the most significant influence on the system's dynamics. Once a set of feasible, alternative system objectives have been created and analysed, effective policies may be designed to achieve these different objectives. Finally, a model is a very useful tool to facilitate communication and interaction between and among the different players in the problem solving process: those who design, choose, and endure the policies (staff, decision makers, citizens).

The model developed for the system under study need not be a numerical simulation model. As Holling, [41] noted, a number of different techniques are available for creating useful models. The type of model most appropriate for a given problem will depend upon such factors as [41]:

i. the number of variables, management actions, and spatial elements;
ii. the level and breadth of understanding of the underlying physical, ecological, and economic processes; and
iii. the number and quality of the data.

In some instances a conceptual model will provide a sufficient level of detail to understand the problem, generate and evaluate solutions and policy options, and communicate the results; while in other situations, a mathematical model will be required to achive such objectives. A more detailed investigation into the structure of the rural energy system will help to illuminate the type of model needed to effectively study the system.

Historically, the structure of the rural domestic energy system has been very poorly understood. In fact, most development attempts did not examine a household energy system at all, but rather simply considered a stove or a biogas plant as an independant device or a tree plantation as an income generation activity for the village panchayat. As described in the previous chapter, the lack of understanding of the complex nature of the household energy system meant that renewable energy technology intervention programmes in general met with failure.

In order to understand the complex structure of the domestic energy system, the role which different cooking devices play in the household system must be clear. In past problem solving attempts one improved cookstove was designed to be used with one particular fuel for all cooking tasks. In reality, however, one household may have several different cooking devices, use different fuels in and perform specific cooking tasks on each. Furthermore, a cookstove is not simply an independant 'cooking device' which may be introduced on a wide scale to a large number of very different households, but a component whose introduction into the kitchen system affects both the structure and function of the complete complex system.

For example, in terms of an ICS the type of stove used depends on the cooking task to be performed and the type of fuels available. The fuel availability is governed by a number of interrelated and not necessarily easily identifiable factors such as cost of fuel, distance to source, and preference. The types of cooking tasks which may be performed on the cookstove depend on factors such as the diet of the user and the perference for certain cooking methods. Thus, any changes to the cooking device in the system must consider the effects of the fuel and the task performed by the device. As well, in order to genuinely understand the household energy system, these decisions must be captured and considered.

This understanding can be best facilitated by modelling the cooking energy system at the household level. A model of the household cooking energy system will facilitate understanding of the nature and function of the complex structure of the system. The model will establish the components and the linkages among components in the cooking system, thereby establishing the current cooking energy use pattern in the household.

As outlined above, a model of the system under study may be useful for understanding the relationship of the system within a larger system hierarchy. Assessing the demographic level at which the intervention programs were historically targeted will indicate the level in the overall system hierarchy where a model of the rural energy system should be centred. Historically, the approach taken has been to design a renewable energy technology, such as an ICS, in a laboratory, independant of the intended users, and then attempt to disseminate the technology on a wide scale to a large number of households. India, however, is a vast country, each region having different languages, cultures, customs, and traditions. Similarly, cooking habits, traditions, and techniques vary not only from region to region but also from village to village and even, in some cases, from household to household within a village. Thus, a technology which is appropriate for one household may be entirely unacceptable to a neighbouring household. Consequently, the design of one type of intervention (eg. cookstove) to be disseminated on a large scale has proven to be inappropriate. Because of its diverse nature, instead of large scale intervention programmes targeting a large number of different users, the household energy system should be examined at a micro level in direct consultation with the intended beneficiaries and users, the rural women.

A model is useful for generating and investigating alternative solutions. At the level of the user, a conceptual model provides a simple way to identify the fuel/stove/task combinations used by the household and the factors or decisions affection these combinations. For the expert, a model provides a simple tool which would allow them to see the complete cooking system, understand how changes in one area (eg. type of agricultural crop grown) could drastically affect the household in another seemingly unrelated ares of the home (fuel (crop residues) for cookstove), and then to predict, based on indicator levels, how the system will react to these changes. For policy planners, a model can help to identify where development efforts should be aimed by facilitating their understanding of both the current energy needs of the household and the role that cooking energy plays in the overall domestic energy system. Also, planners may examine what if scenarios to determine the behaviour of the system under different conditions or in terms of what would be the impact on the entire household energy system if a certain intervention was introduced into the system. Finally, a model can facilitate communication among the users, stove design experts, and the program managers designing dissemination projects. A model provides a common language for discussion and the creation of the model requires input from all affected parties.

To develop such a model of the domestic energy system, to be used by program managers and policy planners, a modelling theory must be chosen which provides a mathematical structure appropriate for modelling the system under study. To select such a theory, past modelling approach need to be assessed.

3.4 Past Modelling Approaches

As part of the process of selecting a modelling theory upon which to base the mathematical model of the rural domestic energy system, several past modelling approaches were investigated. Numerous researchers have developed basic models of the rural domestic energy system in their attempts to study and understand the rural energy scenario at the village level. The existing mathematical models for the domestic energy system can be broadly classifed into three different types: *Energy Audits, Decision Support Planning Tools, and Input/Output Models.*

3.4.1 Energy Audits

Energy audits provide a detailed view of the energy flows in the village under study. Kumar and Ramakrishnan [60] and Maikhuri and Ramakrishnan [61] extensively studied the energy flows through village ecosystems in two different states in Northeastern India, the former in Arunachal Pradesh and the latter in Meghalaya. Bose, Puri, and Joshi [17] examined the energy profiles of three un-electrified villages in eastern Uttar Pradesh, and Vidyarthi [94] studied the village energy scenario, emphasing the effects of the rural energy crisis on the poorest families, in a village 60 kms north of Lucknow, the capital of Uttar Pradesh. Nisanka and Misra in their three paper series [68, 69, 70] presented an extremely detailed ecological and economic study of an Indian village ecosystem in the eastern state of Orissa. Finally Revelle [81], in his now classic paper, examined in general the energy use in rural India. For each of the models examined, the authors dedicated a significant effort to rigourous data collection, which was summarised in charts and ultimately used to create the energy flow diagrams. These diagrams provide a static snapshot of the current energy consumption levels in the village, usually in terms of total MJ or GJ for the study period. As such, their use is limited to providing understanding at the conceptual level of the structure and current level of function of the aggragate village system. In terms of predicting changes in the energy scenario induced by modifications in the structure of the system i.e. through changes in the availability of resources or technologies, however, the usefulness of these types of models is severely limited.

3.4.2 Decision Support Planning Tools

The second type of energy models use linear programming techniques to develop economic optimisation models for energy planning at the village level. Joshi, Bhatti, and Bansal's [49] model attempts to minimize the total annual cost of the energy output from various technologies subject to both demand constraints for various end uses and supply constraints for various sources. They also present a conceptual model of the energy flows for the village under study. Parikh [73] presents a rural energy system model which is used in Parikh and Kromer's [74] companion paper for examining the food-fodder-fuel-fertilizer relationship for biomass in Bangladesh. In this model, the objective function attempts to maximise for a given rural area the revenues from crops minus the cost of purchasing fertilizers, commercial energy, feed, and hired labour. A third linear programming model, developed by Singh and Marsh [88], attempts to maximise the biomass energy production through optimum selection of the area under various crops subject to two groups of constraints - resource limitations and minimum production requirements. A fourth linear programming model was developed by Zhen [99] to minimise the cost of energy supply subject to resource demand, energy conversion devices, and energy consuming devices restraints, and maximum and minimum limits to the consumption of energy in various end use devices. The model was applied to a village in North China.

The chief difficulty with each of these types of models lies in the limited availability of market prices for many of the parameters. Noteably, both Parikh and Singh and Marsh concentrated on the agricultural sectors of the domestic energy system, which are monetized systems. Also, while an economic model which optimises cost is useful for policy planning, it does not facilitate understanding of the dynamics of the rural energy system. Because a significant portion of the rural domestic (cooking) energy system is non-monetised, the usefulness of such economic models for this sector is limited.

3.4.3 Input / Output Models

The third type of models may be classified as input-output models. These models begin with conceptual energy flow diagrams for the system under study and translate these diagrams into input/output mathematical models for analysis. Specifically, Hurst and Rogers [42] presented a simple mathematical model, based on the first law of thermodynamics, for capturing the animal energetics of cattle and buffalo in India. They begin with a simple model of the energy flows through a cow/buffalo and translate this into a linear model which calculates energy consumption as a function of useful output energy, basal metabolism, and animal weight change. Bormann, Smith, and Bormann [16] developed a detailed microcomputer model for comparing biofuel systems which they used to investigate the trade-offs between woodfuel and charcoal systems in energy, mass, volume, and air pollution for supplying an urban population with cooking fuel. They began with establishing the stages in wood and charcoal systems from harvesting of wood to the enduse of cooking. Three fuel variables are followed through at each stage (mass, energy, and volume) and at appropriate points a variety of related output variables is calculated. The model does not allow for economic analysis, but economic trade-offs may be explored. The final two modelling approaches examined were developed for studying energy systems in general, as opposed to many of the former, which were specifically aimed at the rural energy system. Maxim and Brazie [63] presented a multistage input-output model for evaluating the environmental impact of energy systems. This model considers the efficiency and environmental impacts of each stage (extraction, storage, conversion, transmission etc.) of alternative energy producing chains. Finally, Koenig and Tummala [58] and Tummala and Conner [92] present a mass-energy based economic model in which an ecosystem is defined as a system which comprises both natural environmental components and human made material transformation, transportation, and storage processes driven by physical, solar, and human forms of energy. To develop the mass-energy theory, a system with three material inputs, one useful output, and one waste byproduct is considered. A series of flow rates for the inputs and the byproduct are given in terms of the output. For each material flow rate, three energy costs are derived in terms of human, solar, and physical energy expenditures. In the second paper a detailed example is given. Birkett and Roe [14] draw on the work of Tummala and Conner to develop bondgraph models of ecosystems. They specifically translate the linear graph based material transformation, transformation, and storage processes into analogous bondgraph components and illustrate the use of these bondgraph components by presenting Tummala and Connor's two process production / recycling example modelled using bondgraph theory.

3.4.4 Selection of Modelling Theory

After considering the various modelling theories and approaches available, Koenig, Tummala and Conner's mass-energy modelling approach was selected as the modelling theory for this work. There are several reasons why this theory is preferred for the creation of a rural domestic energy system model. At a conceptual level, the mass-energy theory is preferred because it is the most 'systems oriented' as compared to the other available input-output type models. Because it is based on the Graph Theoretic Method which fundamentally incorporates systems concepts, ideas such as a system boundary, componets, interconnections, and through and across variables are inherent to the mass-energy method. As well, the systems orientation of the mass-energy method means that the theory easily accomodates the investigation of various levels of abstraction. Since the concepts of systems, subsystems, and suprasystems are integral to the mass-energy theory (and not to the other input-output models discussed previously), the examination of different levels in the rural energy system hierarchy is easily achieved with a mass-energy model. At a more practical level, the modularity of the mass-energy theory means that each component of the rural energy system may be modelled as a separate, generic process. Consequently, these processes may be arbitrarily interconnected to form a system and different system configurations are modelled by simply adding or eliminating components and modifying the interconnections. The inherent Graph Theoretic Method concepts allow the connectivity to be translated into a system of equations, which are easily put into a matrix form to be solved in a systematic way, using simple computer algorithms. In contrast, in the input-output models described in the previous section, the interconnections and components are essentially 'hard-wired', such that as soon as the structure of the system changes all of the system equations must be modified, making changes to these models more cumbersome and time-consuming.

To close this chapter, a checklist given in Bormann, Smith, and Bormann [16] of five characteristics which a good model should have to be useful is presented. This list provides an excellent guide or reference against which to compare and evaluate the mass-energy model developed in this thesis. Specifically, to be most useful systems models should be [16]:

i. simple enough to be easily learned;
ii. operable by hand calculator or on a simple microcomputer;
iii. flexible enough to take many possible local variations into account;

iv. designed to generate outputs of direct interest to managers, economists, and policy makers and;

v. easily refined and updated

The mass-energy model described in this work is developed based on well-founded principles of the Graph Theoretic Method. This theory provides a simple, yet elegant methodology for modelling the rural energy system. The basic theory of the Graph Theoretic Method is given in the following chapter and this general introduction provides sufficient information for readers with various different backgrounds to understand and learn the modelling method. As is demonstrated in the model application examples given in Chapters 6 and 7, the mass-energy modelling theory is easily implemented using readily available software packages, such as Matlab, on a simple microcomputer. The inherent modularity of the mass-energy modelling theory means that it is very easy to create and implement new components as desired, to more accurately model local household/village conditions. As well, since the user specifies all of the component parameter values, the model is very flexible and can easily be modified to take into account different local variations in the rural domestic energy system. Also, because of the modularity and parameter flexibility, the mass-energy model is easily refined and updated to incorporate the most up-to-date available data. Finally, the output of the model provides both the monetary cost of different household energy scenarios and the expected resource consumption levels, which would be of direct interest to policy planners and economists.

In the next chapter a more detailed description of the mass-energy theory chosen for the rural domestic energy system model development is given; including a comprehensive discription of the process components and an example of the model formulation and solution.

Chapter 4

Background on Mass-Energy Theory

A key element of the systems approach for rural energy intervention design is the definition of the rural energy system under consideration. As described in the previous chapter, the rural energy system is a complex system whose precise definition will vary greatly from one location to another. Consequently, models of the system, both conceptual and mathematical, can greatly facilitate both understanding of the system structure and function, and studying the impact intervention alternatives may have on the system. In the previous chapter, we discussed a number of different approaches previously used for modelling the rural energy system. In this chapter we present in detail the background theory for the modelling approach developed in this work. The model developed in this thesis is created as an integral component of the systems approach to intervention design; it is intended that the model be used as one tool to facilitate appropriate intervention design.

The mathematical model developed in this work is based on theoretical principles of mass-energy modelling formulated by Koenig and Tummala [58] and Tummala and Conner [92]. The fundamental concepts upon which mass-energy theory is based are rooted in the Graph Theoretic Method (GTM); a simple, organised technique for creating mathematical models of discrete physical systems. GTM provides a mathematical foundation for the understanding, analysis, and simulation of systems. Before discussing a detailed example of the derivation and solution of a simple mass-energy model, the basic definitions and principles from GTM needed to formulate and solve the mass-energy model are first presented. Building upon this understanding, an introduction to the basics of mass-energy theory, as described by the original authors is then presented. The chapter closes with a simple two-process example which illustrates the mass-energy problem formulation and solution techniques and interpretation of simulation results.

4.1 Concepts from Graph Theoretic Methods

The Graph Theoretic Method combines linear graph theory, which derives from Topology (the study of how things are interconnected - a branch of the mathematical field of Combinatorics), with the physical characteristics of engineering components. The theoretical basis of GTM began in the 1600s with the topological work of Leonhard Euler [13]; it was not until 1967, however, that Koenig, Tokad and Kesavan [57] both presented the concepts as a clearly unified 'system theory' and illustrated the application of GTM to engineering systems. Since that time, numerous research projects have extended the basic work into a number of different fields and applications, and many of these diverse research papers have been summarised in a recent publication [24].

4.1.1 Linear Graph Terminology

A *linear graph* is a collection of lines and points; where a line is called an *edge* (*branch, link or chord*) and the point where the edges are connected is called a *node* or *vertex*. A graph is denoted as G(n,e), where n is the number of nodes and e is the number of edges in the graph. The nodes are usually designated by letters and the edges by numbers. Edges of an *oriented* graph have arrows used for defining measurement conventions for quantities associated with the edges. An edge is said to be *incident* on a node if it is connected to it and positive if oriented away from it (negative otherwise). The topology of a linear graph is defined when one specifies which edges are connected to or incident upon each and every node. This topology can be written in a simple mathematical form using the *incidence matrix*, defined in Section 4.1.2. A graph is used to represent the connectivity of a system. For example, a graph may represent an electrical circuit, where each edge represents an electrical component such as resistors, capacitors, and voltage or current sources; the nodes represent the points of interconnection of these components in the circuit. A linear graph G(4,5) is illustrated in Figure 4.1 below.

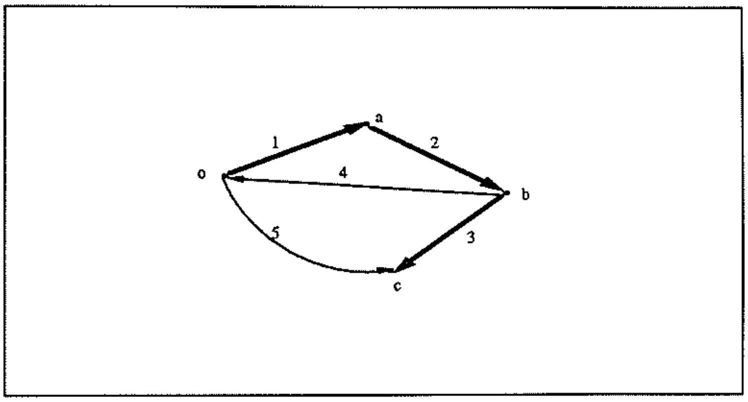


Figure 4.1 - A Linear Graph, $G(4,5)$

A *subgraph* of a graph is defined as a subset of edges and the associated nodes of the graph. A *path* between a pair of nodes p and q is a subgraph such that i) there is exactly one edge incident at p and q, and ii) at every other node there are exactly two edges incident. A graph G is said to be *connected* if every node can be reached from any other node by traversing a sequence of edges and nodes which define a *path*. If G is not connected, then it exists in *parts* where each part is a connected subgraph of G. A *circuit* or *loop* is a subgraph of G which is i) connected and ii) has exactly two edges incident at each node. A *cutset* is a subgraph of G which has the following two properties: i) the deletion of the subgraph from the graph leaves the graph in two parts, and ii) no subset of edges in the resulting subgraph has this property. A *tree* of a connected graph G is defined as any subgraph which is i) connected, ii) contains all the nodes of G, and iii) has no circuits. An important feature of a tree is that it has exactly one path between every pair of nodes and has exactly ($b = v - 1$) edges. A *forest* is a set of trees each associated with a part of an unconnected graph . A *cotree* is defined as the subgraph of G that remains after deleting the edges of a tree, and hence there are ($c = e - v + 1$) edges in the cotree. Similarly a *coforest* is comprised of the remaining edges after the forest has been removed from the unconnected graph. The edges in the tree or forest are called the *branches* and the edges in the cotree or coforest are called the *chords or links*. A *fundamental cutset* is a cutset selected such that it contains exactly one tree edge and a unique set of chords; there is one *f-cutset* for each branch in the tree. A *fundamental circuit* is a circuit consisting of a single chord and a unique set of branches; there is one *f-circuit* for each chord of the graph.

Example 4.1.1

To illustrate some of these concepts and to demonstrate the use of linear graphs in representing the topology of a physical system, consider the electrical network shown in Figure 4.2 (a) below. The electrical network consists of a voltage source E_1, four resistors $R_{2\text{-}5}$, and a current source I_6. Figure 4.2 (b) shows the linear graph which is topologically equivalent (isomorphic) to the electrical network. The linear graph is constructed by drawing a node for each point at which two elements connect and by replacing these elements with directed line segments (edges) in a one-to-one correspondence.

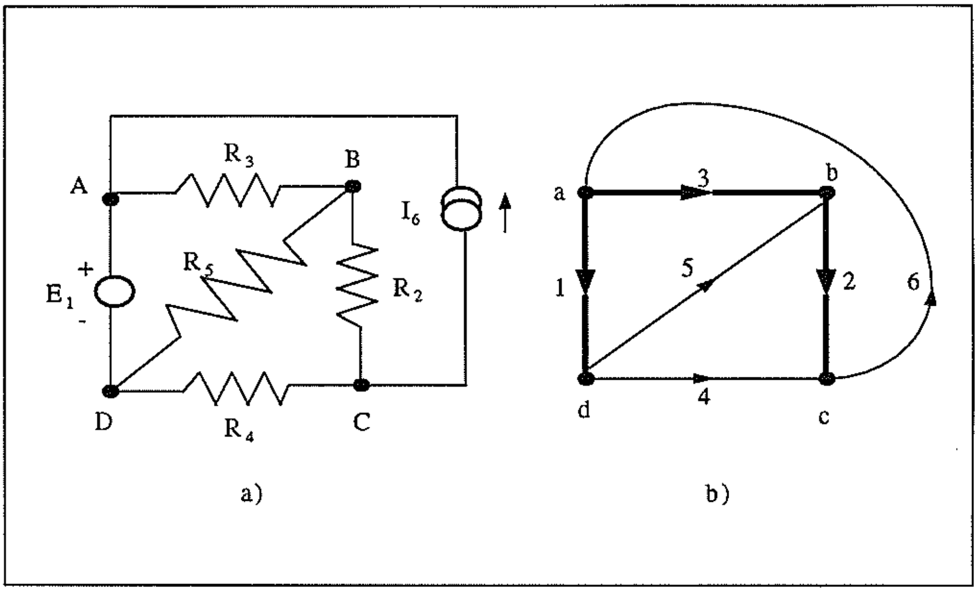


Figure 4.2 - A Simple Electrical Network - a) System Diagram, b) Linear Graph

In this example, the edges 1, 2, and 3, shown in bold, have been selected as the branches of the tree, while the remaining edges 4, 5, and 6 comprise the chords of the cotree. This system has three f-cutsets (one for each branch) and three f-circuits (one for each chord) defined as follows:

Fundamental Cutsets	*Fundamental Circuits*
f-cut 1 - {1, 4, 5}	f-cir 4 - {4, 1, 2, 3}
f-cut 2 - {2, 4, 6}	f-cir 5 - {5, 1, 3}
f-cut 3 - {3, 4, 5, 6}	f-cir 6 - {6, 2, 3}

4.1.2 From Graphs to Matrices

The most fundamental matrix is called the incidence matrix, denoted *A*, which contains the incidence information of each edge on each node in a graph *G*. Matrix *A* has dimensions [n - 1, e] and the elements are defined as follows:

$$a_{ij} = \left\{ \begin{matrix} 0 \\ +1 \\ -1 \end{matrix} \right\} \text{ if edge i is } \left\{ \begin{matrix} \text{not incident on} \\ \text{incident on and away from} \\ \text{incident on and towards} \end{matrix} \right\} \text{ the jth node}$$

As a matter of convention, an edge oriented away from a node is considered positive. Thus for example 4.1.1, illustrated in Figure 4.2, matrix *A* is defined as:

$$A = \begin{array}{c} a \\ b \\ c \end{array} \begin{bmatrix} 1 & 0 & 1 & 0 & 0 & -1 \\ 0 & 1 & -1 & 0 & -1 & 0 \\ 0 & -1 & 0 & -1 & 0 & 1 \end{bmatrix} \qquad [4.1]$$

Matrix *A* is also called the reduced incidence matrix; since the information of node d, which can be derived (by summing each column of *A* and changing the sign of the result) is redundant, and hence may be omitted. It can be shown that the rows of *A* are linearly independent, i.e. that row *A* is a full rank matrix. This is important both for selecting a tree and determining several fundamental matrices associated with the graph, as described below. Since *A* represents the basic connectivity information about the graph, all other relevant matrices and associated structural or topological information can be derived from *A*, using simple techniques of row-reduction and Gaussian elimination.

The two fundamental matrices derived from the incidence matrix A are the *fundamental cutset matrix Q* and *the fundamental circuit matrix B*. The former comprises the complete collection of the fundamental cutsets and the latter the complete collection of the fundamental circuits. Since there are n - 1 edges in the tree matrix Q has the dimension [n - 1, e]. Similarly, since there are e - n + 1 edges in the cotree matrix B has dimension [e-n+1, e]. For the linear graph illustrated in Figure 4.1.2, with the tree T: {1, 2, 3} the fundamental cutset matrix Q is:

$$Q=\begin{bmatrix}1 & 0 & 0 & -1 & -1 & 0\\ 0 & 1 & 0 & 1 & 0 & -1\\ 0 & 0 & 1 & 1 & 1 & -1\end{bmatrix} \quad [4.2]$$

The columns of the matrix, each representing an edge in the linear graph, are partitioned into the tree {1, 2, 3} and cotree {4, 5, 6} (i.e. column 1 = edge 1, column 2 = edge 2 etc.). An identity matrix is defined by the tree edges and all of the entries in Q are 1, -1, or 0. In order to understand the sign convention used in the matrix, consider row three { 0 0 1 1 1 -1}. Each f-cutset is defined with respect to a tree branch, in this case edge 3, and hence this defining edge is assumed to be positively oriented. If an imaginary cut or line is drawn across the page such that it 'cuts' edges 3, 4, 5, and 6 and divides the graph into two parts, then using the orientation of edge 3 as the defining direction for the edges 'connecting' the two parts, edges 4 and 5 are oriented in the same direction as edge 3 and edge 6 is oriented in the opposite direction as edge 3. Consequently, in the f-cutset matrix edges 4 and 5 are represented by '1's and edge 6 is represented by a '-1', or the cutset is defined as: {0 0 1 1 1 -1}.

Continuing with example 4.1.1, in Figure 4.2, the fundamental circuit matrix B for the cotree CT: {4, 5, 6} is:

$$B=\begin{bmatrix}1 & -1 & -1 & 1 & 0 & 0\\ 1 & -1 & 0 & 0 & 1 & 0\\ 0 & 1 & 1 & 0 & 0 & 1\end{bmatrix} \quad [4.3]$$

Similar to the fundamental cutset matrix, the columns of the fundamental circuit matrix, each represent an edge in the linear graph and are partitioned into the tree {1, 2, 3} and cotree {4, 5, 6}. An identity matrix is defined by the cotree edges and all of the entries in *B* are 1, -1, or 0. Each row of *B* defines a unique circuit in the graph. For example, the first row consists of entries {1 -1 -1 1 0 0} and defines the circuit consisting of edges 1, 2, 3, and 4. Here the defining chord edge (4) is assumed to have the positive orientation, and the other edges assume positive, negative, or zero values depending on if they are aligned with (1) or opposite (-1) the defining edge, or not associated with the circuit (0); i.e. if the path of the circuit is traced following the orientation of edge 4, edges 2 and 3 are oriented opposite (-1) to edge 4 and edge 1 is aligned with edge 4 and edges 5 and 6 are not in the circuit (0). Before presenting the methodology for obtaining *B* and *Q* directly from *A* by elementary row operations, we state a number of interesting results without proof.

Orthogonality of Q and B Matrices

A fundamental theorem in graph theory states that each row of *Q* is orthogonal to each row of *B*. As a consequence, the matrix product QB' is a null matrix:

$$Q\,B' = [0] \qquad [4.4]$$

This result follows from the following observation: If *Q* is redefined as [U Q_c] (where U represents the unit or identity matrix) and *B* as [B_t U] corresponding to the partitioning of *Q* and *B* according to the tree and cotree edges, then:

$$Q_c = -\,B_t' \qquad [4.5]$$

In effect, once *Q* or *B* is known, the other can be immediately obtained, i.e. the non-identity portions of *Q* and *B* are the negative transpose of each other.

Through and Across Variables

In example 4.1.1, we showed how linear graphs may be used to encapsulate the topology of a physical system. We now present how linear graph theory may specifically be used to create mathematical models of engineering systems. To accomplish this, we need to introduce a set of physical quantities, commonly encountered in systems, known as the *through* and *across variables.*

A *through* variable Y, associated with each edge of a linear graph, has the property that it is measured at a point or corresponds to a quantity that would be measured by an instrument in series with the physical element represented by the edge. For an electrical network a suitable through variable would be the current passing through each element. In a hydraulic network, it might be a flow rate, while in a mechanical system it could be a force or torque.

An *across* variable X is also associated with each edge of a linear graph. An *across* variable has the property that it is measured across two points or nodes or it corresponds to a quantity measured by an instrument placed in parallel with the physical element represented by the edge. An across variable might be: the voltage drop across each electrical element in an electrical network, the pressure differential across a hydraulic component, or the displacement, velocity, or acceleration of a mechanical element. Notably, the derivatives and integrals of through and across variables are themselves through and across variables, respectively. It is possible to associate a pair of Y and X variables with each edge of the graph since each edge corresponds to a component in the system which would have the related measurements. For example, an electrical resistor represented by an edge will have associated with it a current (through variable Y) and a voltage drop (across variable X). Also, the through and across variables can take on scalar, complex, or vectorial values depending on the physical domain. The product $X * Y$ has the units of energy or power in each discipline (e.g. electrical, mechanical, hydraulic, or thermal).

Finally, it is occasionally convenient to introduce a set of auxiliary variables known as the *nodal variables*. Essentially, a nodal variable, X_n corresponds to an across variable measured between a given node and a datum or reference node. In an electrical system, the nodal variables correspond to the voltage difference between the nodes and the ground (datum) node. In a linear graph with e elements and v nodes, there will be $2e$ through and across variables and $v - 1$ nodal variables.

4.1.3 From Matrices to Equations

Each physical domain or discipline has natural laws which apply to an assembly, a collection of interconnected components, or a system. These laws pertain to the Y and X variables of the system separately. For example, the Kirchoff's current and voltage laws involve currents Y and voltages X

of the electrical system respectively. Similarly, the force balance and compatibility laws apply to the forces F and displacements r in a mechanical system. Within this context, the fundamental cutset and fundamental circuit matrices have interesting interpretations, expressed as the *Vertex Postulate* and the *Circuit Postulate* respectively.

The *Vertex Postulate* states that *the sum of the through variables at any node of a linear graph must equal zero when due account is taken of the orientation of the edges incident upon that node,* regardless of the type of physical system represented by the graph. Mathematically, the Vertex Postulate may be written for all v nodes of the graph by multiplying the full [v,e] incidence matrix A by the column matrix $\{\tau\}$ containing all e through variables and setting the result to zero:

$$[A]\,\{\tau\} = [0] \qquad [4.6]$$

which gives one scalar equation for each node in the system. For the system illustrated in Figure 4.1.2 above, the vertex postulate may be expressed mathematically as:

$$\begin{bmatrix} 1 & 0 & 1 & 0 & 0 & -1 \\ 0 & 1 & -1 & 0 & -1 & 0 \\ 0 & -1 & 0 & -1 & 0 & 1 \\ -1 & 0 & 0 & 1 & 1 & 0 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ i_4 \\ i_5 \\ i_6 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad [4.7]$$

The set of equations generated by the Vertex Postulate are not linearly independent. In order to generate a set of linearly independent equations the *Cutset Postulate,* which is related to the Vertex Postulate is used. The *Cutset Postulate* states that if Y represents the through variables associated with a system and Q is its cutset matrix then:

$$Q\,Y = 0 \qquad [4.8]$$

The Cutset Postulate then gives rise to the set of linearly independent cutset equations, which for the linear graph in example 4.1.1, may be written as:

$$QY = \begin{bmatrix} 1 & 0 & 0 & -1 & -1 & 0 \\ 0 & 1 & 0 & 1 & 0 & -1 \\ 0 & 0 & 1 & 1 & 1 & -1 \end{bmatrix} \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \\ y_5 \\ y_6 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad [4.9]$$

The second major postulate of linear graph theory, the *Circuit Postulate,* states that *the sum of across variables around any circuit of a graph must be equal to zero when due account is taken of the direction of edges in the circuit.* Analogous to the Vertex Postulate, the *Circuit Postulate* holds for any physical system represented by a linear graph. In order to generate the linearly independent set of circuit equations the Circuit Postulate is restated as: if X represents the across variables associated with a system and B its circuit matrix, then:

$$\mathrm{B\,X = 0} \qquad [4.10]$$

For the linear graph in example 4.1.1, the circuit equations may be written as:

$$BX = \begin{bmatrix} 1 & -1 & -1 & 1 & 0 & 0 \\ 1 & 0 & -1 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad [4.11]$$

Matrices Q and B may be derived directly from A or formulated by inspection of the linear graph, once a tree has been selected. If matrix A is arranged such that the first n-1 columns correspond to the tree and the last e - n + 1 columns correspond to the cotree or:

$$\mathrm{A = [\ A_t\ \ A_c\ ]} \qquad [4.12]$$

Then Q and B may be derived from A by performing elementary row operations on A. Also, since we know that:

$$Q_c = B_t' \text{ or } B_t = Q_c' \qquad [4.13]$$

hence given A that:

$$B = [B_t\ U] = [-Q_c'\ U] = [-(A_t^{-1}\ A_c)'\ U] \qquad [4.14]$$

Together the cutset and circuit equations constitute a set of $b + c = e$ linear equations in terms of the through and across variables. Since there is one through and one across variable for each edge in the linear graph, there is a total of $2e$ unknown quantities. To obtain a necessary and sufficient set of equations for solving for all 2e unknown quantities, the topological circuit and cutset equations are supplemented by the e constitutive *or terminal equations* that relate the through and across variables for each physical component in the system. In essence, the terminal equations represent the physical behaviour that characterises a component of a particular type and can only be determined through experimentation. A functional relationship is established for each element by carefully measuring the through and across variables under a variety of conditions. This relationship may be conveniently expressed in one of the following forms:

$X = X(t)$ → across driver

$Y = Y(t)$ → through driver

$X = F(Y)$ → resistive element

$Y = G(X)$ → conductive element

$H(X, Y, t) = 0$ → hybrid element

Unlike the cutset and circuit equations, the terminal equations may be highly non-linear differential-algebraic equations. For example, for an electrical system where the symbols R, C, and L represent resistance, capacitance, and inductance of the corresponding elements, the terminal equations that relate the voltages v across and currents i through a number of common linear components are given in Table 4.1 below.

Element	**Terminal Equation**
Voltage Source	$v = v(t)$
Current Source	$i = i(t)$
Resistor	$v = R(i)$
Capacitor	$i = C(dv/dt)$
Inductor	$v = L(di/dt)$

Table 4.1 - Terminal Equations for Common Electrical Components

As seen above, a total of 2*e* equations are obtained when the cutset, circuit, and terminal equations are assembled for a given physical system. These 2*e* equations form a necessary and sufficient set for solving for the 2*e* through and across variables, or they provide a complete mathematical model of the system. For the linear graph in example 4.1.1, the complete system of equations necessary for solving for the $2e = 12$ unknown variables arise from the collection of the 3 fundamental cutset equations given in [4.2], plus the 3 fundamental circuit equations given in [4.3], in addition to the 6 terminal equations. If each resistor is assumed to have value of $R_n = 10\ \Omega$, then the terminal equations may be given as:

$$E_1 = 5V \tag{4.15}$$

$$v_2 = 10\ I_2 \tag{4.16}$$

$$v_3 = 10\ I_3 \tag{4.17}$$

$$v_4 = 10\ I_4 \tag{4.18}$$

$$v_5 = 10\ I_5 \tag{4.19}$$

$$I_6 = 1A \tag{4.20}$$

The solution to this set of 12 linear equations is easily found using any equation solver tool, such as Matlab. With this understanding of the fundamentals of GTM, we now present the basic concepts from mass-energy theory, recalling that mass-energy theory is based on GTM.

4.2 Mass-Energy Theory

The mass-energy based approach for modelling ecosystems was first postulated and developed by Koenig and Tummala in their 1972 paper entitled, "Principles of Ecosystem Design and Management" [58]. The theory was further elucidated and applied in Tummala and Conner's companion paper, "Mass-Energy Based Economic Models" [92]. In these papers, an ecosystem in an industrialised society is defined as a system which comprises both natural environmental components and human-made material transformation, transportation, and storage process components, driven by solar, human, and physical forms of energy. The natural environmental components are characterised by a specified 'quality' level, to be maintained by the system, and as such each is considered to have a limited capacity for processing defined classes of human-made materials and energy.

According to Koenig and Tummala, the design of new human-made developments occurs as a complex, dynamic, and iterative process of ecosystem design and management. As such, the authors were primarily interested in providing a means or method by which different industrial or commercial agricultural options for human-made developments in the natural landscape could be designed and managed, taking into consideration the limited capacity of the environment to process waste and the sustainable extraction of natural resources. The principle objective of the original mass-energy work was not to simulate the human-made developments themselves, but rather to identify regulatory policies and pricing mechanisms (economic incentives) that would manage or direct the developments towards a desired, ecologically feasible, equilibrium state.

Because the mass-energy theory is rooted in holistic systems approaches to design, which integrally incorporate concepts of hierarchical analysis; the theory includes operational procedures for moving systematically from one level of spatial analysis and or functional organisation to another. At one level of analysis a regional ecosystem is characterised as a set of interacting objects, such as agricultural and industrial production units, human settlements, and natural environmental components. The linkages between the components are viewed as taking place through the exchange of materials and energy and these interconnections unify the components into a functioning system. In moving to a macro level of analysis, the regional ecosystem is viewed as a single object interacting with other regional ecosystems (objects) through the exchange of mass and energy. These objects or components interact together to form a larger supersystem. Conversely, the system may be analysed from a micro perspective by considering a subsystem of the original regional ecosystem as the system for analysis. For example, one human settlement may be taken as a system and the objects within this settlements e.g. house, barn, animals, considered as components interacting via an exchange of mass and energy.

Each component of the ecosystem is conceptualised as performing one or a combination of three basic functions: material transformation, material transportation, or material storage. Each process requires several input materials which combine together to produce one useful output and one or more secondary or waste products. The flow rates of the materials of identifiable species *i* into and out of the process are defined as the y_i, $i = 1 \ldots n$ flow variables. Each of these processes (transformation, transportation, and storage) is carried out at a cost to society in terms of: human energy - x^1 (labour), solar energy - x^2 (land), and physical energy - x^3. This energy cost vector $X = (x^1, x^2, x^3)$ essentially represents the cost of non-renewable resources used to alter the form and spatial distribution of renewable or recyclable resources.

Of the three components, the most fundamental is the material transformation process; the transportation and storage processes are specialised cases. Koenig and Tummala and Tummala and Conner, interested in modelling the production processes in industry and agriculture, define these processes to be transformations of materials to achieve a well defined change in the physical, chemical, technological, or biological structure of the materials, achieved through the application of human, solar and/or physical energy.

Material Transformation Process

Conceptually, material transformation defines a process where several different materials are combined together in some pre-defined way to produce a new material. The transformation can be a physical transformation, e.g. raw steel entering a car manufacturing plant and being transformed into the frame of a vehicle; a chemical transformation, e.g. the combination of hydrogen and oxygen to produce water; a technological transformation e.g. the transformation of mechanical force into electrical energy in an electromechanical transducer; or a biological transformation, e.g. the ingestion of protein into a human body which is transformed into muscle tissue. The transformation process may also produce some secondary outputs or waste products, such as scrap metal (in the case of the physical transformation example).

In mass-energy terms, any such transformation of material may be abstracted as a material input/output process characterised by m inputs, m+1 ... n secondary outputs or 'waste' products, and one 'primary' or useful output (or input). The general topological representation for a material transformation process, P_i, is given in Figure 4.3 below.

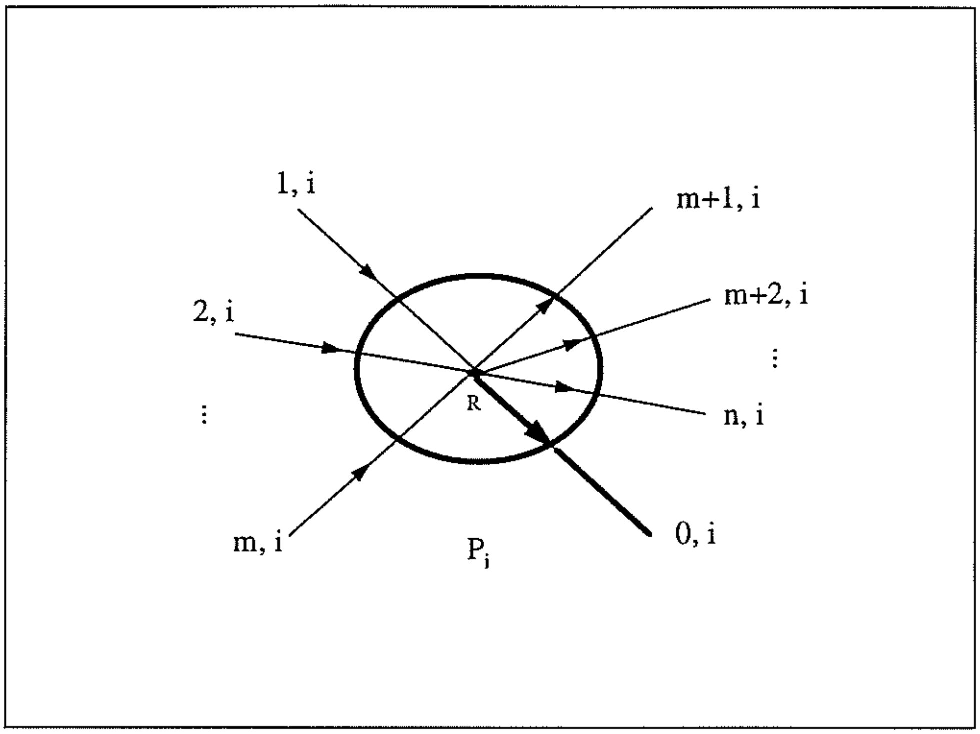


Figure 4.3 - General Material Transformation Process Component

In the same way that a component characterised by the GTM has a *y* through and *x* across variable associated with each edge of its terminal graph, the material transformation process has a *y* and *x* variable associated with each edge in the component diagram shown in Figure 4.3. The *y* variable represents a quantity or 'mass' of material 'flowing' into or out of the component and the *x* variable the cost incurred in order to provide that *y* material to the transformation process. Notably differing from GTM, however, the mass-energy material transformation process has *four* different x across variables associated with each edge: x^1 represents the cost in terms of human energy required to provide one unit of the y material to the process, x^2 represents the cost in terms of solar (land) energy required to provide one unit of y to the process; x^3 represents a cost in terms of physical energy, and x^4 represents an actual monetary cost.

Referring again to Figure 4.3, the material flow or input/output rates associated with the process P_i are represented by the y_{ji}, j = 1...n variables, each of which is represented by a directed line segment in the Figure. Associated with each material flow rate y_{ji}, are three energy costs x^1_{ji}, x^2_{ji}, x^3_{ji} and a monetary cost x^4_{ji}. Once again, these costs represent respectively the human (1), solar(land) (2), and physical energy (3), and monetary costs (4) per unit of y_{ji} required to provide the material *j* to process *i* at a given spatial location. All of the costs are measured with respect to a datum point R_i associated with the process and are considered to be positive if the representative edge is oriented as flowing into the datum node and negative if the edge is oriented as flowing out of the datum node. Note that this definition of positive edge orientation is opposite to that generally defined in GTM.

As an example, consider a pulp and paper mill conceptualised as a material transformation process; where harvested wood and used (to be recycled) fine white paper enter the mill to be combined in some pre-defined way to produce a useful output - new fine white paper. As part of this process of transforming wood into paper, we can conceptualise a solid waste product also being produced. Such a 'material transformation' process would then have two inputs (wood and recycled paper), one primary output (fine white paper), and one secondary output (solid waste).

Recalling GTM, the terminal equations define the relationship between the *y* and *x* variables for any given component. In a similar fashion, the *process equations* define or characterise the mathematical relationship among the *y* and *x* variables for the material transformation process. Specifically, equations [4.21] and [4.22] below give the mathematical model of the component.

$$y_{ji} = k_{ji} y_{0i} \qquad [4.21]$$

$$x^l_{0i} = -\sum_{j=1}^{n} k_{ji} x^l_{ji} - f^l_i(y_{0i})\ ;\ j = 1,2,\ldots,n\ ;\ l = 1,2,3,4 \qquad [4.22]$$

The first equation in the mathematical model [4.21] represents the laws that govern how the input and secondary output materials are combined to form the primary output (input) material. In the second equation [4.22], the cost equation, the first term to the right of the equality sign represents the costs involved in making the inputs available to the process and to remove the secondary outputs from the process. For l = 1,2,3 the last term represents the processing energy per unit of output required to carry out the transformation and for l = 4 it represents the monetary cost of production per unit of output. The function $f^l(y_{0i})$ accounts for the impact of the scale of production or economies of scale on energy and labour requirements and monetary values.

The technical processing coefficients k_{ji}, characterise the transformation by describing the composition of the output material in terms of the inputs and secondary outputs. If in the abstraction of the material transformation process *all* of the possible input and output materials are accounted for, then the laws of conservation of mass must apply, within the framework of a consistent system of units, requiring that:

$$y_1 + y_2 + y_3 + \dots + y_m - y_{m+1} - y_{m+2} - \dots - y_n - y_0 = 0 \qquad [4.23]$$

and for $y_0 \neq 0$:

$$k_1 + k_2 + k_3 + \dots + k_m - k_{m+1} - \dots - k_n = 1 \qquad [4.24]$$

In general, however, the technical coefficients are not constrained by this relationship; all materials need not be included in the abstraction of a material transformation process and the units used to measure the input and output rates need not be the same.

In terms of our example of the pulp and paper mill, the k values represent the quantity of raw wood, recycled paper, and solid waste required to produce one unit of new fine white paper. For this example, we have conceptualised the pulp and paper mill with only two inputs and two outputs; these may be the only materials of relevance to our system of study. In reality, however, other inputs may be required or outputs produced by the process and since we have not included all possible input and output materials [4.23] and [4.24] would not hold for our example. The 'y mass' equations define the quantities of raw wood, recycled white paper, and solid waste required to produce (or produced as a consequence of the production of) the total y_0 quantity of new fine white paper. The 'x energy' equations define the quantity of energy (or monetary cost) required to produce the fine white paper. As an example of how the costs are defined, consider the wood harvested from forests. The three energy costs could be defined as: x^1_{11} = the human labour required to supply one unit (e.g. ton) of wood to the mill, x^2_{11} = the acres of forest land harvested to supply one ton of wood to the mill, and x^3_{11} = the physical energy, in terms of gas (etc.) required to supply the wood to the mill, and finally x^4_{11} = the total monetary cost per ton of wood required to supply the wood to the pulp and paper mill.

Material Transportation Process

The second type of mass-energy process, the material transportation process, represents the transportation of a given material from one geographic location to another at a given cost. The nature of the material does not change, just the spatial location; the input and output materials are identical. The general topological representation of a material transportation process is given in Figure 4.4 and the mathematical model for the component is described by equation [4.25] below. If the material is being transported from region A_1 to region A_2, then y_o represents the material flow rate from A_1 to A_2 and x^l_o, l = 1,2,3,4 represents the energy and monetary cost per unit of material required for the transportation or the *change* in cost between the two 'terminals' A_1 and A_2.

$$x_0^l = -g^l y_o \ ; \ l = 1,2,3,4 \qquad [4.25]$$

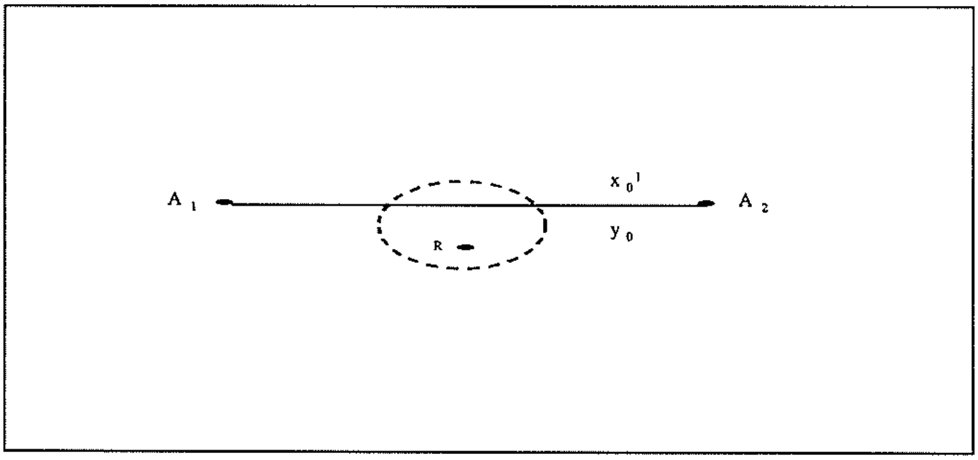


Figure 4.4 - General Material Transportation Process Component

As a conceptual example of a material transportation process, consider the solid waste material produced as a secondary output from the pulp and paper mill. To dispose of this waste, it must be transported from the mill to a solid waste treatment facility. When it is transported, the composition of the waste does not change physically, just its geographic location changes. The material flow rate, y_0, would then represent the quantity of solid waste transported from the mill to the waste treatment facility in some specified time period (e.g. kg / day). The costs would represent the x^1_0 - human labour (kcals of energy expended), x^2_0 - solar energy (in this case this may be zero), and x^3_0 - physical energy (e.g. equivalent kcal of gasoline required to power transport vehicle) required to transport one kg of waste from the mill to the treatment facility.

Material Storage Process

In the material storage process, similar to the transportation process, the nature of the input and output material is identical. This process represents the storage of a material over time at an energy and monetary cost. The general topological representation of a material storage process is given in Figure 4.5 below and the mathematical model for the component is given in equations [4.26], [4.27], and [4.28]. In this model ψ and s^l, l = 1,2,3,4, are state variables which represent the accumulation of material and energy or monetary value associated with the accumulated material respectively. The functions f^l, l = 1,2,3,4 represent the instantaneous energy input per unit of material to the storage process or the maintenance costs. In general, they depend on the flow rates y_n and reflect any efficiency increases gained by the scale of the process.

$$\frac{d\psi}{dt} = y_1 - y_2 \qquad [4.26]$$

$$\frac{ds^l}{dt} = (x_1^l y_1 - x_2^l y_2 + f^l(\psi, y_1, y_2, t) \qquad [4.27]$$

$$x_2^l = \frac{s^l}{\psi} \qquad [4.28]$$

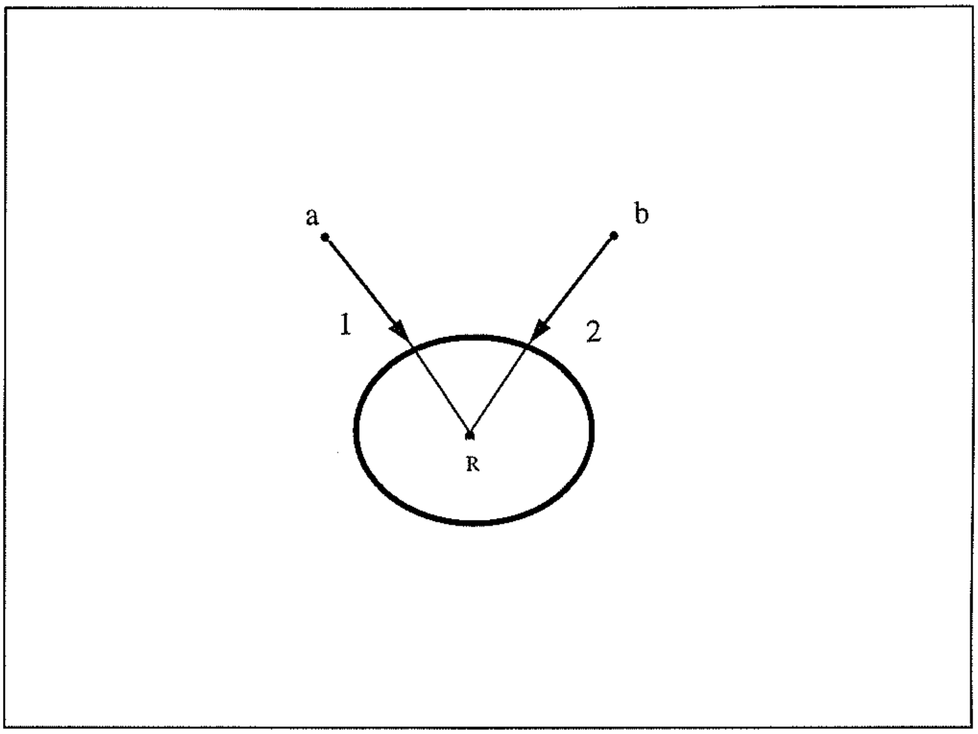


Figure 4.5 - General Material Storage Process Component

Continuing the example of the pulp and paper mill, when the solid waste reaches the waste treatment facility, it may have to be stored for a period of time before it is treated. The costs represent the costs to store the material and the differential equation modelling the flow represents the accumulation of solid waste in the storage facility.

4.3 A Simple 2-Process Mass-Energy Example

In the previous section we introduced the three basic components used in mass-energy theory, material transformation, transportation, and storage processes, and we conceptualised these to be the creation of paper from forest products, the transport of solid waste from the mill to the waste treatment plant, and the storage of the solid waste before processing, respectively. To illustrate the basic mass-energy equation formulation and solution technique we now combine these components into a system in the following example. This example is a modified version of one given in Tummala and Conner [92].

Example 4.3.1

For this example, consider a system which consists of two material transformation components connected by a material transportation network. For simplicity, no storage components are included in the example. The topological structure of the system is illustrated in Figure 4.6.

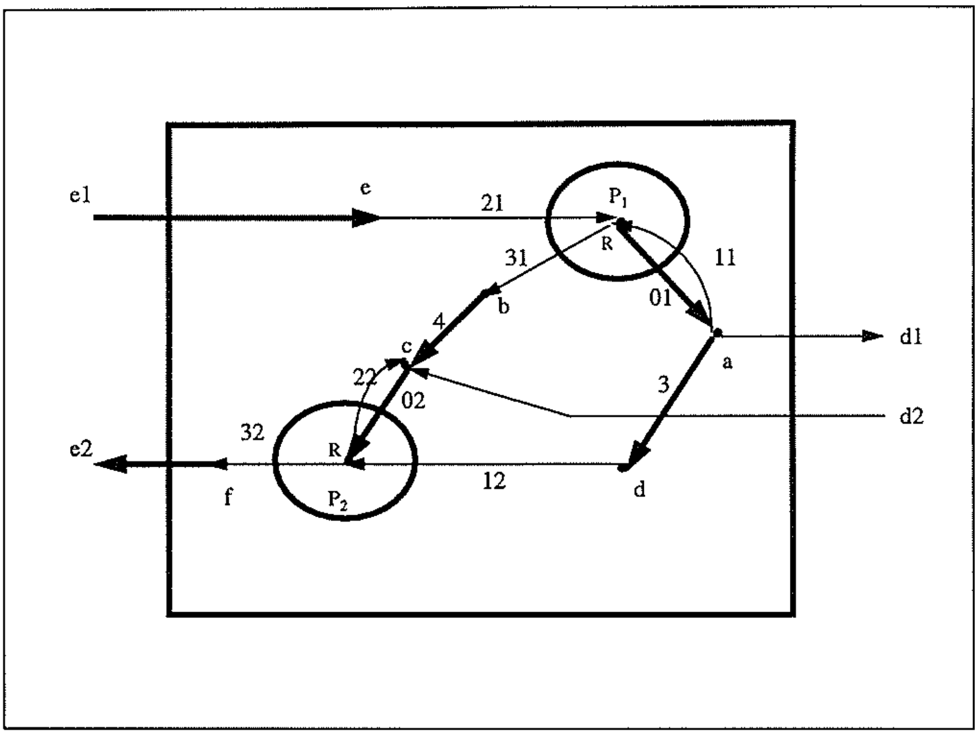


Figure 4.6 - Simple 2 Process System Example - System Diagram

The first process, P_1, represents a pulp and paper mill, where raw forest products are transformed into fine white paper and waste. Fine white paper is considered to be the useful product, y_{01}, produced by the process is to meet a market demand. Two different materials are input into the mill process to make the paper: y_{11} represents a portion of the 'useful product' (perhaps used fine white paper being recycled by the mill) which is required for its actual production and y_{21} represents the raw wood resource harvested from the natural environment. Finally, a solid waste product, y_{31}, is also produced by the process of transforming wood into paper. Each of these four materials is supplied to or produced by the process at a cost, given by x^l_{01}, x^l_{11}, x^l_{21}, x^l_{31}. Where l = 1 is the human labour cost, l = 2 is the land cost, l = 3 is the physical energy cost, and l = 4 is the monetary cost per unit of material.

The second process, P_2, may be considered to be a solid waste treatment plant which takes as its primary input, y_{02}, the solid waste product (y_{31}) from the pulp and paper mill process P_1. This primary input is combined with the input y_{12}, which represents some of the useful output fine white paper product (y_{01}) required for the recycling process, to produce y_{32}, the recycled waste product which is now 'safe' or 'acceptable' to be returned back to the natural environment (e.g. in the form of a material deposited into a landfill). The recycling process P_2 also produces some amount of the 'waste' y_{22}, which must be fedback to the recycling process. The fine white paper required for the waste treatment process P_2 (y_{12}) is transported from the pulp and paper mill (P_1) to the waste treatment facility (P_2) via transportation process P_3, and the solid waste product y_{31} is transported from the process P_1 site to the process P_2 site via transportation process P_4. The material and energy costs of the transport processes P_3 and P_4 are represented by x^l_3 and x^l_4 where l = 1,2,3,4. The demand rate of society for paper is denoted y_{d1} and the demand rate of society for the removal of the solid waste product as y_{d2}. The objective of the analysis is to determine the energy and monetary costs x^l_{d1} and x^l_{d2} associated with the two demands y_{d1} and y_{d2}, as a function of the energy and monetary costs x^l_{e1} and x^l_{e2} specified for the material flows y_{e1} and y_{e2}. All reference points 'R' are considered to be a common datum point.

The system linear graph corresponding to the system diagram is presented in Figure 4.7. A tree, T = {y_{01}, y_{02}, y_3, y_4, y_{e1}, y_{e2}}, is selected to specifically include: graph edges representing the primary input or output of interest from each material transformation process (y_{01},y_{02}), graph edges representing the material transportation processes (y_3, y_4), and the graph edges representing the exchange of materials with the natural environment (y_{e1}, y_{e2}). The tree edges are identified on the system graph by heavy weight lines. The tree is used to subdivide the system variables into two mutually exclusive, but all inclusive subsets: the *stimulus* (independent) variables consisting of all the material flow rates y_{ij} associated with the branches of the tree and all costs x^l_{mn} corresponding to the cotree; and the *response* (dependent) variables consisting of all material flow rates y_{mn} associated with the cotree edges and all costs x^l_{ij} corresponding to the tree.

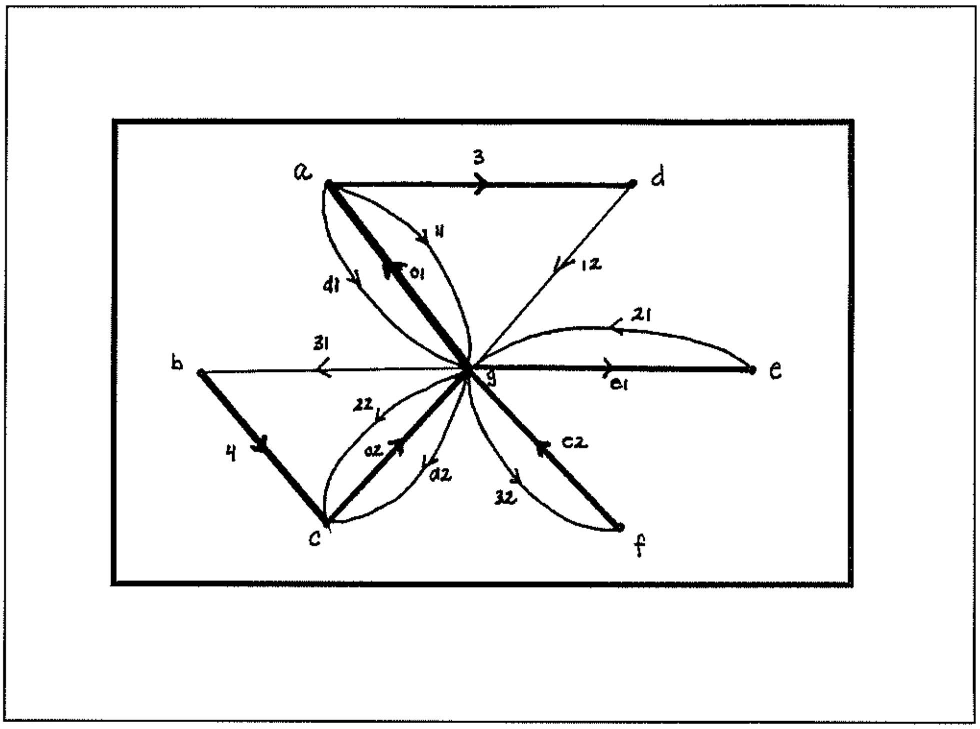


Figure 4.7 - 2 - Process System Linear Graph

To derive the set of equations which constitute the mathematical model of the system first the component process equations are required as follows:

$$\begin{bmatrix} y_{11} \\ y_{21} \\ y_{31} \end{bmatrix} = \begin{bmatrix} k_{11} \\ k_{21} \\ k_{31} \end{bmatrix} y_{01} \quad ; \quad x^l_{01} = -\begin{bmatrix} k_{11} & k_{21} & k_{31} \end{bmatrix} \begin{bmatrix} x^l_{11} \\ x^l_{21} \\ x^l_{31} \end{bmatrix} - f^l_1(y_{01}) \; ; \; l = 1,2,3,4$$

Transformation Process 1 [4.29]

$$\begin{bmatrix} y_{12} \\ y_{22} \\ y_{32} \end{bmatrix} = \begin{bmatrix} k_{12} \\ k_{22} \\ k_{32} \end{bmatrix} y_{02} \quad ; \quad x_{02}^{l} = -\begin{bmatrix} k_{12} & k_{22} & k_{32} \end{bmatrix} \begin{bmatrix} x_{12}^{l} \\ x_{22}^{l} \\ x_{32}^{l} \end{bmatrix} - f_2^l(y_{02}) \; ; \; l = 1,2,3,4$$

Transformation Process 2 [4.30]

$$x_3^l = -g_3^l(y_3)$$

Transport Process 3 [4.31]

$$x_4^l = -g_4^l(y_4)$$

Transport Process 4 [4.32]

The set of constraint equations, compatible with these component models, are given from the complete set of fundamental cutset and fundamental circuit equations for the defined tree. The six fundamental cutset equations are:

$$y_{01} = y_{11} + y_{21} + y_{d1}$$ [a]

$$y_{02} = y_{21} + y_{22} + y_{d2}$$ [b]

$$y_3 = y_{12}$$ [c]

$$y_4 = y_{31}$$ [d]

$$y_{e1} = y_{21}$$ [e]

$$y_{e2} = y_{32}$$ [f]

Fundamental Cutset Equations [4.33]

and the eight fundamental circuit equations are:

$$x_{d1}^l = -x_{01}^l$$ [a]

$$x_{d2}^l = -x_{02}^l$$ [b]

$$x_{11}^l = -x_{01}^l$$ [c]

$$x_{22}^l = -x_{02}^l$$ [d]

$$x_{21}^{l} = -x_{e1}^{l} \qquad \text{[e]}$$

$$x_{32}^{l} = -x_{e2}^{l} \qquad \text{[f]}$$

$$x_{12}^{l} = -x_{01}^{l} - x_{3}^{l} \qquad \text{[g]}$$

$$x_{31}^{l} = -x_{02}^{l} - x_{4}^{l} \qquad \text{[h]}$$

Fundamental Circuit Equations [4.34]

To establish an input-output model of the production system, the component equations [4.29]-[4.32] are substituted into the constraint equations [4.33] and [4.34] and all internal material and cost variables are eliminated as follows. Note that for simplicity the f_n^l (y_{0n}) quantities are all set to zero.

Starting with cutsets 4.33-a and 4.33-b

$$\begin{aligned} y_{01} &= k_{11}y_{01} + k_{12}y_{02} + y_{d1} \\ y_{02} &= k_{21}y_{01} + k_{22}y_{02} + y_{d2} \end{aligned}$$

and rearranging to give:

$$\begin{bmatrix} 1-k_{11} & -k_{12} \\ -k_{21} & 1-k_{22} \end{bmatrix} \begin{bmatrix} y_{01} \\ y_{02} \end{bmatrix} = \begin{bmatrix} y_{d1} \\ y_{d2} \end{bmatrix} \qquad [4.35]$$

Then using cutsets 4.33-e and 4.33-f:

$$\begin{aligned} y_{e1} &= k_{21}y_{01} \\ y_{e2} &= k_{32}y_{02} \end{aligned}$$

and rearranging to give:

$$\begin{bmatrix} y_{e1} \\ y_{e2} \end{bmatrix} = \begin{bmatrix} k_{21} & 0 \\ 0 & k_{32} \end{bmatrix} \begin{bmatrix} y_{01} \\ y_{02} \end{bmatrix} \qquad [4.36]$$

Then starting with the x process equations for components 1 and 2:

$$\begin{aligned} x_{01}^{l} &= -k_{11}x_{11}^{l} - k_{21}x_{21}^{l} - k_{31}x_{31}^{l} - f_{1}^{l}(y_{01}) \\ x_{02}^{l} &= -k_{12}x_{12}^{l} - k_{22}x_{22}^{1} - k_{32}x_{32}^{l} - f_{2}^{l}(y_{02}) \end{aligned}$$

and substituting circuit equations 4.34-c to 4.34-h:

$$\begin{aligned} x_{01}^{l} &= -k_{11}(-x_{01}^{l}) - k_{21}(-x_{e1}^{l}) - k_{31}(-x_{02}^{l} - x_{4}^{l}) - f_{1}^{l}(y_{01}) \\ x_{02}^{l} &= -k_{12}(-x_{01}^{l} - x_{3}^{l}) - k_{22}(-x_{02}^{l}) - k_{32}(-x_{e2}^{l}) - f_{2}^{l}(y_{02}) \end{aligned}$$

and then substituting cutset equations 4.33-c and 4.33-d to give:

$$\begin{aligned} x_{01}^{l} &= k_{11}x_{01}^{l} + k_{31}x_{02}^{l} + k_{21}x_{e1}^{l} + k_{31}[-g_{4}^{l}(k_{31}y_{01})] - f_{1}^{l}(y_{01}) \\ x_{02}^{l} &= k_{12}x_{01}^{l} + k_{22}x_{02}^{l} + k_{32}x_{e2}^{l} + k_{12}[-g_{3}^{l}(k_{12}y_{02})] - f_{2}^{l}(y_{02}) \end{aligned}$$

and rearranging to give:

$$\begin{bmatrix} 1-k_{11} & -k_{31} \\ -k_{12} & 1-k_{22} \end{bmatrix} \begin{bmatrix} x_{01}^{l} \\ x_{02}^{l} \end{bmatrix} = \begin{bmatrix} k_{21} & 0 \\ 0 & k_{32} \end{bmatrix} \begin{bmatrix} x_{e1}^{l} \\ x_{e2}^{l} \end{bmatrix} + \begin{bmatrix} 0 & -k_{31} \\ -k_{12} & 0 \end{bmatrix} \begin{bmatrix} g_{3}^{l}(k_{12}y_{02}) \\ g_{4}^{l}(k_{31}y_{01}) \end{bmatrix} - \begin{bmatrix} f_{1}^{l}(y_{01}) \\ f_{2}^{l}(y_{02}) \end{bmatrix} \qquad [4.37]$$

Finally, rearranging directly circuit equations 4.34-a and 4.34-b:

$$\begin{bmatrix} x_{d1}^{l} \\ x_{d2}^{l} \end{bmatrix} = -\begin{bmatrix} x_{01}^{l} \\ x_{02}^{l} \end{bmatrix} \qquad [4.38]$$

Recalling the solution objectives; to show how the material demand rates of society are transformed into the material demand rates placed on the environment, equation [4.35] is solved using the given demand rates $[y_{d1}, y_{d2}]$ and the results substituted in [4.36] to calculate the desired rates $[y_{e1}, y_{e2}]$. In a similar fashion, to calculate how the energy and monetary costs associated with the environment $[x^{1}_{e1}, x^{1}_{e2}]$ are transformed into costs to society $[x^{1}_{d1}, x^{1}_{d2}]$; equation [4.37] is solved for $[x^{1}_{01}, x^{1}_{02}]$ and the results substituted into equation [4.38] to find x_{d1}^{1} and x_{d2}^{1}.

Chapter 5

Mass-Energy Models For Rural Energy Systems

The detailed analysis of the rural energy crisis presented in Chapter 2 highlighted the fact that decisions taken in the household are strongly delineated along gender lines. Women are important managers of natural resources and within the domestic energy system they are the energy providers and users. In performing the daily tasks within their sphere of household production women take decisions about which resources to use and how to use them. Furthermore, the village traditions, resource availability, access to technology and income disposability all have direct implications on the technology choices made by women. In terms of the domestic cooking energy system model, these decisions significantly affect the structure and function of the household system. Consequently, the impact of these decisions must be clearly understood in order to genuinely capture the underlying interactions driving the system. For policy planners and other decision makers the need to comprehend the types of decisions being made in the household is critical both for realising the differing priorities of rural men and women and viewing how these priorities affect men's and women's decisions to adopt or reject technological innovations.

Thus, for the mass-energy model to realistically capture the structure and function of the domestic cooking energy system, these gender based household decisions have to be directly incorporated into the model. In order to achieve this, two new general 'decision' components are developed. Conceptually, the decision components capture the resource procurement and allocation decisions taken in the household. The decisions are modelled as a special case of the material transformation process, where the nature of the material passing through the process does not change, i.e. no actual transformation occurs. The two general decision components are called *decision joiners* and *decision splitters.* Conceptually joiners model the decision to gather one resource from a number of different sources and allocate this total amount of material to a specific resource use. While splitters conceptually represent the decision to take a quantity of one resource and allocate it among a number of different tasks or use options. Two other types of decision components are also developed, based on the general decision joiners and splitters. The first is called a '2-demand-driver' and the second a weighted decision material transformation process. In this chapter, then we first present the derivation of the general decision joiners and splitters, and the more specific joiner and splitter special cases. This is followed by a discussion of the derivation of the 2-demand-driver component and the weighted decision material transformation process. The chapter closes with a small example of the application of mass-energy modelling within the context of the rural energy system.

5.1 Joiner and Splitter Decision Components

The decisions taken by rural women to procure and allocate natural resources within the domestic cooking energy system fundamentally affect the structure of the system. For the creation of representative mass-energy model components, these decisions are conceptualised in two ways:

i. decisions to collect a given material from a variety of different sources in order to combine it into one total output to be used as the input to another process; and
ii. decisions to divide and distribute a given material among a variety of options or several different processes.

These two types of conceptual decisions are translated into components consequently named *joiners* and *splitters*. A joiner decision process has multiple inputs and one primary output and the splitter decision process has one primary input and multiple secondary outputs. Diagramatically, both joiners and splitters are represented by triangles; where the multiple inputs (outputs) appear as edges entering (leaving) the base of the triangle and the single output (input) appears as an edge leaving (entering) the apex of the triangle. The y-through variables associated with the decision joiners and splitters represent material flowing through and being joined or split by the process. For joiners, the x-across variables represent the costs in an identical way as to the general material transformation processes. For the splitters, however, the costs associated with each edge are zero, that is the cost of the output is identical to the cost of the input. The model parameters for the two types of decision processes represent the preferences for different decision options via percentages or weights assigned by the household for each possible decision. For the joiner component we consider the decision to collect fuelwood from several different sources as an example; while for the splitter component we consider the case of the decision to divide dung among a number of possible different uses.

Joiner Component Parameters

The output from the joiner component representing the decision to collect fuelwood from several different sources would be a total quantity of wood. The inputs represent fuelwood collected from these several different sources and the component parameters then specify the percentage of the total quantity of wood collected from each source, for example:

w_1 - % of fuelwood purchased
w_2 - % of fuelwood collected from own land
w_3 - % of fuelwood collected from roadside
w_4 - % of fuelwood collected from village tree plantation

Where $w_1 + w_2 + w_3 + w_4$ must equal 100%, or 1.0. More specifically, the weights are calculated considering a 'typical' day for the household, e.g. if 20 kg of fuelwood is required daily to meet cooking demands, the household may decide to purchase all of the fuelwood, making w_1 = 100% or 1.0, and w_2, w_3, and w_4 = 0. Conversely, the household may not be able to afford to purchase fuelwood and consequently may decide to collect 75% of its daily fuelwood requirement from trees on its own land and 25% from the roadside, making $w_1 = 0$, $w_2 = 75\%$ or 0.75, $w_3 = 25\%$ or 0.25, and $w_4 = 0$.

Splitter Component Parameters

The outputs from the splitter component modelling the decision to divide dung would represent quantities of dung allocated for each different option, while the input represents the total quantity of dung available to the household on any given day. The model parameters represent decision weightings or preferences for the allocation of the dung. For example, for the decision to divide dung, the component model parameters could be:

w_5 - % of dung sold
w_6 - % of dung input to biogas plant
w_7 - % of dung made into dung cakes
w_8 - % of dung used as manure/fertiliser

Similar to the joiner case, $w_5 + w_6 + w_7 + w_8$ must equal 100% or 1.0. Different decisions or preferences for the use of the dung may be represented by different values being given to the weightings by different family members. For example, the male head of the household, concerned with agricultural production and profit generation, may want to sell all of the dung to neighbours and use the profits to purchase a higher grade commercial fertiliser for his fields. Thus, he would select $w_5 = 100\%$ or 1.0 and $w_6, w_7, w_8 = 0$. The female head of the household, however, recognising the time saving, drudgery reduction, and health benefits derived from cooking with biogas, may prefer to allocate 90 % of the dung for input into a biogas plant and 10 % of the dung for making dung cakes for specialised cooking tasks such as simmering milk. Thus, she would select $w_5 = 0$, $w_6 = 90\%$ or 0.9, $w_7 = 10\%$ or 0.1, and $w_8 = 0$. For both types of decision components, different decision scenarios may be investigated by varying the values assigned to the weightings.

In order to actually use the joiner and splitter components in the mass-energy model formulation, the general component models need to be refined into specific cases based on the number of input or output edges and the number of known and unknown variables. For both the joiner and splitter decision component there are four specific cases:

- Case 1 - Demand Specified, Environmental Inputs Unknown
- Case 2 - Demand Specified, Environmental Inputs Specified
- Case 3 - Demand Unknown, Environmental Inputs Specified
- Case 4 - Demand Unknown, Environmental Inputs Unknown

Slack Variables

To ensure consistency among the number of unknown variables and equations to be solved in the system, *slack* variables are introduced. The slack variables represent a surplus or deficit demand for material. Because of the sign convention chosen for the mass-energy system graph (edges incident onto a node are positive and edges incident away from a node are negative), the interpretation of the sign convention is opposite for joiners and splitters. For the joiner components, if the slack variable is positive then supply of the material is greater than demand and the slack represents a surplus going to ground. If the slack variable is negative then demand is greater than supply and the slack is being added to eliminate the deficit demand. Conversely, for the splitter component, if the slack variable is positive then demand is greater than supply and the slack represents adding to the supply to meet the demand deficit. If the slack variable is negative then supply is greater than demand and the surplus is cycled back to the ground. The number of non-zero slack variables associated with a given joiner or splitter will depend on the case being investigated, that is it will depend on whether one of or both of the demands or environmental inputs are specified.

The utility of the slack variables lies in the interpretation of the material surplus or deficit. Ideally, the slack variables should be zero; where given supply meets desired demand. If the slack variable identifies a surplus or deficit of material, then the household must take some action to either modify demands or rethink the material allocation decisions. For example, if the household daily demand for a material required as input to a given process, e.g. daily dung requirement for input into the biogas plant so that gas production is sufficient to meet the daily cooking demand, is greater or less than the amount of that material allocated to that process via a decision weighting, then a conflict in the system would be identified and a reallocation of the households resources is required. The identification of these points of potential conflict in resource allocation or device adoption/use is very useful for individuals planning an intervention, as is discussed in detail in Chapter 8.

The general component models for the joiner and splitter components are illustrated in Figures 5.1a and 5.1b below. A slack variable is associated with each input (joiner) or output (splitter) edge but is considered to be identically zero unless its use is necessitated by the given case. Consequently, to preserve diagram clarity, the slack edges are hereafter only shown in the component models when they are actually used. The specific cases for the joiner component are less complicated than for the splitter, and thus will first be considered followed by a discussion of the specialised cases for the splitter component.

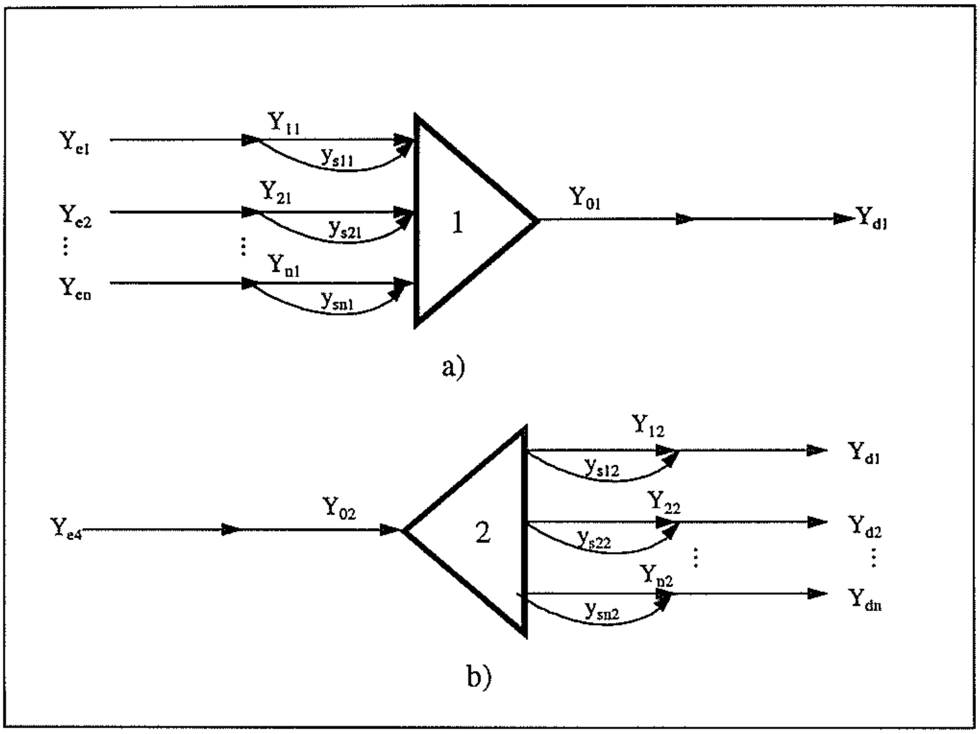


Figure 5.1 - (a) General Decision Joiner Component (b) General Decision Splitter Component

5.1.1 Case 1 Joiner - Demand Specified, Environmental Inputs Unknown

Case 1 represents the most general joiner case, where the demand for the resource is specified and the quantities of the environmental inputs available are unknown. For this case the structure of the system of equations needed to describe the joiner component is identical to that needed to describe a general material transformation process. Recall that for clarity, the edges representing the slack variables are not shown on the component model diagram unless they are non-zero. Since for this general Case 1, all slack variables are set to be identically equal to zero no slack edges are included in the component model.

Y - Equation Derivation

In Figure 5.2 four general joiner decision components are illustrated and for each component model the number of unknowns and equations are listed. In Figure 5.2a, the simplest case is shown, a joiner with one input and one output. From an examination of the Figure we see that this simple system has three unknowns, y_{e1}, y_{11}, and y_{01}, y_{d1} being a specified demand. The three equations required to solve this simple system are derived from:

1) the one process equation:

$$y_{11} = w_{11} * y_{01}$$

2) the two nodal cutset equations arising from the cutsets formed at node a and node b:

$$y_{e1} - y_{11} = 0 ; \qquad y_{01} = y_{d1}$$

Figure 5.2b illustrates the case for two inputs, Figure 5.2c for three inputs, and Figure 5.2d for four inputs. For clarity the actual equations are not included in the Figure, nor are the *x* variables explicitly labelled on the component models, recall however, that associated with each edge there is *both* a *y* and an *x* variable.

From these four examples of the *Case 1 Joiner* the general pattern for the structure of the y-mass system of equations may be stated as:

> *"if the number of input edges is given by n, the number of unknown y variables will be equal to 2n+1 and the total number of nodal cutset and process equations required will be 2n+1."*

X - Equation Derivation

For the derivation of the 'x energy-equations', the methodology for a Case 1 Joiner is analogous to the derivation of the energy and monetary cost equations for a standard material transformation process. Referring again to Figure 5.2 a-d as described above; in Figure 5.2a the simplest case one input one output joiner is illustrated. This simple system has three unknown variables, x^1_{11}, x^1_{01}, x^1_{d1} and one known variable, x^1_{e1}. The three equations required to solve this system arise from:

1) the two circuit equations:

$$x^1_{e1} = -x^1_{11}; \qquad x^1_{01} = -x^1_{d1}$$

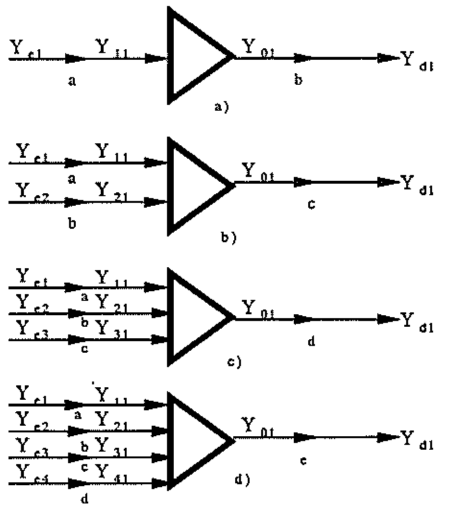
2) the one process equation:

$$x^1_{01} = -w_{11}x^1_{11} - f_1^1(y_{01})$$

The case is illustrated for two, three, and four input joiners in Figures 5.2 b-d respectively.

For the *Case 1 Joiner*, the general pattern for the structure of the x-energy system of equations may be stated as:

> *"if the number of input edges is given by n, the number of unknown x variables will be equal to n+2 and the total number of circuit and process equations required will be n+2."*



# Unknowns Variables	# Equations	
3 - y_{e1}, y_{01}, y_{11}	2 Cutset	1Process
3 - $x^1_{11}, x^1_{01}, x^1_{d1}$	2 Circuit	1 Process
5 - $y_{e1}, y_{e2}, y_{01}, y_{11}, y_{21}$	3 Cutset	2 Process
4 - $x^1_{11}, x^1_{21}, x^1_{01}, x^1_{d1}$	3 Circuit	1 Process
7 - $y_{e1}, y_{e2}, y_{e3}, y_{01}, y_{11}, y_{21}, y_{31}$	4 Cutset	3 Process
5 - $x^1_{11}, x^1_{21}, x^1_{31}, x^1_{01}, x^1_{d1}$	4 Circuit	1 Process
9 - $y_{e1}, y_{e2}, y_{e3}, y_{e4}$ y_{01}, $y_{11}, y_{21}, y_{31}, y_{41}$	5 Cutset	4 Process
6 - $x^1_{11}, x^1_{21}, x^1_{31}, x^1_{41}, x^1_{01}, x^1_{d1}$	5 Circuit	1 Process

Figure 5.2 a-d - Case 1 Joiner Component Models

5.1.2 Case 2 Joiner - Demand Specified, Environmental Inputs Specified

In this second case, one or more of the quantities available for the environmental resource inputs are specified, in addition to the resource demand at the output. The structure of the equations will vary depending on the number of environmental inputs specified. In general, for the derivation of the 'y mass-equations', a slack variable (and associated edge) is introduced when the environmental input associated with a given joiner input edge via the nodal cutset is specified, in addition to the demand y_{d1}.

Y-Equation Derivation

Figure 5.3a illustrates the simplest case, the joiner with one input and one output. If both y_{e1} and y_{d1} are specified, leaving y_{11} and y_{01} unknown, a third variable is required to ensure that the system of equations is not over-determined. Thus the slack variable, y_{s11}, is introduced and the component diagram modified as in Figure 5.3a (note the extra edge representing the slack variable).

Figure 5.3b illustrates a Case 2 Joiner with three inputs, where one environmental input, y_{e1}, is specified. In Case 1, this Joiner system would have seven unknown variables (y_{e1}, y_{e2}, y_{e3}, y_{11}, y_{21}, y_{31}, y_{01}) and seven equations to be solved (4 nodal cutset and 3 process). If y_{e1}, *or* y_{e2}, *or* y_{e3}) is specified, then a slack variable y_{s11}, *or* y_{s21}, *or* y_{s31} respectively, must be introduced to ensure that the system of equations is not over-determined. If *two* of y_{e1}, y_{e2}, and y_{e3} are specified, e.g. y_{e1} and y_{e3}, then *two* slack variables must be introduced, y_{s11} *and* y_{s31}, as shown in Figure 5.3c. Finally, if *all three* environmental inputs are specified, then *three* slack variables must be introduced, y_{s11}, y_{s21}, and y_{s31}, as shown in Figure 5.3d. When slack variables are introduced, the process equations for the joiner component remain unchanged. The nodal cutset(s), however, is modified to reflect the introduction of the new edge(s) into the system graph. As a general convention, the positive direction for the slack edge is drawn away from the node and into the datum.

The general heuristic for the *Case 2 Joiner* may be stated as follows:

> *"When the environmental input variable, associated with a joiner input variable via a nodal cutset, is a specified or known quantity, a slack variable, represented by a slack edge, must be introduced into the component model, associated with the aforementioned joiner input edge."*

Also, for the *Case 2 Joiner*, the general pattern for the structure of the y-mass system of equations may be stated as:

> *"if the number of natural (non-slack) input edges is given by n, the number of unknown y variables will be equal to 2n+1 and the total number of nodal cutset and process equations required will be 2n+1."*

<u>*X-Equation Derivation*</u>

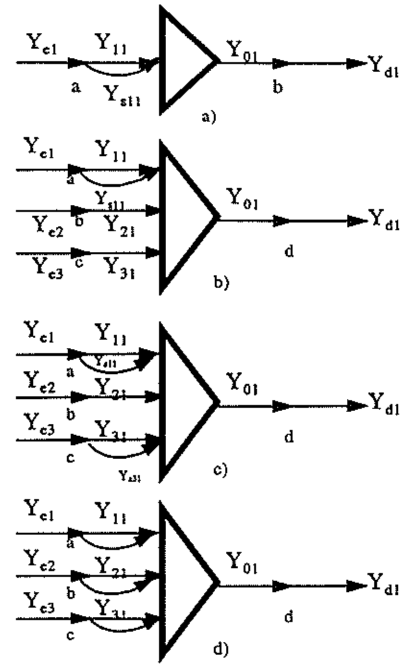
For the 'x energy-equation' derivation, Figure 5.3 a-d is again considered. The derivation of the energy equations is straightforward, the same format is followed as for the general material transformation process x-equations. For the simplest Case 2 Joiner, Figure 5.3a y-mass equations, a y-slack variable was introduced, thus it must have associated with it a x^{1}_{sn} variable. Thus, there are four unknown variables in the system, x^1_{11}, x^1_{s11}, x^1_{01}, and x^1_{d1} and the four equations required to solve the system arise from:

1) the 3 circuit equations
2) the one process equation

Figure 5.3 b-d illustrates the variable and equation count for the different possible configurations for a Case 2 Joiner with three input edges. The use of the slack variable introduces both another unknown and gives rise to another equation (a circuit equation) thus guaranteeing the consistency of the system of equations.

For the *Case 2 Joiner*, the general pattern for the structure of the x-energy system of equations may be stated as:

> *"if the number of natural (non-slack) input edges is given by n and the number of specified environmental variables is given by e, the number of unknown x variables will be equal to n+e+2, and the total number of circuit and process equations required will be equal to n+e+2."*



# Unknowns Variables	# Equations
2 - y_{01}, y_{11} + 1 Slack y_{s11}	2 Cutset & 1Process
4 - $x^1_{11}, x^1_{01}, x^1_{d1}, x^1_{s11}$	3 Circuit & 1Process
7 - $y_{e2}, y_{e3}, y_{01}, y_{11}, y_{21}, y_{31}$ + 1 Slack y_{s11}	4Cutset & 3 Process
6 - $x^1_{11}, x^1_{21}, x^1_{31}, x^1_{01}, x^1_{d1}, x^1_{s11}$	5 Circuit & 1Process
7 - $y_{e2}, y_{01}, y_{11}, y_{21}, y_{31}$ + 2 Slack y_{s11}, y_{s31}	4 Cutset & 3 Process
7 - $x^1_{11}, x^1_{21}, x^1_{31}, x^1_{01}, x^1_{d1}$, x^1_{s11}, x^1_{s31}	6 Circuit & 1Process
7 - $y_{01}, y_{11}, y_{21}, y_{31}$ + 3 Slack $y_{s11}, y_{s21}, y_{s31}$	4 Cutset & 3 Process
8 - $x^1_{11}, x^1_{21}, x^1_{31}, x^1_{01}, x^1_{d1}$, x^1_{s11}, x^1_{s21} x^1_{s31}	7 Circuit & 1Process

Figure 5.3 a-d - Case 2 Joiner Component Models

5.1.3 Case 3 Joiner - Demand Unknown, Environmental Inputs Specified

The Case 3 joiner represents the situation where the demand for the total resource output from the joiner is unknown but the quantities of environmental input materials from each source are known. In this third case, for the derivation of the 'y mass-equations', slack variables are necessitated to ensure that the system of equations remains consistent. The number of slack variables introduced depends on the total number of specified environmental input variables; the demand y_{d1} is always unknown in this case.

Y-Equation Derivation

Figure 5.4 a-c illustrates the complete component model for a Case 3 Joiner with one input edge, two input edges, and three input edges respectively. In Figure 5.4a, the simplest one input one output case is shown and for this configuration, no slack variables are required. The system has three unknown y variables: y_{11}, y_{01}, y_{d1} and one known: y_{e1}. The three equations required for solution arise from:

1) the 2 nodal cutsets at nodes a and b
2) the one process equation

In Figure 5.4b (i) a Case 3 Joiner with two input edges is illustrated, where either y_{e1} *or* y_{e2} is specified. Again in this case no slack variables are required. The system having five unknown y variables and a system of five equations. In Figure 5.4b (ii), however, where both y_{e1} *and* y_{e2} are specified one slack variable is required to ensure that the system of equations is not over-determined.

In Figure 5.4c (i) a Case 3 Joiner with three input edges is illustrated where either y_{e1} *or* y_{e2} *or* y_{e3} is specified. Once again, where only one environmental input variable is specified no slack variables are required, as is shown in the Figure. When y_{e1} *and* y_{e2} *or* y_{e3} are specified, as illustrated in Figure 5.4c (ii), one slack variable is required to ensure that the system equations is not over-determined. When y_{e1} *and* y_{e2} *and* y_{e3} are all specified, two slack variables must be introduced, as shown in Figure 5.4c (iii).

The general heuristic for the *Case 3 Joiner* may be stated as follows:

> *"if the number of specified environmental input variables is given by e, then the number of slack variables s, represented by a slack edge, which must be introduced into the component model is equal to s = e - 1."*

Also, for the *Case 3 Joiner*, the general pattern for the structure of the y-mass system of equations may be stated as:

> *"if the number of natural (non-slack) input edges is given by n, the number of unknown y variables will be equal to 2n+1 and the total number of nodal cutset and process equations required will be equal to 2n+1."*

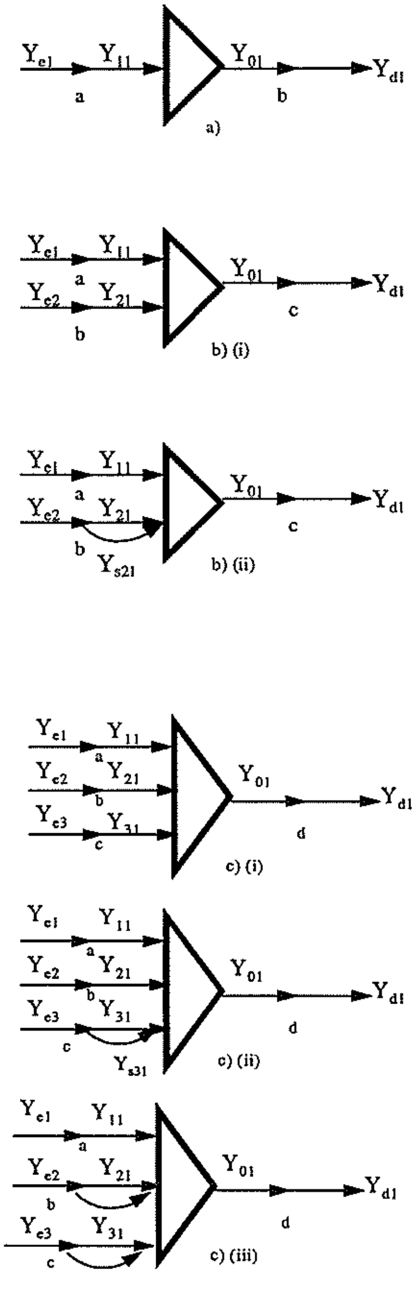
X-Equation Derivation

For the 'x energy-equation' derivation, Figure 5.4 a-c is again considered. The derivation of the energy equations is straightforward, the same format is followed as for the general material transformation process x-equations. Where slack variables are introduced into the component model, the x-process equation remains unchanged and each slack edge creates a circuit with the environmental input edge associated via a node.

For the *Case 3 Joiner*, the general pattern for the structure of the x-energy system of equations may be stated as:

> *"if the number of natural input edges is given by n and the number of specified environmental input variables is given by e, the number of unknown x variables will be equal to n+e+1 and the total number of circuit and process equations required will be equal to n+e+1."*

A note on the selection of the placement of the slack edge(s) for a Case 3 Joiner. As a convention, the slack edge(s) are associated with the 'highest number' input edge first and sequentially in descending order as necessitated. For example, for a Case 3 Joiner with three input edges (11, 21, 31): if there is one specified environmental input variable, no slack variables are required; if there are two specified environmental input variables, the slack edge would be associated with the edge 31, three specified environmental input variables, the two slack variables would be associated with the edges 31 and 21.



# Unknowns Variables	# Equations
3 - y_{d1}, y_{01}, y_{11}	2 Cutset & 1 Process
3 - $x^1_{11}, x^1_{01}, x^1_{d1}$	2 Circuit &1 Process
5 - $y_{d1}, y_{01}, y_{11}, y_{21}$ and y_{e1} or y_{e2}	3 Cutset & 2 Process
4 - $x^1_{11}, x^1_{21}, x^1_{01}, x^1_{d1}$	3 Circuit & 1Process
5 - $y_{d1}, y_{01}, y_{11}, y_{21}$ + 1 Slack y_{s21}	3 Cutset & 2 Process
5 - $x^1_{11}, x^1_{21}, x^1_{01}, x^1_{d1}, x^1_{s21}$	4 Circuit & 1Process

# Unknowns Variables	# Equations
7 - $y_{d1}, y_{01}, y_{11}, y_{21}, y_{31}$ and two of y_{e1}, y_{e2}, y_{e3}	4 Cutset & 3 Process
5 - $x^1_{11}, x^1_{21}, x^1_{31}, x^1_{01}, x^1_{d1}$	4 Circuit & 1Process
7 - $y_{d1}, y_{01}, y_{11}, y_{21}, y_{31}$ and one of y_{e1}, y_{e2}, y_{e3} + 1 Slack y_{sn1} (n = 1 | 2 | 3)	4 Cutset & 3 Process
6 - $x^1_{11}, x^1_{21}, x^1_{31}, x^1_{01}, x^1_{d1}$ and x^1_{sn1}	5 Circuit & 1Process
7 - $y_{d1}, y_{01}, y_{11}, y_{21}, y_{31}$ + 2 Slack y_{s21}, y_{s31}	4 Cutset & 3 Process
7 - $x^1_{11}, x^1_{21}, x^1_{31}, x^1_{01}, x^1_{d1}$ and x^1_{s21}, x^1_{s31}	6 Circuit & 1Process

Figure 5.4 a-c - Case 3 Joiner Component Models

5.1.4 Case 4 Joiner - Demand Unknown, Environmental Inputs Unknown

Finally, in Case 4, where both the demand and the environmental inputs are unknown, the system of equations is always under-specified: there are more unknown variables than system equations. This case is purely hypothetical, however, as either one of y_{e_n} OR y_{d_n} must be specified, i.e. the system must have a driver. For this reason, the equation derivation is not given.

The four Cases for the Joiner decision component are summarised in Table 5.1 below, where the number of natural input edges is given by *n* and the number of specified environmental input variables is given by *e*.

Case # - Description	**# of Unknown y Variables**	**# of y Eqn's**	**# of Unknown x Variables**	**# of x Eqn's**	**Figure #**
Case 1-Demand Specified, Env. Inputs Unknown	2n+1	2n+1	n+2	n+2	Figure 5.1.2 a-d
Case 2-Demand Specified, Env. Inputs Specified	2n+1	2n+1	n+e+2	n+e+2	Figure 5.1.3 a-d
Case 3-Demand Unknown, Env. Inputs Specified	2n+1	2n+1	n+e+1	n+e+1	Figure 5.1.4 a-c
Case 4-Demand Unknown, Env. Inputs Unknown	-	-	-	-	-

Table 5.1 - Joiner Component Case Summary

5.1.5 Case 1 Splitter - Demands Specified, Environmental Input Unknown

The specification of the splitter decision component is more complicated than for the joiner decision component; because even in the general case (Case 1), where the demands for the various quantities of the 'split' resource are specified and the environmental input, or total quantity of the resource available each day to be divided among the alternative uses, is unknown, slack variables are necessitated to ensure consistency between the number of unknowns and the number of system equations.

Y-Equation Derivation

Figure 5.5 a-d illustrates four general splitter decision components, with the number of *y* and *x* variables and equations required to solve each system given. The derivation of the 'y mass-equations' is first considered. The simplest Case 1 Splitter with one input and one output, shown in Figure 5.5-a, has three unknowns *y* variables, y_{11}, y_{01}, and y_{e1} to be solved from a system of three equations derived from:

1) 2 cutset equations arising from the nodal cutsets at nodes a and b

$$y_{e1} - y_{01} = 0 \; ; \; y_{11} = y_{d1}$$

2) the 1 process equation :

$$y_{11} = w_{11} * y_{01}$$

For this simplest Case 1 Splitter, the slack variable may be thought to be set identically to zero.

In Figure 5.5b, a Case 1 Splitter with two output edges is shown. Here we see that without the slack variable the system has four unknown variables, y_{01}, y_{11}, y_{21}, y_{e1} and a system of five equations, three cutset and two process. In order that the system of equations is not over-determined, a slack variable y_{s21}, is necessitated, such that the number of unknowns is now five (y_{01}, y_{11}, y_{21}, y_{e1} and y_{s21}) and the five equations to be solved for the system are:

1) the 3 cutset equations at nodes a, b, and c

$$y_{e1} - y_{01} = 0 \; ; \; y_{11} = y_{d1} \; ; \; y_{21} + y_{s21} = y_{d12}$$

2) the 2 process equations

$$y_{11} = w_{11} * y_{01} \; ; \; y_{21} = w_{21} * y_{01}$$

Figure 5.5c illustrates a Case 1 Splitter with three output edges and Figure 5.5d for a Case 1 Splitter with four output edges.

The general heuristic for the *Case 1 Splitter* may be stated as follows:

> *"if the number of natural (non-slack) splitter output edges is given by n, the number of slack variables s, represented by a slack edge, which must be introduced into the component model to ensure that the system of equations is not over-determined is equal to s = n - 1."*

From these four general examples of the *Case 1 Splitter* the general pattern for the structure of the y-mass system of equations may be stated as:

> *"if the number of natural (non-slack) output edges is given by n, the number of unknown y variables will be equal to 2n+1 and the total number of nodal cutset and process equations required will be equal to 2n+1."*

X-Equation Derivation

The 'x-energy equations' for a Case 1 Splitter deviate from the general convention for a material transformation process. The general derivation of the x-energy equations is best understood by considering a Case 1 Splitter with two output edges, as illustrated in Figure 5.5b. If the general convention for a material transformation component were followed, then the system would have six unknown variables, x^1_{01}, x^1_{11} x^1_{21}, x^1_{s21}, x^1_{d1}, x^1_{d2} but only five equations derived from: 1) the four circuit equations and 2) the one process equation; an underdetermined system. To derive a consistent set of variables and equations the actual nature of the component must be considered. When a Splitter is introduced into a system, its function is to act as a type of 'sorter'. The material enters the sorter and is allocated to 'different exits' via a defined algorithm (the decision weightings). A cost associated with an output edge would represent a cost to provide or make available a unit of the material to that process. Because the input material to a splitter comes from one source at one cost, 'splitting' the material does not alter this cost. Thus all of the output costs may be represented by one cost, denoted X^1_{cn}, where *n* denotes the process number P_i. For the Case 1 Splitter with two output edges under consideration, x^1_{11}, x^1_{21}, and x^1_{s21} are all considered to be equal to x^1_{c1}. Then, the four unknown variables are: x^1_{01}, x^1_{c1}, x^1_{d1}, x^1_{d2}, and the system of four equations required for their solution arises from:

1) the three circuit equations:

$$x^1_{e1} = -x^1_{01} \; ; \; x^1_{d1} = -x^1_{c1} \; ; \; x^1_{d2} = -x^1_{c1}$$

2) the one modified process equation:

$$x^1_{01} = x^1_{c1}.$$

Figure 5.5c illustrates the x-energy variable and equation count for a Case 1 Splitter with three output edges and Figure 5.5d for a Case 1 Splitter with four output edges. For clarity, the actual set of equations for Figure 5.5c and d are given below:

Case 1 Splitter - 3 Output Edges

1) 4 Circuit equations -

$$x^1_{e1} = -x^1_{01}\ ;\ x^1_{d1} = -x^1_{c1}\ ;\ x^1_{d2} = -x^1_{c1}\ ;\ x^1_{d3} = -x^1_{c1}$$

2) 1 Modified Process equation -

$$x^1_{01} = x^1_{c1}$$

Case 1 Splitter - 4 Output Edges

1) 5 Circuit equations -

$$x^1_{e1} = -x^1_{01}\ ;\ x^1_{d1} = -x^1_{c1}\ ;\ x^1_{d2} = -x^1_{c1}\ ;\ x^1_{d3} = -x^1_{c1}\ ;\ x^1_{d4} = -x^1_{c1}$$

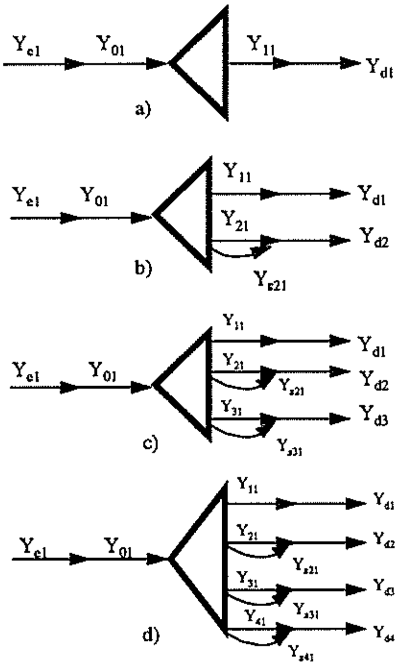
2) 1 Modified Process equation -

$$x^1_{01} = x^1_{c1}$$

For the *Case 1 Splitter*, the general pattern for the structure of the x-energy system of equations may be stated as:

> *"if the number of natural (non-slack) output edges is given by n, the number of unknown x variables will be equal to n+2 and the total number of circuit and process equations required will be equal to n+2."*

A note on the selection of the placement of the slack edge(s) for a Case 1 Splitter. As a convention, the slack edge(s) are associated with the 'highest number' output edge first and sequentially in descending order as necessitated, e.g. if there are two output edges, the slack edge would be associated with the edge 21, three output edges the two slack variables would be associated with the edges 31 and 21, four output edges the three slack variables would be associated with edges 41, 31, 21, etc.



# Unknowns Variables	# Equations
3 - y_{e1}, y_{01}, y_{11}	2 Cutset & 1Process
3 - $x^1_{11}, x^1_{01}, x^1_{d1}$	2 Circuit & 1Process
4 - $y_{e1}, y_{01}, y_{11}, y_{21}$ + 1 Slack y_{s21}	3 Cutset & 2 Process
4 - $x^1_{01}, x^1_{d1}, x^1_{d2}, x^1_{c1}$	3 Circuit & 1Modified Process
5 - $y_{e1}, y_{01}, y_{11}, y_{21}, y_{31}$ + 2 Slack y_{s21}, y_{s31}	4 Cutset & 3 Process
5 - $x^1_{01}, x^1_{d1}, x^1_{d2}, x^1_{d3}, x^1_{c1}$	4 Circuit & 1 Modified Process
6 - $y_{e1}, y_{01}, y_{11}, y_{21}, y_{31}, y_{41}$ + 3 Slack $y_{s21}, y_{s31}, y_{s41}$	5 Cutset &4 Process
6 - $x^1_{01}, x^1_{d1}, x^1_{d2}, x^1_{d3}, x^1_{d4}, x^1_{c1}$	5 Circuit & 1 Modified Process

Figure 5.5 a-d - Case 1 Splitter Component Models

5.1.6 Case 2 Splitter - Demands Specified, Environmental Input Specified

For the Case 2 Splitter, the environmental input quantity available to the splitter is specified, in addition to the demands for the various quantities of the 'split' material. In this second case then, for the derivation of the 'y mass-equations', when the environmental input variable is specified in addition to the demands, each output edge requires an associated slack edge to ensure that the system of equations is consistent.

Y-Equation Derivation

Figure 5.6 a-c illustrates the complete component model for a Case 2 Splitter with one output edge, two output edges, and three output edges respectively. In Figure 5.6a, the simplest one input one output case is shown and for this configuration, one slack variable is required. In

Figure 5.6b, a Case 2 Splitter with two output edges is illustrated, where two slack variables are required. Finally, in Figure 5.6c, the Case 2 Splitter with three output edges, we see that three slack variables are required to ensure that the system of equations is not over-determined.

The general heuristic for *Case 2 Splitters* may then be expressed as:

> *"if the number of natural output edges is given by n, the number of slack variables s, represented by a slack edge, which must be added to the component model to ensure consistency of the system equations is equal to n."*

Also, for the *Case 2 Splitters,* the general pattern for the structure of the y-mass system of equations may be stated as:

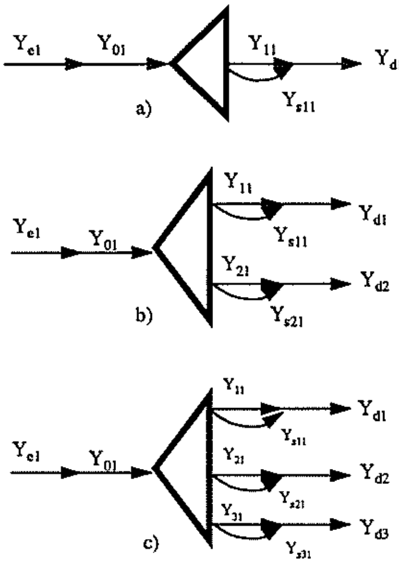
> *"if the number of natural (non-slack) output edges is given by n, the number of unknown y variables will be equal to 2n+1 and the total number of nodal cutset and process equations required will be equal to 2n+1."*

X-Equation Derivation

For the derivation of the 'x energy-equations', the methodology for a Case 2 Splitter is analogous to the derivation of the energy and monetary cost equations for Case 1 Splitter. The complete component models for a Case 2 Splitter with one, two and three output edges is given in Figure 5.6 a-c respectively.

For the *Case 2 Splitters,* the general pattern for the structure of the x-energy system of equations may be stated as:

> *"if the number of natural (non-slack) output edges is given by n, the number of unknown x variables will be equal to n+2 and the total number of circuit and process equations required will be equal to n+2."*



# Unknowns Variables	# Equations
2 - y_{01}, y_{11} + 1 Slack y_{s11} 3 - $x^1_{11}, x^1_{01}, x^1_{d1}$	2 Cutset & 1Process 2 Circuit & 1Process
3 - y_{01}, y_{11}, y_{21} + 2 Slack y_{s11}, y_{s21}, 4 - $x^1_{01}, x^1_{d1}, x^1_{d2}, x^1_{c1}$	3 Cutset & 2 Process 3 Circuit & 1Modified Process
4 - $y_{01}, y_{11}, y_{21}, y_{31}$ + 3 Slack $y_{s11}, y_{s21}, y_{s31}$ 5 - $x^1_{01}, x^1_{d1}, x^1_{d2}, x^1_{d3}, x^1_{n1}$	4 Cutset & 3 Process 4 Circuit & 1 Modified Process

Figure 5.6 a-c - Case 2 Splitter Component Models

5.1.7 Case 3 Splitter - Demands Unknown, Environmental Input Specified

In this third case, for the derivation of the 'y mass-equations', when the environmental input variable is specified and the demands are unknown, slack variables are required to ensure that the system of equations is consistent depending on the number of unknown demands.

Y-Equation Derivation

Figure 5.7 a-c illustrates the complete component model for a Case 3 Splitter with one output edge, two output edges, and three output edges respectively. In Figure 5.7a, the simplest one input one output case is shown and for this configuration, no slack variable is required. In Figure 5.7b, a Case 3 Splitter with two output edges is illustrated. The number of slack variables required depends on the number of unknown demands. In Figure 5.7b (i) either y_{d1} *or* y_{d2} is unknown and one slack is needed. Whereas, in Figure 5.7b (ii) where both y_{d1} *and* y_{d2} are unknown no slack is required. Finally, in Figure 5.7c, the Case 3 Splitter with three output edges is illustrated. In Figure 5.7c (i) either y_{d1} *or* y_{d2} or y_{d3} is unknown and two slack variables are needed. In Figure 5.7c (ii) either y_{d1} *and* y_{d2} *or* y_{d1} and y_{d3} *or* y_{d2} *and* y_{d3} are unknown and one slack variable is needed. Finally, in Figure 5.7c (iii) y_{d1} *and* y_{d2} *and* y_{d3} are all unknown and consequently no slack variables are required to ensure that the system of equations is consistent.

The general heuristic for *Case 3 Splitters* may then be expressed as:

> *"if the total number of demand edges is given by td and the number of unknown demands is given by ud, the number of slack variables s, represented by a slack edge, which must be added to the component model to ensure consistency of the system equations is equal to s = td - ud."*

Also, for the *Case 3 Splitters*, the general pattern for the structure of the y-mass system of equations may be stated as:

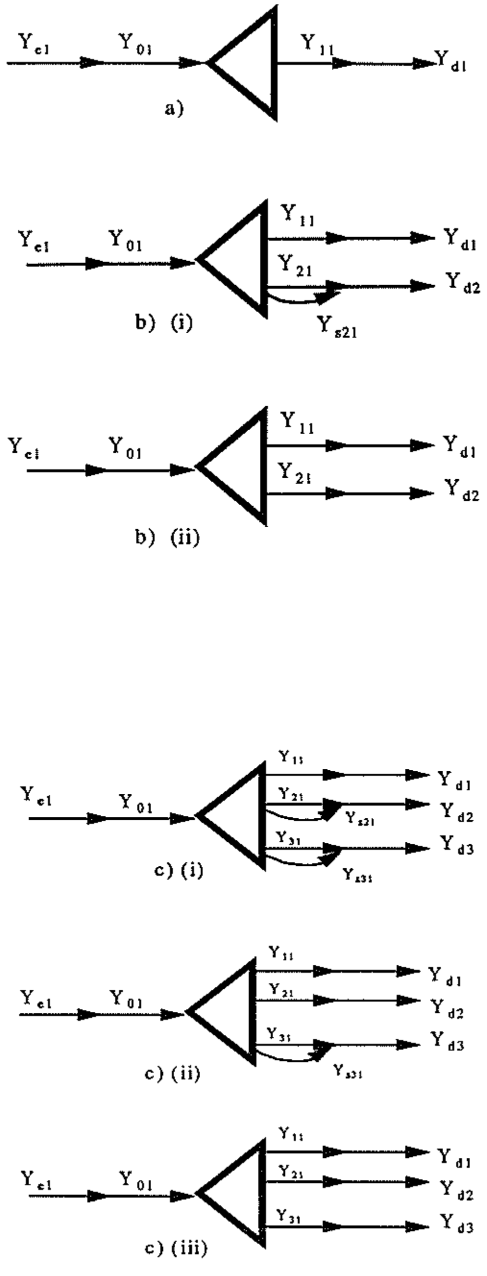
> *"if the number of natural (non-slack) output edges is given by n, the number of unknown y variables will be equal to 2n+1 and the total number of nodal cutset and process equations required will be equal to 2n+1."*

X-Equation Derivation

For the derivation of the 'x energy-equations', the methodology for a Case 3 Splitter is analogous to the derivation of the energy and monetary cost equations for Case 1 Splitter. The complete component models for a Case 3 Splitter with one, two and three output edges is given in Figure 5.7 a-c respectively.

For the *Case 3 Splitters*, the general pattern for the structure of the x-energy system of equations may be stated as:

> *"if the number of natural (non-slack) output edges is given by n, the number of unknown x variables will be equal to n+2 and the total number of circuit and process equations required will be equal to n+2."*



# Unknowns Variables	**# Equations**
3 - y_{01}, y_{11}, y_{d1} 3 - $x^1_{11}, x^1_{01}, x^1_{d1}$	2 Cutset & 1Process 2 Circuit & 1Process
3 - y_{01}, y_{11}, y_{21} + y_{d1} *or* y_{d2} + 1 Slack y_{s21} (or y_{s11}) 4 - $x^1_{01}, x^1_{d1}, x^1_{d2}, x^1_{n1}$	3 Cutset & 2 Process 3 Circuit & 1Modified Process
3 - y_{01}, y_{11}, y_{21} + y_{d1} *and* y_{d2} 4 - $x^1_{01}, x^1_{d1}, x^1_{d2}, x^1_{n1}$	3 Cutset & 2 Process 3 Circuit & 1Modified Process

# Unknowns Variables	**# Equations**
4 - $y_{01}, y_{11}, y_{21}, y_{31}$ + y_{d1} *or* y_{d2} *or* y_{d3} + 2 Slack y_{s21}, y_{s31} (or y_{s11}) 5 - $x^1_{01}, x^1_{d1}, x^1_{d2}, x^1_{d3}, x^1_{c1}$	4 Cutset & 3 Process 4 Circuit & 1 Modified Process
4 - $y_{01}, y_{11}, y_{21}, y_{31}$ + y_{d1} *and* y_{d2} *or* y_{d3} + 1 Slack y_{s11}, *or* y_{s21}, *or* y_{s31} 5 - $x^1_{01}, x^1_{d1}, x^1_{d2}, x^1_{d3}, x^1_{c1}$	4 Cutset & 3 Process 4 Circuit & 1 Modified Process
4 - $y_{01}, y_{11}, y_{21}, y_{31}$ + y_{d1} *and* y_{d2} *and* y_{d3} 5 - $x^1_{01}, x^1_{d1}, x^1_{d2}, x^1_{d3}, x^1_{n1}$	4 Cutset & 3 Process 4 Circuit & 1 Modified Process

Figure 5.7 a-c - Case 3 Splitter Component Models

5.1.8 Case 4 Splitter - Demands Unknown, Environmental Input Unknown

In the final Case 4, where both the demand and the environmental inputs are unknown, the system of equations is always under-specified: there are more unknown variables than system equations. This case is purely hypothetical, however, as either one of y_{e_n} *or* y_{d_n} must be specified, i.e. the system must have a driver. For this reason, the equation derivation is not given.

The four Cases for the Splitter decision component are summarised in Table 5.2 below, where the number of natural output edges is given by *n* and the number of specified environmental input variables is given by *e*.

Case # - Description	**# of Unknown y Variables**	**# of y Eqn's**	**# of Unknown x Variables**	**# of x Eqn's**	**Figure #**
Case 1 - Demand Specified, Env. Inputs Unknown	2n+1	2n+1	n+2	n+2	Figure 5.1.5 a-d
Case 2 - Demand Specified, Env. Inputs Specified	2n+1	2n+1	n+2	n+2	Figure 5.1.6 a-c
Case 3 - Demand Unknown, Env. Inputs Specified	2n+1	2n+1	n+2	n+2	Figure 5.1.7 a-c
Case 4 - Demand Unknown, Env. Inputs Unknown	-	-	-	-	-

Table 5.2 - Splitter Component Case Summary

5.2 Other Specialised Process Components

For the creation of the mass-energy model of the rural domestic energy system, two other types of specialised components are derived. Both of these new components, similar to the joiner and splitter decision components, are specialised cases of a general material transformation process. The first, called a '2-demand-drive process', differs from the general material transformation process in that where the general process has only one primary output driving the transformation, the '2-d-d' process has at least two outputs (or primary inputs) which are essentially 'competing' to drive the transformation. The second component, called a 'weighted decision material transformation process', combines a decision process with a regular material transformation process.

5.2.1 2-Demand-Drive Process

The general component model for a '2-Demand-Drive' or 2-d-d process is illustrated in Figure 5.8 below. Recalling the general material transformation process, P_i, described in Chapter 4.2; the process is considered to have one primary input or output, labelled 0i, 'connected' to a demand driver via a nodal cutset, one or more (m) inputs labelled 1i...mi each of which is 'connected' via a nodal cutset to an unspecified environmental input and (m+1 ... n), and one or more secondary outputs labelled m+1,i ... n, i. In Figure 5.8 a simple 2-d-d process with one input, secondary output, and primary output is shown. An explanation of nature of the situation which would give rise to the use of a 2-d-d process provides an understanding of the logic underlying the equation derivation. In the case of the 2-d-d process, one or more of the secondary outputs or one or more of the inputs is *known*, or 'connected' via a nodal cutset to a specified demand driver (either a demand y_{dn} or a specified environmental input y_{en}). This means that there are two or more demands each 'attempting' to drive the transformation process. Considering Figure 5.8, if both y_{d1}, associated with y_{01} via the cutset at node b and y_{d2}, associated with y_{21} via the cutset at node c are known, then a discrepancy could occur between the amount of materials demanded (y_{d1} and y_{d2}) and the amount output by the transformation process (y_{01}, y_{21}). To ensure that no discrepancy occurs, a slack variable y_{eos1} is introduced associated with the secondary output (or input) edge to 'absorb' a surplus or 'supplement' a deficit between the secondary output y_{21}, as calculated given the primary output $y_{01} = y_{d1}$, and the secondary demand y_{d2}.

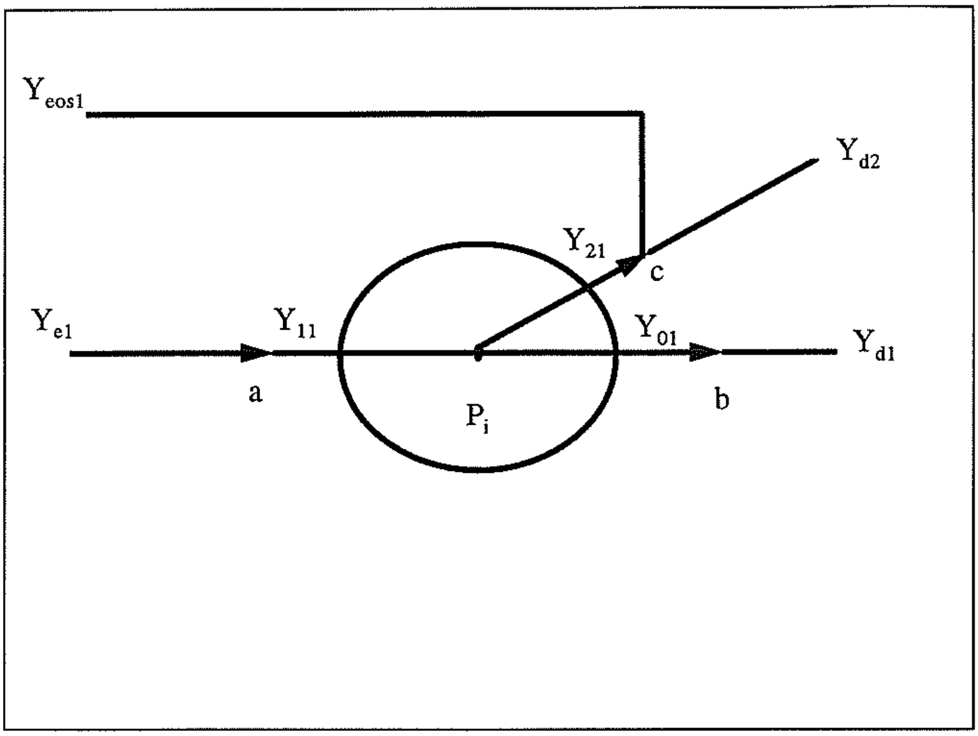


Figure 5.8 - 2-Demand-Drive Process Component

__*Equation Derivation*__

Before the slack variable is introduced into the component model, the y-mass system equations are under-specified since there are:

1) four unknown y variables -

$y_{e1}, y_{11}, y_{21}, y_{01}$

2) five equations - 3 Cutset at nodes a, b, and c

$y_{e1} - y_{11} = 0$; $y_{21} = y_{d2}$; $y_{01} = y_{d1}$

and 2 Process equations -

$y_{11} = k_{11} * y_{01}$; $y_{21} = k_{21} * y_{01}$

Thus, a slack edge and variable y_{eos1} are introduced into the component model, associated with the specified secondary output edge, in order to ensure that the system of equations is consistent. For the x-energy system of equations, the new slack variable cost, x^{1}_{eos1}, is considered to be known, as all environmental input costs are taken to be known, retaining the consistency of the system of equations i.e.:

1) five unknown x variables -

$x^1_{11}, x^1_{21}, x^1_{01}, x^1_{d1}, x^1_{d2},$

2) five equations - 4 Circuits

$x^1_{e1} = -x^1_{11}\ ;\ x^1_{21} = -x^1_{d2}\ ;\ x^1_{01} = -x^1_{d1}\ ;\ x^1_{eos1} = x^1_{21}$

and 1 Process

$x^1_{01} = -k_{11} * x^1_{11} - k_{21} * x^1_{21} - f^1_1\,(y_{01})$

The general heuristic for the 2-d-d process may be stated as follows:

> *"A slack variable, eosn, and representative edge is introduced into the component model for each input or secondary output edge which is associated via a nodal cutset with a specified environmental input or demand."*

5.2.2 Weighted Decision Material Transformation Process

The second type of specialised material transformation process developed for the mass-energy model of the rural domestic cooking energy system is a combination of a weighted decision process and a material transformation process. In a general material transformation process it is assumed that to produce one unit of the primary input/output y_{01} requires k_{11} units of material y_{11}, *and* k_{21} units of material y_{21}, *and* ... k_{n1} units of material y_{n1}. The key concept being that ALL *n* input and secondary output materials are required to produce the primary input/output. In the case of the weighted decision material transformation (wdmt) process, the primary input/output could be produced from material y_{11} *or* material y_{21} *or* ... material y_{n1}, *or* some fractional combination of these *n*. To incorporate the ability to consider 'OR' situations, a decision weighting section is added to the material transformation component, such that a weighting is associated with each k parameter value. In this case the decision weightings, w_{11} ... w_{n1}, represent the percentage of the input or secondary output material to be used in the transformation process to produce the primary input/output.

The complete component model for this 'wdmt' process is illustrated in Figure 5.9 using a traditional mud chulha (stove) process as an example. A traditional mud chulha is a multi-purpose stove which accepts many different types of fuels, in particular fuelwood, crop residues and/or dung cakes. Thus a household may decide to use fuelwood *OR* crop residues *OR* dung cakes as fuel or some combination of the three. The 'k' parameters need to be modified to reflect the percentage of each fuel being used in the stove. For this 'wdmt' component, three decision parameters:

w_{11} - % of dung cakes used in the stove
w_{21} - % of fuelwood used in the stove
w_{31} - % of crop residue used in the stove

and three process parameters:

$k_{11} = w_{11} * 1$ / effective fuel efficiency of dung cakes
$k_{21} = w_{21} * 1$ / effective fuel efficiency of fuelwood
$k_{31} = w_{31} * 1$ / effective fuel efficiency of crop residue

are defined. Once the parameters have been set, the derivation of the y-mass and x-energy equations follows analogously the derivation for the general material transformation process equations; consequently they are not included here.

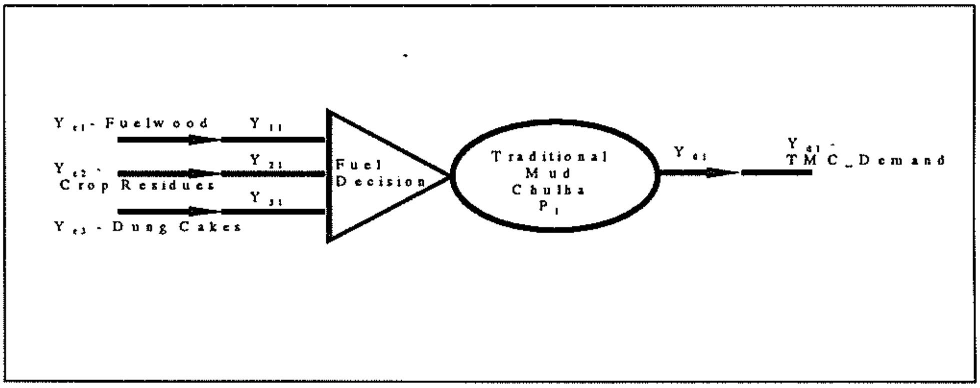


Figure 5.9 - Weighted Decision Material Transformation Component

5.3 A Simple Mass-Energy Example for the Domestic Cooking Energy System

Prior to presenting the complete General Household Model of the rural domestic cooking energy system in the next Chapter; a simple but detailed mass-energy example is given which illustrates the model development, parameter specification, and equation derivation processes specifically within the context of the rural domestic cooking energy system. The example covers the derivation of the system model for one subsystem of the general household model, the 'Buffalo' subsystem.

Model Development

The first step in the model development, as discussed in detail in the next Chapter, is the creation of a conceptual model of the system. The Buffalo system is most generally conceptualised as illustrated in Figure 5.10. In this most basic form, the system consists of one component, buffaloes, animals which consume food and water, and produce milk and dung. The conceptual system definition is refined by defining the types of food consumed and the uses for the dung and milk, as shown in Figure 5.11.

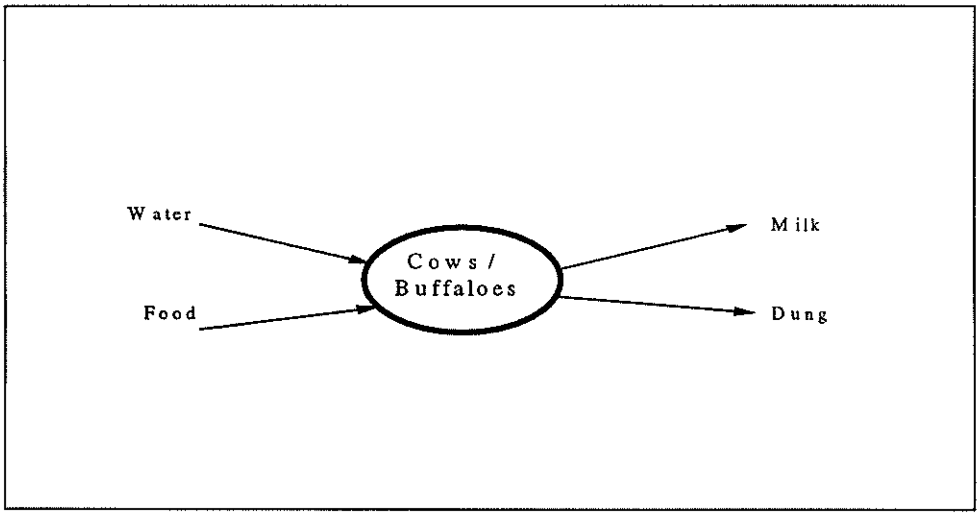


Figure 5.10 - Conceptual Buffalo System Model

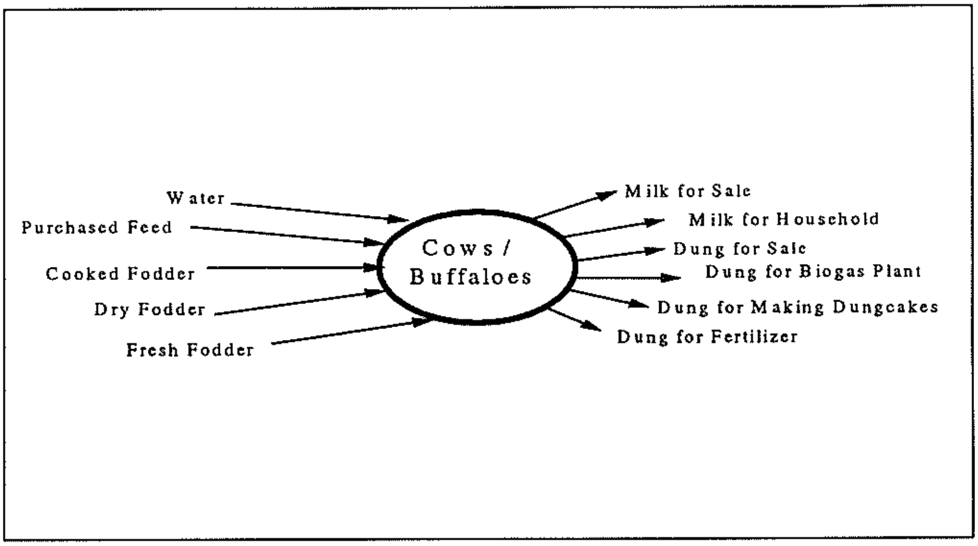


Figure 5.11 - Refined Conceptual Buffalo System Model

In order for the model to be useful at more than a conceptual level, the components must be defined as specific mass-energy process components. Figure 5.12 illustrates the mass-energy Buffalo system model with the conceptual components translated into mass-energy components. Figure 5.13 gives the linear graph for the system. The 'buffalo' conceptual component is defined as constituting three material transformation process components, one Case 1 joiner decision process, and one Case 1 splitter decision process. The first process, P_1, labelled 'Ration', represents the food fed to the buffaloes. One ration is composed of three different types of food: cooked fodder, dry fodder, and fresh fodder. These three inputs are combined in a ratio given by the component 'k' values to make up one daily ration for one buffalo. The second process, P_2, labelled 'Shed', represents the cattle shed or area where the animals are tethered. Food and water to feed the buffaloes enters the shed and a number of animals are 'output' from the shed. This process is obviously not an exact representation of how one may conceptualise an animal shed, but for the purposes of modelling it is a useful conceptualisation. The 'shed' itself is not essential, however, the idea that in order to maintain one buffalo the household must feed and water the animal a given amount is important. The third process, P_3, labelled, 'Buffaloes', represents the actual buffaloes owned by the household. The animals produce milk and dung. The dung from the household animals is collected for use; possibly in addition to dung collected from the roadside or collected from a neighbours homestead. This collecting of dung is represented by the fourth process, a joiner process P_4, labelled 'Collect Dung'. All of the dung 'joined together' from the various sources must then be allocated between a number of different uses. The final component in the system, a splitter process P_5, labelled 'Divide Dung', represents the decision by the household to divide the dung between inputting the dung to the biogas plant, making dung cakes, using the dung as manure fertiliser, or selling the dung for profit. The system y-mass and x-energy variables are described below in Tables 5.3 and 5.4.

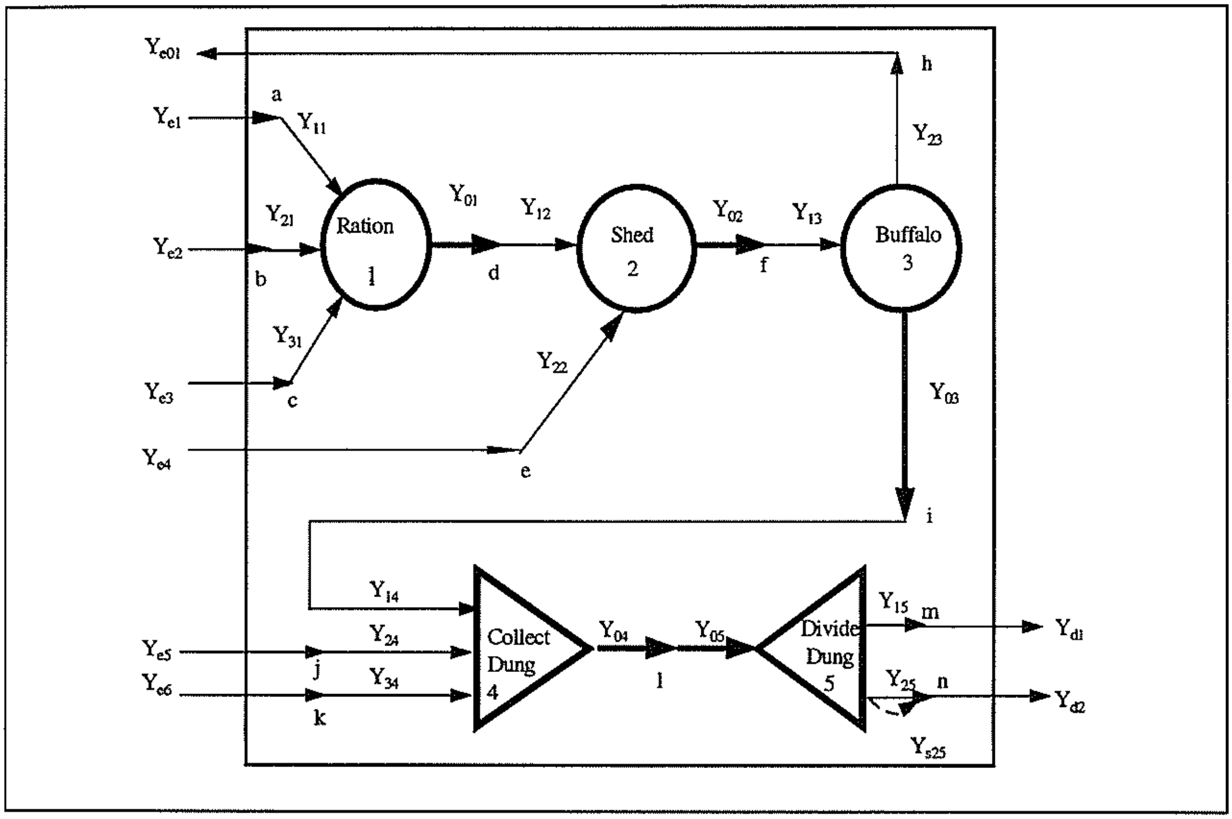


Figure 5.12 - Buffalo System Mass-Energy Model

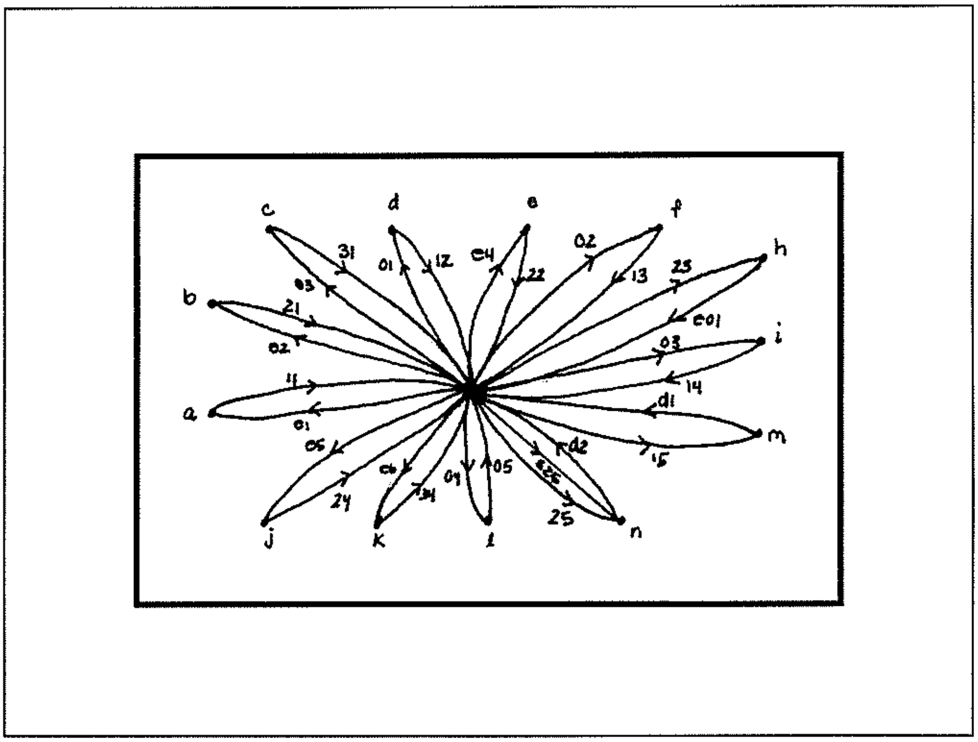


Figure 5.13 - Buffalo System Linear Graph

Environmental	Variables [Cost (Rs) per unit]	Demand	Variables
y_{e1} - kg of cooked fodder	x'_{e1} - Rs/kg cooked fodder	y_{d1} - kg dung for biogas plant	x'_{d1} - Rs to meet biogas demand
y_{e2} - kg of dry fodder	x'_{e2} - Rs/kg dry fodder	y_{d2} - kg dung for dung cakes	x'_{d2} - Rs to meet dung cake demand
y_{e3} - kg of fresh fodder	x'_{e3} - Rs/kg fresh fodder		
y_{e4} - l of water	x'_{e4} - Rs/ l water		
y_{e5} - kg of dung from other HH	x'_{e5} - Rs/kg dung from other HH		
y_{e6} - kg of dung from roadside	x'_{e6} - Rs/kg dung from roadside		
y_{ep1} - kg of milk	x'_{ep1} - Rs/kg milk		

Table 5.3 - Environmental Variables and Demand Variables

Process 1 - Ration		**Process 2 - Shed**		**Process 3 - Buffalo**		**Decision 4 - Collect Dung**		**Decision 5 - Divide Dung**	
y_{11} - kg of cooked fodder	x^{i}_{11} - Rs/kg cooked fodder	y_{12} - # of food rations	x^{i}_{12} - Rs/food ration	y_{13} - # of buffaloes	x^{i}_{13} -Rs/1 buffalo	y_{14} - kg dung from HH	x^{i}_{14} - Rs/kg of dung from HH	y_{15} - kg of dung for biogas plant	x^{i}_{05} - Rs/ kg of dung
y_{21} - kg of dry fodder	x^{i}_{21} - Rs/kg dry fodder	y_{22} - 1 of water	x^{i}_{22} - Rs/1 water	y_{23} - kg of milk	x^{i}_{23} - Rs/kg of milk	y_{24} - kg dung from other HH	x^{i}_{24} - Rs/kg dung from other HH	y_{25} - kg dung for dung cakes	x^{i}_{06} - Rs/kg of dung
y_{31} - kg of fresh fodder	x^{i}_{31} - Rs/kg fresh fodder	y_{02} - # of buffaloes	x^{i}_{02} - Rs/1 buffalo	y_{03} - kg of dung	x^{i}_{03} - Rs/kg of dung	y_{34} - kg dung from roadside	x^{i}_{34} - Rs/kg dung from roadside	y_{06} - kg total dung	
y_{01} - # of food rations	x^{i}_{01} - Rs/1 food ration					y_{04} - kg total dung	x^{i}_{04} - Rs/kg total dung		

Table 5.4 - Process Component Variables

Parameter Specification

Before the system equations are defined, the model parameters must be specified. In general, the process parameters define the fraction or amount of each input and secondary output material required to produce one unit of the primary input/output. For the P_1 - Ration process, one ration is defined as being comprised of 1 kg of cooked fodder, 7.5 kg of dry fodder, and 30 kg of fresh fodder. Thus the parameters are given as:

$$k_{11} = 1 \; ; k_{21} = 7.5 \; ; k_{31} = 30$$

For the P_2 - Shed process, to 'produce' or support one animal requires 1 food ration and 35 l of water. Thus the parameters are given as:

$$k_{12} = 1 \; ; k_{22} = 35$$

For the P_3 - Buffalo process the primary output is dung, the input is # of buffaloes, and the secondary output is milk. The parameters for this process are derived in what at first appears to be a convoluted manner, because the output of interest is dung, not # of animals. The parameters are defined in terms of # of buffaloes and kg of milk required to produce one kg of dung. Thus, if one buffalo produces 20 kg of dung and 6 kg of milk the parameters are given as:

$$k_{13} = 1/20 \; ; \; k_{23} = 6/20$$

For the P_4 - Collect Dung joiner process the primary output is dung. The dung is collected from three possible sources and the decision weighting parameters represent the percentage of dung collected from each source, as such these values will vary from household to household. For example a household may decide to collect 80 % of its dung from its own animals and an additional 20 % from the roadside, giving the decision weighting parameters values as:

$$w_{14} = 0.8 \; ; \; w_{24} = 0 \; ; \; w_{34} = 0.2$$

For the p5 - Divide Dung Splitter the process primary input is total dung and the secondary outputs are dung for biogas plant, dung for dung cakes, dung for manure, and dung for sale. The decision weightings will be different for individual households. For example, a household may not sell any of its dung or use it for manure, but rather allocates 90% of the dung for inputting into the biogas plant and 10% for making dung cakes, giving the decision weighting parameter values as:

$$w_{15} = 0.9 \; ; \; w_{25} = 0.1$$

Equation Derivation

The derivation of the two sets of system equations, y-mass equations and x-energy equations, are generally considered separately. By convention we derive the y-mass equations first.

Y-Equation Derivation

There are a total of twenty-five unknown y variables:

$y_{e1}, y_{e2}, y_{e3}, y_{e4}, y_{e5}, y_{e6}, y_{er01}$

$y_{01}, y_{02}, y_{03}, y_{04}, y_{05}$

$y_{11}, y_{21}, y_{31}, y_{12}, y_{22}, y_{13}, y_{23}, y_{14}, y_{24}, y_{34}, y_{15}, y_{25}$

y_{s25}

Thus, we need twenty-five equations for a consistent system of equations. The twenty-five required equations are derived from the thirteen cutset equations, where one nodal cutset is formed at each node a - n (excluding node g - ground/datum) and the twelve process equations, given in equations [5.1] - [5.25] below:

node a - $y_{e1} - y_{11} = 0$ [5.1]

node b - $y_{e2} - y_{21} = 0$ [5.2]

node c - $y_{e3} - y_{31} = 0$ [5.3]

node d - $y_{01} - y_{12} = 0$ [5.4]

node e - $y_{e4} - y_{22} = 0$ [5.5]

node f - $y_{02} - y_{13} = 0$ [5.6]

node h - $y_{e01} - y_{12} = 0$ [5.7]

node i - $y_{03} - y_{14} = 0$ [5.8]

node j - $y_{e5} - y_{24} = 0$ [5.9]

node k - $y_{e6} - y_{34} = 0$ [5.10]

node l - $y_{04} - y_{05} = 0$ [5.11]

node m - $y_{15} = y_{d1}$ [5.12]

node n - $y_{25} + y_{s25} = y_{d2}$ [5.13]

$$\begin{bmatrix} y_{11} \\ y_{21} \\ y_{31} \end{bmatrix} = \begin{bmatrix} k_{11} \\ k_{21} \\ k_{31} \end{bmatrix} y_{01}$$

[5.14]
[5.15]
[5.16]

$$\begin{bmatrix} y_{12} \\ y_{22} \end{bmatrix} = \begin{bmatrix} k_{12} \\ k_{22} \end{bmatrix} y_{02}$$

[5.17]
[5.18]

$$\begin{bmatrix} y_{13} \\ y_{23} \end{bmatrix} = \begin{bmatrix} k_{13} \\ k_{23} \end{bmatrix} y_{03}$$

[5.19]
[5.20]

$$\begin{bmatrix} y_{14} \\ y_{24} \\ y_{34} \end{bmatrix} = \begin{bmatrix} w_{14} \\ w_{24} \\ w_{34} \end{bmatrix} y_{04} \qquad \begin{matrix} [5.21] \\ [5.22] \\ [5.23] \end{matrix}$$

$$\begin{bmatrix} y_{15} \\ y_{25} \end{bmatrix} = \begin{bmatrix} w_{15} \\ w_{25} \end{bmatrix} y_{05} \qquad \begin{matrix} [5.24] \\ [5.25] \end{matrix}$$

To solve the system of equations, the twelve process equations are substituted into the thirteen cutset equations to yield a system of equations which may then be solved for the two given specified demands, y_{d1} and y_{d2}. This final system of y-mass equations is given below.

$$\begin{bmatrix} -k_{11} & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -k_{21} & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ -k_{31} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & -k_{22} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -w_{24} & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -w_{34} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & -k_{23} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & -k_{12} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & -k_{13} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -w_{14} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & w_{15} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & w_{25} & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} y_{01} \\ y_{02} \\ y_{03} \\ y_{04} \\ y_{05} \\ y_{s25} \\ y_{e1} \\ y_{e2} \\ y_{e3} \\ y_{e4} \\ y_{e5} \\ y_{e6} \\ y_{eo1} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ y_{d1} \\ y_{d2} \end{bmatrix} \qquad [5.26]$$

X-Equation Derivation

For the x-energy equations, there are a total of 18 unknown x^1 variables:

x^1_{01}, x^1_{02}, x^1_{03}, x^1_{04}, x^1_{05}
x^1_{d1}, x^1_{d2}, x^1_{d3}, x^1_{d4}
x^1_{11}, x^1_{21}, x^1_{31}, x^1_{12}, x^1_{22}, x^1_{13}, x^1_{23}, x^1_{14}, x^1_{24}, x^1_{34}
x^1_{e5}

Thus, we need eighteen equations for a consistent system of equations. The eighteen required equations are derived from the thirteen circuit and the five process equations, given in equations [5.27] - [5.44] below:

$$x^l_{e1} = -x^l_{11} \tag{5.27}$$

$$x^l_{e2} = -x^l_{21} \tag{5.28}$$

$$x^l_{e3} = -x^l_{31} \tag{5.29}$$

$$x^l_{e4} = -x^l_{22} \tag{5.30}$$

$$x^l_{e5} = -x^l_{24} \tag{5.31}$$

$$x^l_{e6} = -x^l_{34} \tag{5.32}$$

$$x^l_{e01} = -x^l_{23} \tag{5.33}$$

$$x^l_{01} = -x^l_{12} \tag{5.34}$$

$$x^l_{02} = -x^l_{13} \tag{5.35}$$

$$x^l_{03} = -x^l_{14} \tag{5.36}$$

$$x^l_{04} = -x^l_{05} \tag{5.37}$$

$$x^l_{c5} = -x^l_{d1} \tag{5.38}$$

$$x^l_{c5} = -x^l_{d2} \tag{5.39}$$

$$x^l_{01} = -k_{11}x^l_{11} - k_{21}x^l_{21} - k_{31}x^l_{31} \tag{5.40}$$

$$x^l_{02} = -k_{12}x^l_{21} - k_{22}x^l_{22} \tag{5.41}$$

$$x^l_{03} = -k_{13}x^l_{13} - k_{23}x^l_{23} \tag{5.42}$$

$$x^l_{04} = -w_{14}x^l_{14} - w_{24}x^l_{24} - w_{34}x^l_{34} \tag{5.43}$$

$$x^l_{05} = x^l_{c5} \tag{5.44}$$

The circuit equations are substituted into process equations [5.40] - [5.43] to yield a system of four equations which are may then be solved, given the environmental cost variables: x^1_{e1}, x^1_{e2}, x^1_{e3},

x^{l}_{e4}, x^{l}_{e5} x^{l}_{e6}, x^{l}_{eol}. Three other equations are required to complete the system mathematical description: first [5.44] is substituted into [5.37] and then circuits [5.38] and [5.39] are solved to yield the final costs to meet the system demands. The final system of x-energy equations are given below.

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ -k_{12} & 1 & 0 & 0 \\ 0 & -k_{13} & 1 & 0 \\ 0 & 0 & -w_{24} & 1 \end{bmatrix} \begin{bmatrix} x^{l}_{01} \\ x^{l}_{02} \\ x^{l}_{03} \\ x^{l}_{04} \end{bmatrix} = \begin{bmatrix} k_{11} & k_{21} & k_{31} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & k_{22} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & k_{23} \\ 0 & 0 & 0 & 0 & w_{24} & w_{34} & 0 \end{bmatrix} \begin{bmatrix} x^{l}_{e1} \\ x^{l}_{e2} \\ x^{l}_{e3} \\ x^{l}_{e4} \\ x^{l}_{e5} \\ x^{1}_{e6} \\ x^{l}_{eol} \end{bmatrix} \tag{5.45}$$

$$x^{l}_{c5} = -x^{l}_{04} \tag{5.46}$$

$$\begin{bmatrix} x^{l}_{d1} \\ x^{l}_{d2} \end{bmatrix} = -\begin{bmatrix} x^{l}_{c5} \\ x^{l}_{c5} \end{bmatrix} \tag{5.47}$$

Different scenario options may be investigated by varying the parameter values and / or the specified demands or environmental costs.

Chapter 6

A Mass-Energy Model of the Rural Domestic Energy System

The creation of the complete General Household Mass-Energy model entailed an iterative process beginning with the definition of a basic conceptual model of the household which was refined over several iterations and stages before reaching the final mathematical form. In this chapter, the evolution of the model development is presented in two parts. In the first section the structure of the conceptual model is given and in the second section the conceptual components are translated into mass-energy material transformation components and decision components. Finally, in the third section a detailed example of the complete model is presented for a sample household in Dhanawas, Farrukh Nagar Block, Gurgaon District, Haryana State.

6.1 The Conceptual Household Model

Before embarking on the assessment of the household energy system's structure, the location of the household in the overall rural energy system hierarchy must be established. As illustrated in Figure 6.1 below the *Household (HH)* is a subsystem of the *Village* which is a subsystem of the *Block* which is in turn a subsystem of the *District* system. Blocks and Districts are political administrative divisions found within each state of India. Since the Government of India is increasingly moving towards decentralised planning initiatives aimed at the district and block levels these political borders serve as useful energy system boundaries. The *districts* could be considered to be subsystems of the *state* and ultimately the *country* systems. However, at this macro level, it may be more appropriate in environmental terms to consider agro-climatic regions rather than states for system boundaries. Nonetheless, in this work, the salient subsystems are the four illustrated in the Figure.

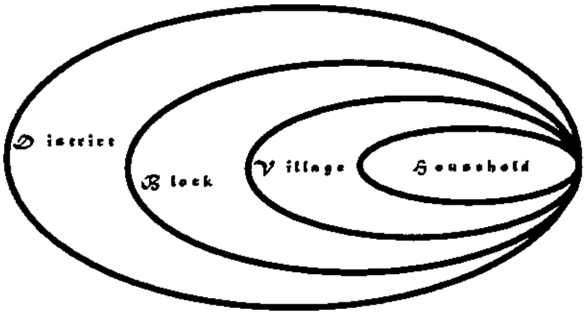


Figure 6.1 - Rural Energy System Hierarchy

At the outset of the model development exercise a critical first step is the recognition of the nature of the household system. Specifically, the fundamental characteristic of the rural domestic cooking energy system is that it is a *complex system* constituting several inter-linking and interwoven subsystems. The boundary of the system may be conceptualised to encompass one household. The basic goal or function of the system is to produce energy from natural resources to meet the household demands for cooking. This goal is translated into the most simple form of the cooking energy system model, constituting three essential subsystems: *resources, technologies, and tasks.* Different households will have access to various types of fuels, will use these fuels in several different types of cooking devices, and will perform different cooking tasks on each cookstove. The cooking energy system does not exist in a vacuum; it is part of the household social system and as such a fourth basic subsystem is the *people* who are involved in the system as either decision makers or labourers. This basic conceptual system structure is illustrated in Figure 6.2.

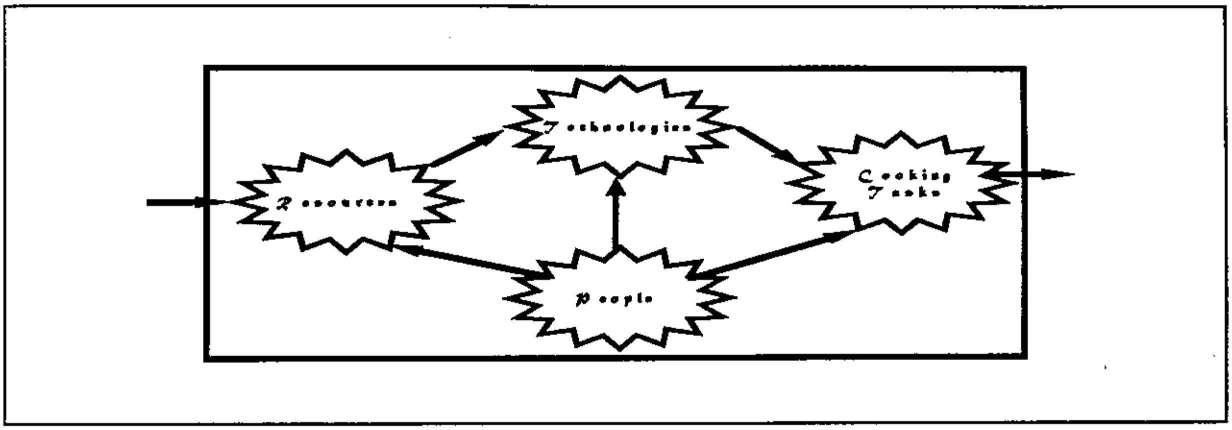


Figure 6.2 - Conceptual Household Model

The conceptual model is refined by considering the components which constitute each subsystem; the different resources and technologies used and tasks performed in the household, as illustrated in Figures 6.3.a-c The *resources* may be broken down into: fuelwood, crop residues, dung cakes, kerosene, LPG, biogas, water, fertiliser, seeds, cows/buffaloes which provide the dung and milk, animal feed, and the agricultural fields which provide the crop residues. The *technologies* available to a household are: the kerosene stove, LPG stove, biogas stove, hara chulha, traditional mud chulha, improved chulha, and the biogas plant. The primary cooking *tasks* performed in the household on a daily basis may be described as: making subji, dal, rice, tea, roti, simmering milk, cooking fodder, and water heating. Cooking stoves also perform a number of secondary tasks such as: providing heating and lighting for the home, creating smoke to repel insects and cure meat, and providing a social gathering centre. The *people* are further defined to be the women, men, and children of the household. Also important for understanding the people in the system are the caste of the family and economic level, usual identified by land and cattle holdings. Additionally, a number of people higher up in the system hierarchy can have a direct influence on the decisions made in the household: the village sarpanch (elected village council leader), village health worker, villagers of higher castes / economic affluence, local village extension workers (from NGO's or government agencies), and block and district officials. This aspect of the conceptual model of the household is depicted in Figure 6.3d.

This system description encompasses an exhaustive list of all of possible components in the domestic cooking energy system for a typical household in Haryana State. The system description for different households will contain some, but not necessarily all of these components and as the number of components increases so does the system's complexity. The system components are further defined by the component parameters and changes in the system complexity may be investigated by varying the parameter values. For example, the economic status of the household is reflected in parameters such as the number of cattle and the size of landholding. The interactions in the system do not occur in a linear, cause and effect fashion and it is this aspect that contributes significantly to the system complexity. For example, any reduction in the number of cattle would affect the amount of dung available for dung cakes, input to the biogas plant, and / or fertiliser to the fields. The reduction in fuel (dung cakes or biogas) would impact on the cooking tasks (both the number of and types of tasks performed) and the reduction in fertiliser would impact on the agricultural productivity, which in turn would influence the availability of crop residues (which are used as fuel and fodder). Thus from this small example, it is evident that the interconnections in the system form a complex web and any changes made to one part of the system will affect several different aspects of the system function.

To complete the conceptual model of the household cooking energy system, the role that people play in the system structure must be understood. Earlier, the roles that 'people' play were generally classified as either labourers or decision makers. The former classification is elucidated when the specific activities the women and men perform in the management of the system are defined, and the second is illustrated by considering the decision making roles in the household.

As discussed in detail in Chapter 2, men and women play very distinct roles within the domestic cooking energy system. The different activities may be generally categorised as: *fuel production, procurement, processing, and use.* Table 6.1 below, describes these activities and segregates them on the basis of gender.

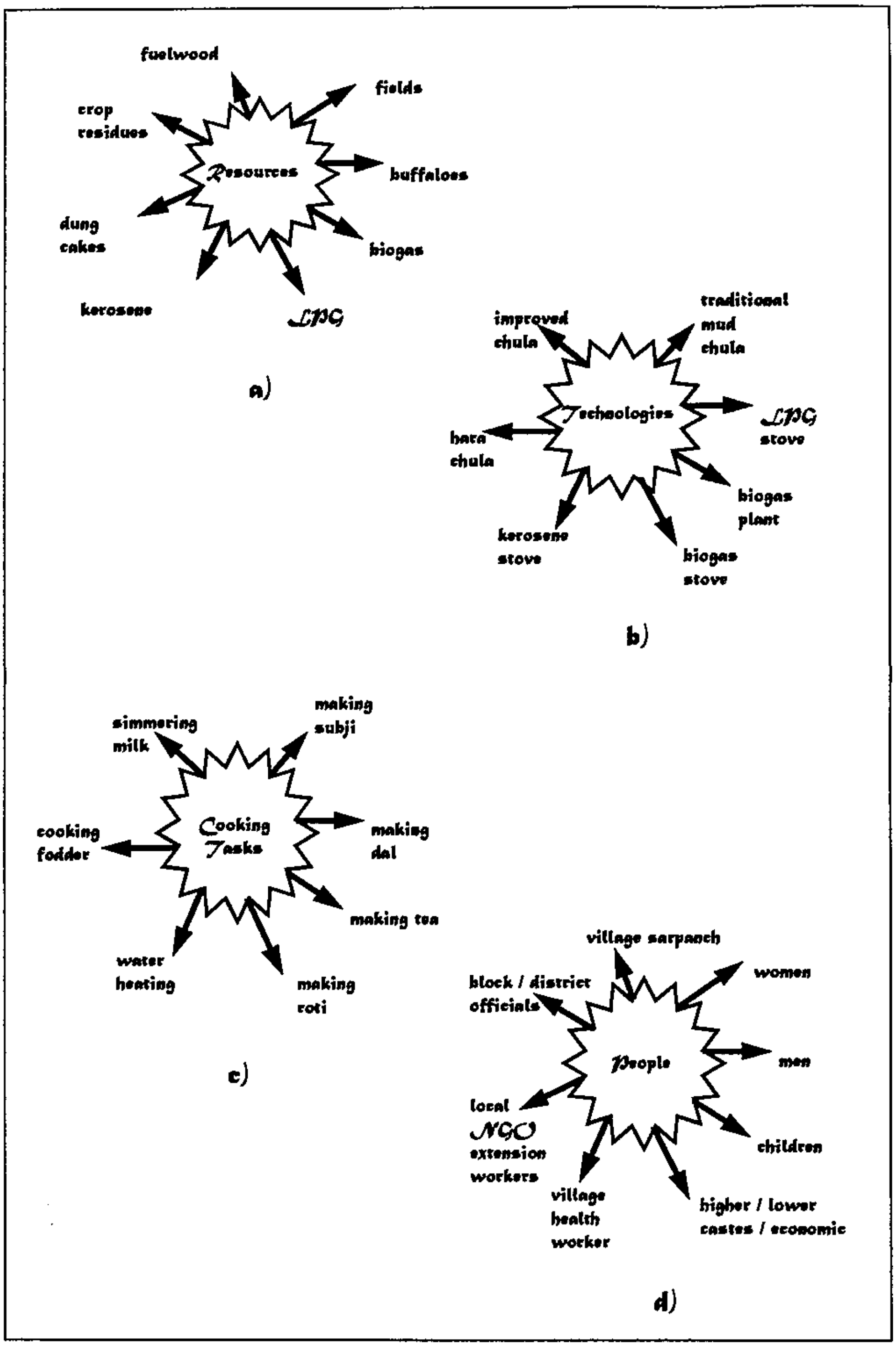


Figure 6.3 a-d - Refined Conceptual Household System Model

Task / Fuel	Fuelwood	Crop Residue	Dung Cakes
Production	Not produced	By-product of farming activity (M, W)	By-product of cattle rearing(M, W)
Procurement	Collection (W, C)	Collection and transportation to household (M, W)	Daily Collection (W)
Processing	Chopping, storing (W)	Chopping, storing (W)	Making dung cakes, storing (W)
Use	Cooking food (W)	Cooking food (W)	Cooking food (W)

M: Task performed by men; W: Task performed by women; C: Task performed by children

Table 6.1 - Activity Matrix in the Domestic Cooking Energy System

From Table 6.1, we seen that women are responsible for the majority of the tasks in the domestic cooking energy system and in this sense are responsible for the management of the system. The decision making responsibilities in the system, however, create a very complex link between the activities of the system and the decisions made which influence the function of the system. As with the allocation of activities, the decision making structure is highly segregated along gender lines. As was discussed in Chapter 2, decisions of a financial nature are made by men. In contrast, decision making responsibilities of the women lie in the domain of the management of resources within the kitchen. Additionally in Chapter 2, the fuelwood crisis was framed as a crisis of choice and three possible decisions which men and women in the rural household could take when faced with a shortage of safe and feasible fuelwood supplies were outlined. These three choices appear in the conceptual model as decision junctures. Specifically, the decision to turn to unsafe wood supplies (when safe supplies become infeasible) is captured by the decision to collect the fuelwood resources from various different sources. The fuel substitution options are captured in the decisions concerning which fuels to use in the traditional mud chulha and improved chulha (moving down the energy ladder to crop residues and dung cakes); which stoves to use i.e. switching to an LPG or kerosene stove (moving up the energy ladder); or adopting alternative technologies such as biogas or solar cookstoves. The structure of the system will change depending on these decisions. For example, if given the option a women may choose to adopt biogas technology, as it greatly reduces her work burden for fuel collecting and cooking. Conversely, her husband may not be willing to invest in the technology. The complete conceptual model, with both the expanded resources, technologies, and tasks and the critical decision junctions, is illustrated in Figure 6.4.

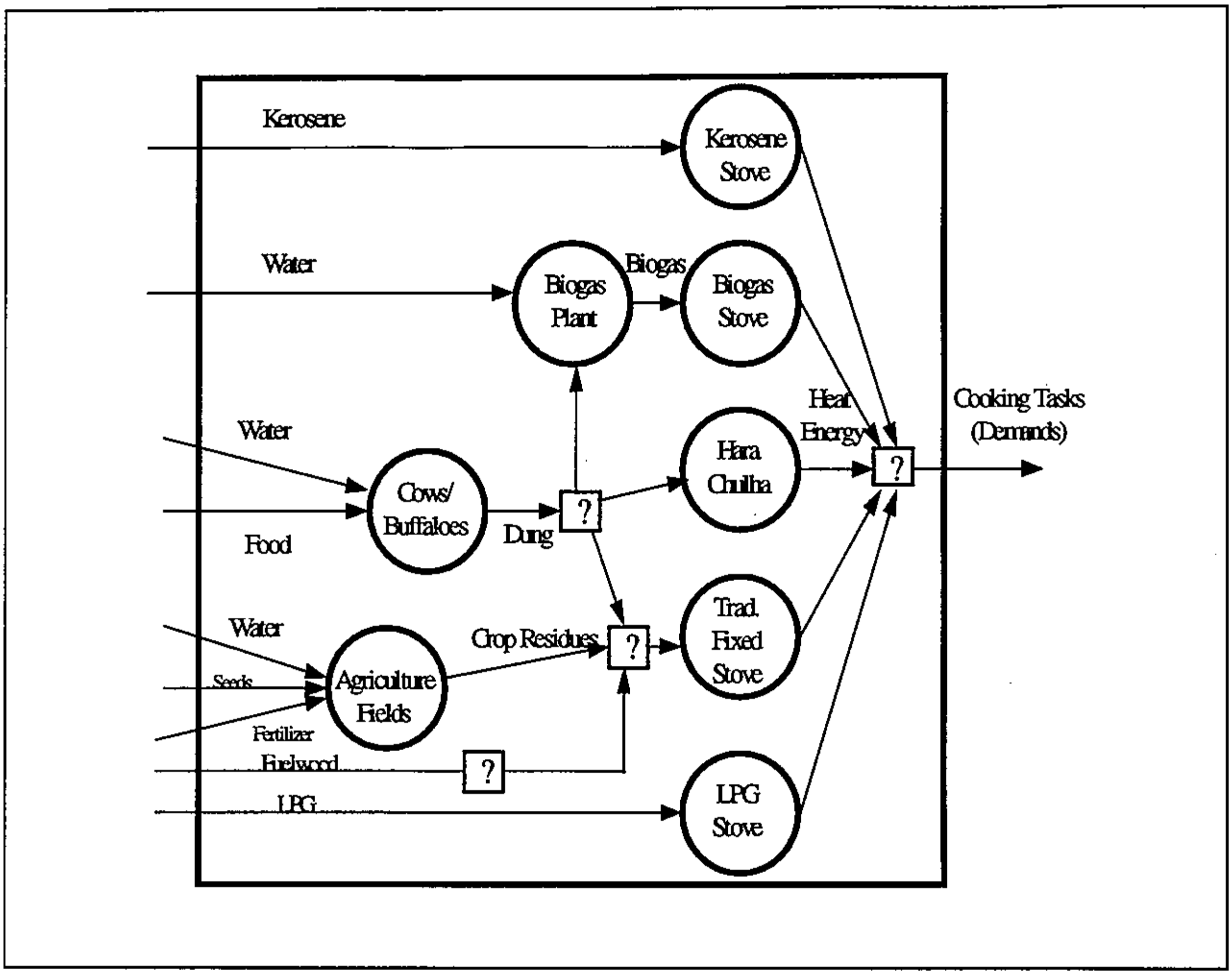


Figure 6.4 - Complete Conceptual Household Model

6.1.1 Study Area and Data Collection

The collection of the household data and model development detailed in this thesis formed part of a larger, CIDA-SICI funded, two year (April 1994 - June 1996) joint project between the University of Waterloo and the Tata Energy Research Institute, New Delhi, India, entitled "The Role of Women in Domestic Energy Systems in Rural Areas of India". The principle aim of the project was to develop a methodology for designing interventions in rural domestic cooking energy systems which would have an enhanced and indeed central role for women and the local people. Significant background research was conducted into the theory on diffusion of innovations and this information was married with the basic concepts of a systems approach for design (discussed in Chapter 3) to devise a comprehensive theoretical framework for rural energy intervention design. The model is developed as a fundamental tool of the systems approach and the intervention design framework is discussed in greater detail in Chapter 8.

The study area chosen for the project was the Farrukh Nagar Block, Gurgaon District in the state of Haryana, highlighted in Figure 6.5. Data collection was carried out primarily in two villages, Dhanawas and Gari Natthe Khan. Information was gathered through observation and informal discussions, held separately with village women and men, conducted over a period of several weeks in March and April 1995. One particular household, identified by Teri researchers who are very familiar with the area, was chosen as representative of a 'typical' village household for this region. A semi-structured questionnaire was created by the research team, which included a number of participatory rural appraisal techniques for gathering the relevant data, and administered over a three day period. Both men and women in the household were questioned in an attempt to uncover any gender biases. The questionnaire is included in Appendix A.

The principal study household has six members: husband, wife, grandmother (not in photo), two sons and one daughter, shown in Figure 6.6 with two Teri team member (at right in photo). The family lives in a cluster of three kutcha (mud) dwellings in their fields, just outside of Dhanawas, shown in Figure 6.7. The family owns 7 acres of land and the primary crops grown are Guar, Bajra, and Jowar in Kharif (season of the rains Mid June - October) and Wheat and Mustard in Rabi (cold weather season November - February). The principle resources used in the household are firewood, crop residues, and dung cakes; illustrated in Figures 6.8 - 6.10 respectively. The family owns four animals: an adult female buffalo, a small male buffalo, a female cow, and a calf. The animals are kept tethered in the household area, as illustrated in Figure 6.11. The family owns a biogas plant, such as the one illustrated in Figure 6.12 and uses a biogas stove (Figure 6.13) for making subji, dal, and tea. The family uses a hara chulha for simmering milk and cooking fodder. Hara chulhas may be constructed above ground, in the ground, or in a covered space, as illustrated in Figures 6.14 and 6.15. The women predominantly make roti and heat bathing water using the traditional mud chulha, shown in Figure 6.16, however, they are hoping to have an improved chulha such as the one illustrated in Figure 6.17 installed to replace the traditional stove.

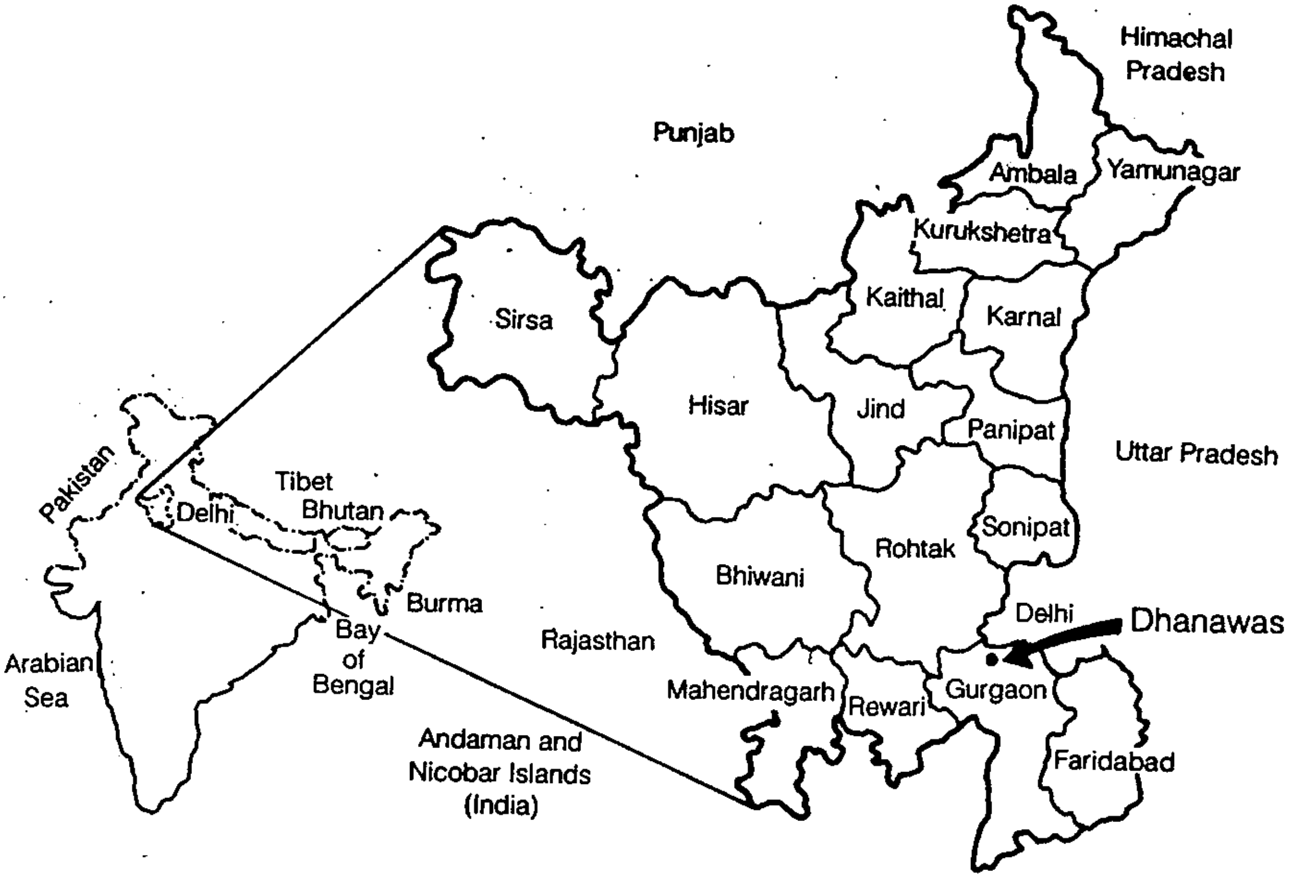


Figure 6.5 - Study Area - Dhanawas, Haryana

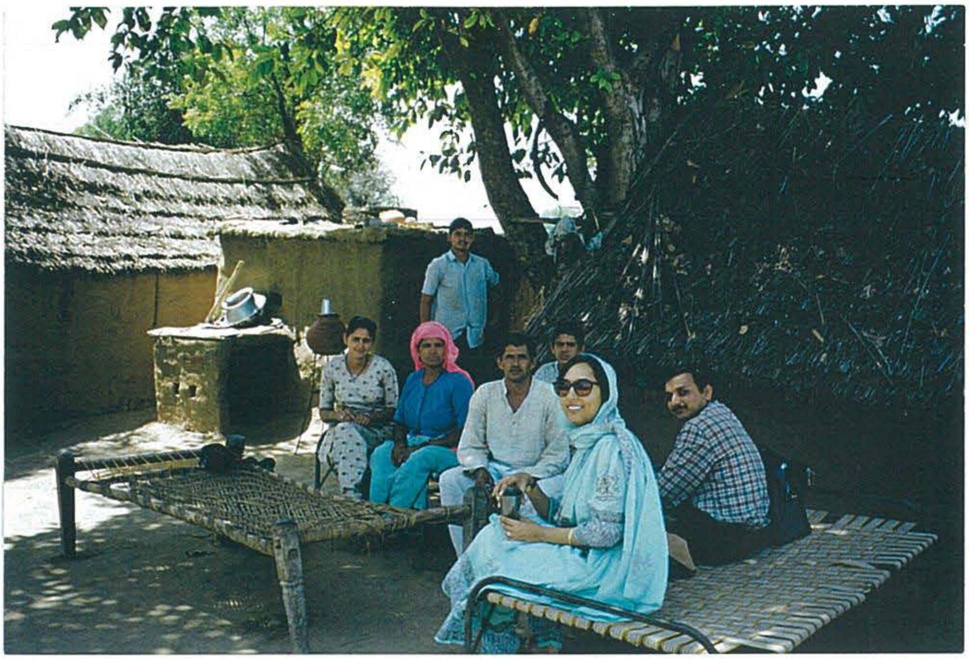


Figure 6.6 - Study Household Members

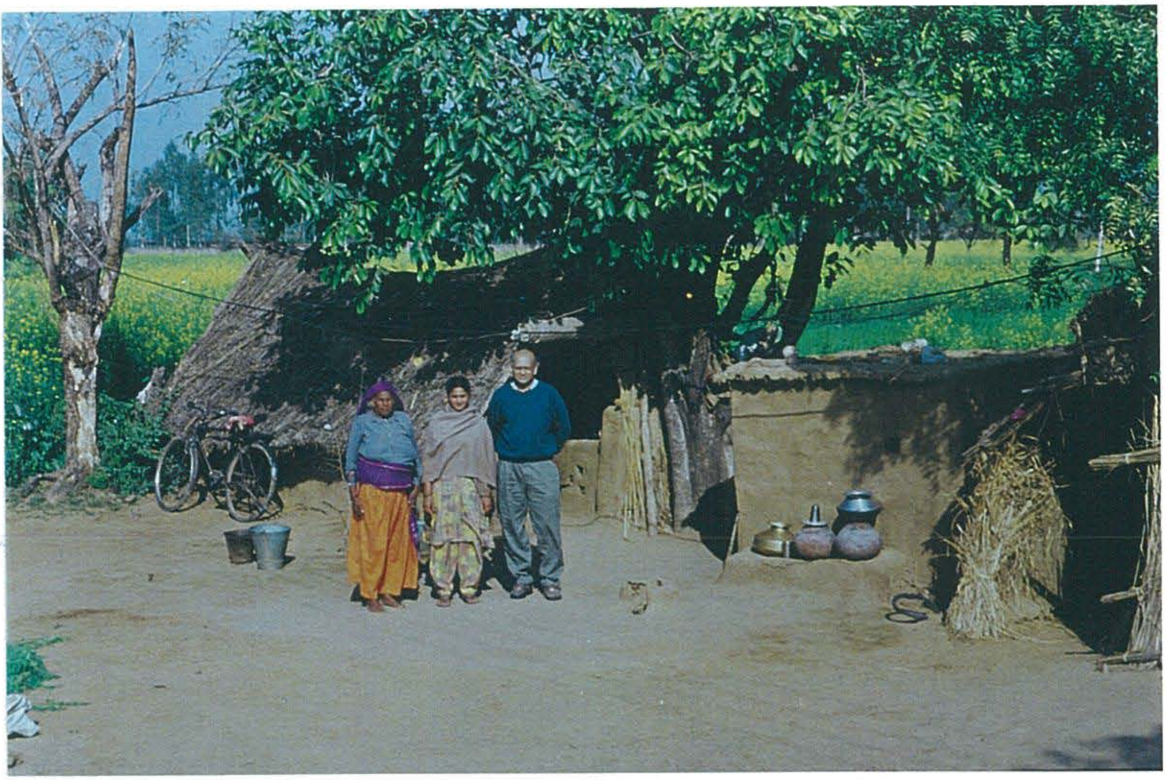


Figure 6.7 - Study Homestead

Figure 6.8 - Dhanawas Tree Plantation - Village Fuelwood Source

Figure 6.9 - Crop Residues

Figure 6.10 - Dung Cakes

Figure 6.11 - Household's Buffaloes and Cows

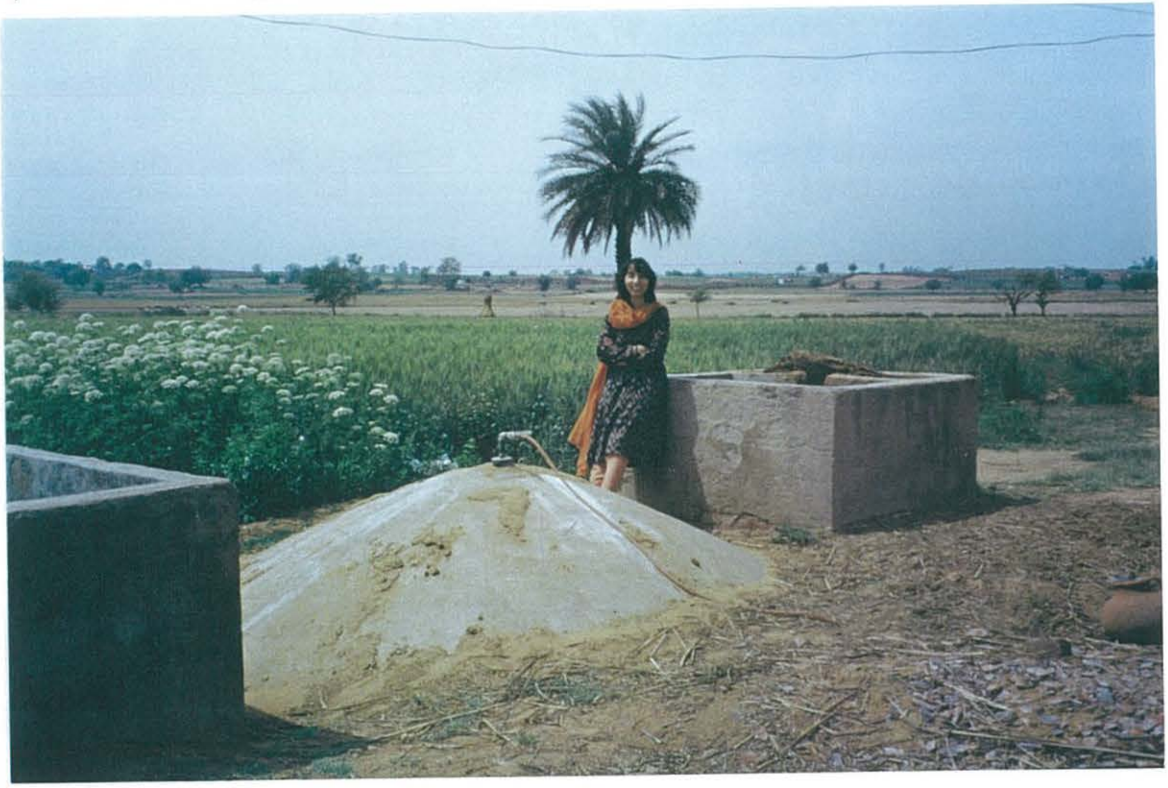


Figure 6.12 - Biogas Plant

Figure 6.13 - Biogas Stove

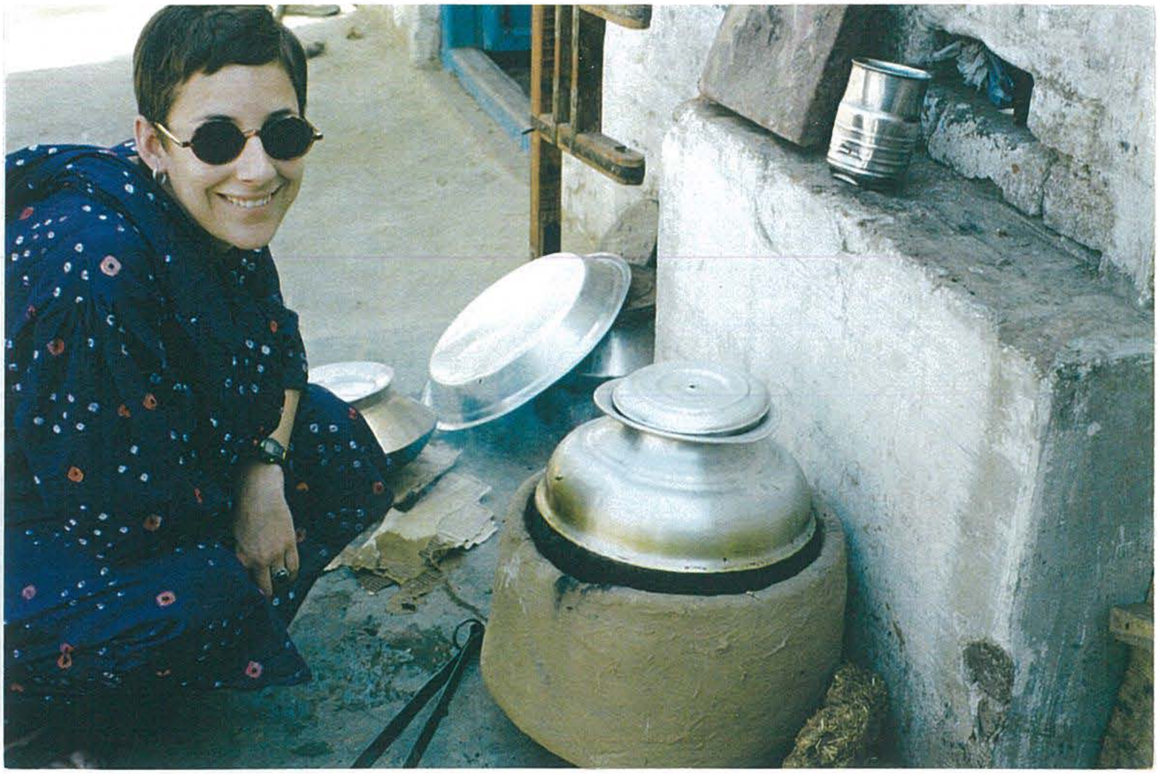


Figure 6.14 - Hara Chulha

Figure 6.15 - Covered Hara Chulha

Figure 6.16 - Traditional Mud Chulha

Figure 6.17 - Improved Mud Chulha

6.2 The General Household Model

Once the complete conceptual model of the household was clearly established and understood, the next step or iteration in the model development process was to translate these general components into specific mass-energy components: material transformation, transportation, and storage. Based on information gained from the informal village interviews and the in depth survey conducted with the study household the Complete General Household Model was established. This model is illustrated in Figure 6.18.

The mathematical model was coded using the Student Version of Matlab, because the general version was not available in India. As a consequence of the 32 x 32 maximum matrix size limitation, the Complete General Household Model simplified, by combining several components and eliminating the material transportation and storage components, and divided into two sections for the programmed implementation: the general household subsystem and the agriculture subsystem. Each of these subsystems are described in detail below; a description of each component is given, along with the parameter and equation specification. A description of how to actually create and run Matlab model scenarios is given in Appendix B.

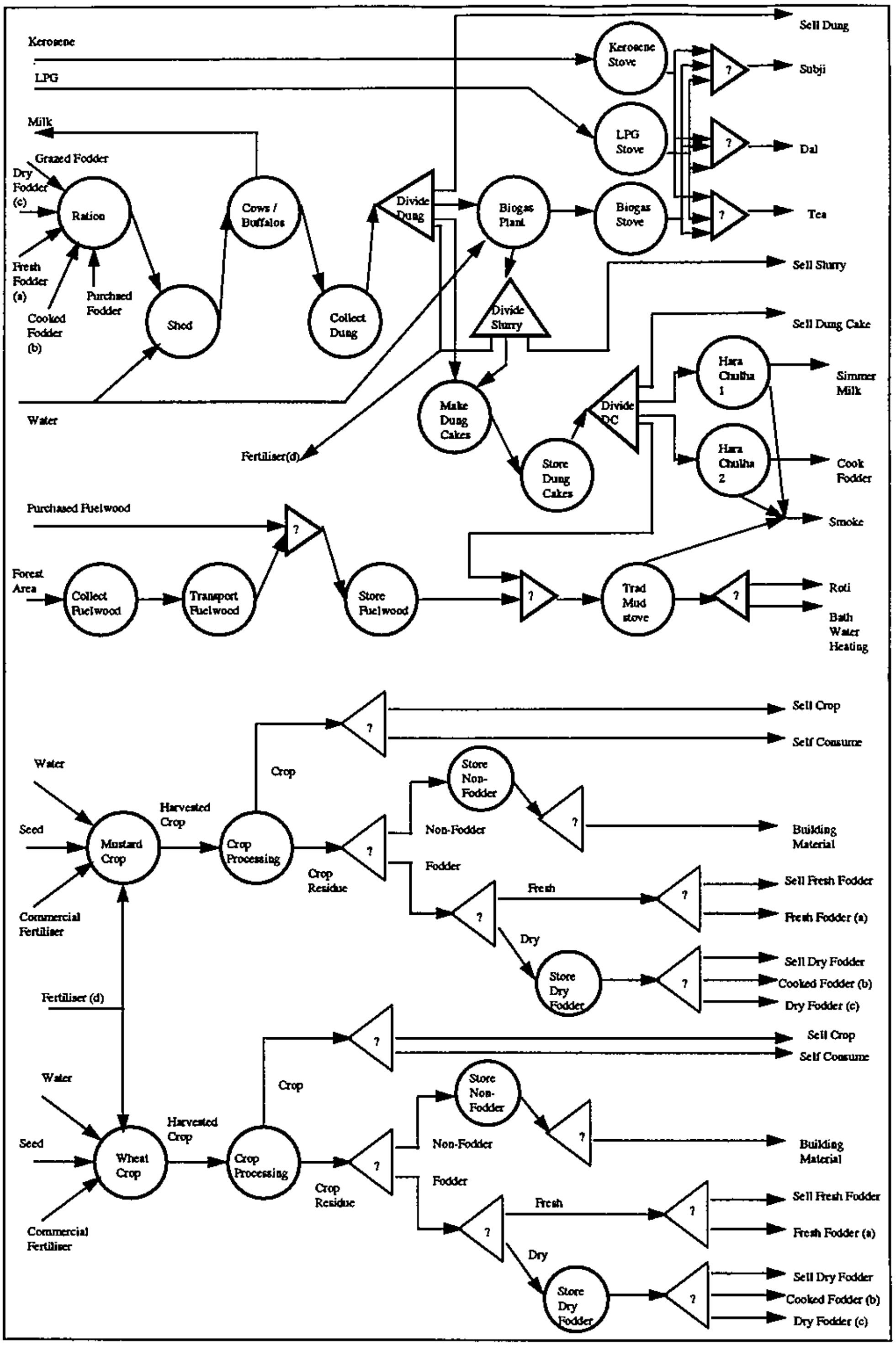


Figure 6.18 - The Complete General Household Model

6.2.1 The General Household System Model

The General Household System Model consists of eleven components:

1. Ration
2. Shed
3. Buffalo
4. Decision to Divide Dung
5. Hara Chulha
6. Biogas Plant
7. Biogas Stove
8. Decision to Collect Fuelwood
9. TMC / ICS and Fuel Decision
10. Kerosene Stove
11. LPG Stove

Using this model different household scenarios may be investigated by varying the fuel / stove / task combinations. For example, first a scenario may be run for a household which has buffaloes, and uses the dung for manure and dung cakes, simmers milk and cooks fodder on the hara chulha, makes roti and heats bathing water on the traditional mud chulha, and cooks subji, dal, and makes tea on an LPG stove. The resource uses and costs can then be compared for the same family but when the LPG stove is replaced with a biogas plant. The system driving functions, or cooking demands in terms of the kg of food to be cooked per day per household are supplied by the user. The user also defines the stoves used by the household as well as the combination of fuels used in the stoves and the various sources the family accesses for fuelwood collection. Additionally, the number of buffaloes owned by the family is user specified as is the allocation of the dung resource. Because the model is run on a per day basis, in order to capture the resource requirements of the household in one year, several runs of the model need to be done and the results combined. Specifically:

1. Run 1 - No bathing water heated (cooking demands = subji + dal + tea + roti)
2. Run 2 - Bathing water heated (cooking demands = subji + dal + tea + roti + bathing water)
3. Run 3 - All cooking tasks performed on kerosene stove (cooking demands = subji + dal + tea + roti)

The first run represents a typical day in the warmer months (8 months of the year in Haryana). The second run represents a typical day in the colder months when water is heated for bathing (3 winter months of December, January, and February in Haryana). The final run represents an extreme day during the monsoon, when the kerosene is used for convenience (for Haryana approximately one month out of the three month monsoon season). To calculate the total annual resource demand the results are combined as follows:

results from run #1 * 242 days + results from run #2 * 92 days + results from run #3 * 31 days

The structure of the model is illustrated in Figure 6.19 and a brief description of each component, including the parameter values and mathematical definition, are given below. Unless otherwise stated, the parameter values are based on data gathered to represent a 'typical' household in Haryana state. To model a household in a different region of India representative values for that region would have to be used. Table 6.2 contains a listing of the parameters, variables, and equations associated with each component and Table 6.3 presents the actual parameter values used in the model.

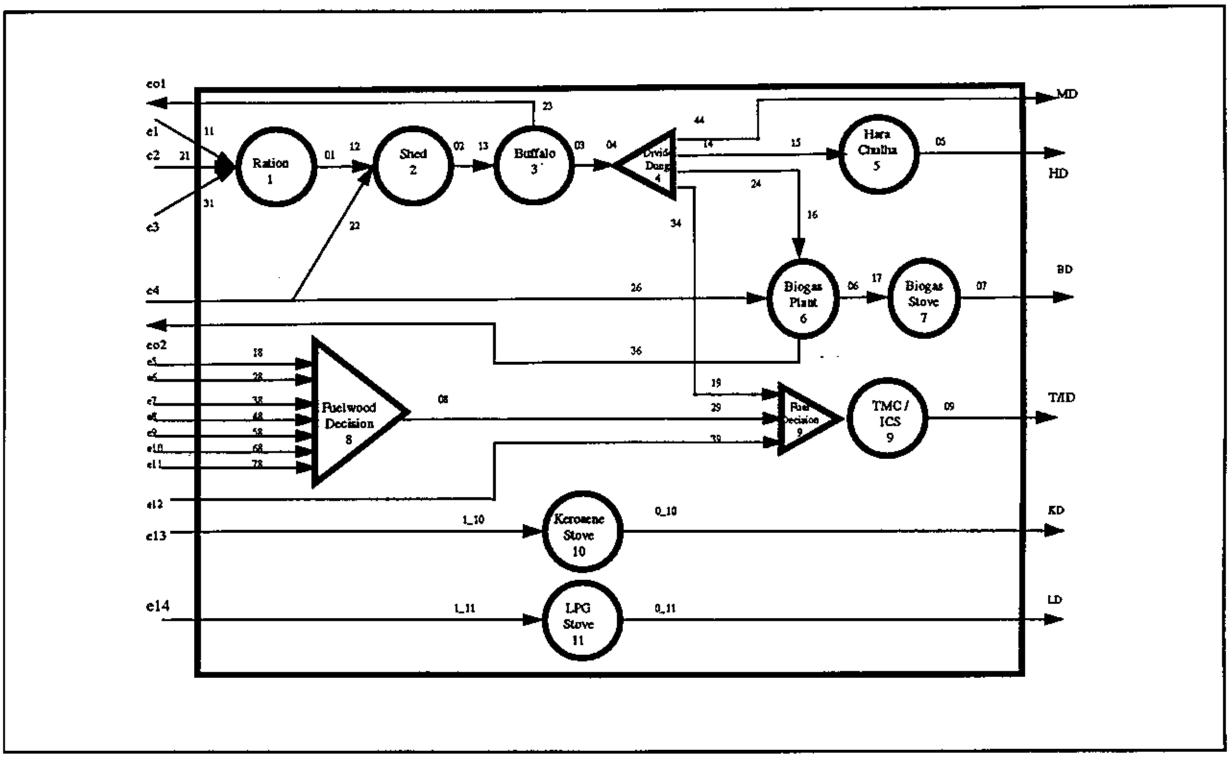


Figure 6.19 - General Household System Model

1. Ration

The output of this process is a number of 'meal' rations to be fed to the buffaloes. One ration will be composed of some fraction of each of the inputs. The "k" values define these fractions.

2. Shed

The output of this process is number of buffaloes and the inputs are rations and water. The "k" values then describe the relationship, "to "produce" one buffalo requires k rations and k l of water".

3. Buffalo

The output of this process is dung, the input is number of buffaloes, and the secondary output is milk produced. The parameters for this process are somewhat convoluted, because the output of interest is dung, not the number of buffaloes. Thus, instead of describing (as would seem most straightforward) the k values as one buffalo produces k kg of milk and k kg of dung, we describe the # of buffaloes and kg of milk associated with one unit (kg) of dung. For example, if one buffalo produces 10 kg of dung and 4 l of milk a day, then 1 kg of dung would require 1/10 buffaloes and 4/10 kg of milk.

4. Decision to Divide Dung:

The household collects an amount of dung (kg) a day and a decision must be taken as to how to distribute the dung: to use it to make dung cakes for the hara chulha, to input it into the biogas plant, to make dung cakes for the TMC, or to use it as manure / fertiliser. The decision parameters must be defined by the user at the beginning of each new scenario. Not explicitly shown on the diagram (to preserve clarity) are the four slack variables associated with the splitter decision component. Some or all of the slack variables will be zero, depending on the 'splitter case' as defined in the Splitter Theory section. In the General Household System Model, for the decision to divide the dung three slack variables are used explicitly:

y_{s24} - slack for biogas dung demand
y_{s34} - slack for TMC / ICS dung cake demand
y_{s44} - slack for dung manure demand

5. Hara Chulha

The input to the process is fuel in the form of dung cakes (kg). The output of the process is heat energy (kcal). For each stove component, the stove parameter defines the material transformation process of converting fuel into heat energy; the 'k' value expresses the relationship, "to produce one unit (kcal) of output heat energy requires k kg of input fuel". Specifically, for the hara chulha, the model parameter defines the quantity of dung cakes required to produce one kcal of heat energy. The effective heat energy of dung cakes is used, in order to take into consideration the efficiency of the stove, where the effective heat energy is defined to be the heat energy per kg of fuel * the stove efficiency. The thermal efficiency for a hara chulha is 8% and the heat energy of dung cakes is 3140 kcal/kg. Thus the parameter value is calculated as: if one kg of dung produces 3140 * 0.08 kcals of energy then 1 / (3140 * 0.08) kg of dung produce one kcal of energy. [91]

6. Biogas Plant

The inputs to the process are dung (kg) and water (l). The outputs of the process are biogas (m^3) and slurry (kg). The model parameters for this component define the dung and water needed and slurry produced to produce one m^3 of biogas. The parameter values given are for ideal gas production conditions [55].

7. Biogas Stove

The input to the process is biogas fuel (m^3), and the output of the process is heat energy (kcal) produced by the combustion of the biogas in the biogas stove. The model parameter for this component defines the heat energy produced per m^3 of biogas. The burner efficiency for a biogas stove is taken as 45% and the heat energy of biogas as 4700 kcal / m^3 [91].

8. Decision to Collect Fuelwood

The woman of the household must make the decision as to where she will collect the fuelwood from, either purchasing it or collecting it from a number of different possible forest areas. The values for each decision parameter must be specified by the user at the beginning of each scenario.

9. TMC / ICS Stove and Fuel Decision

This component is weighted material transformation, thus two sets of parameters are specified. The first set are the decision weightings, which are defined by the user at the beginning of each new scenario. These weights define the percent of the total cooking time during which a given fuel is used. The second set of parameters uses the weightings in conjunction with the effective heat efficiency of the stove to determine the transfer relationship between the input fuel and the output heat energy. In order to streamline the model, it is assumed that the household will have only a traditional mud chulha *or* an improved chulha. Hence, the one component to represent both stove technologies. The stove efficiency used in the calculation of the 'k' value parameters is set automatically depending which stove type is specified by the user.

10. Kerosene Stove

The input to the process is kerosene (kg) as a fuel. The output of the process is heat energy (Kcal) produced by the combustion of kerosene in the kerosene stove. The model parameter for this component defines the heat energy produced per kg of kerosene. The burner efficiency for a kerosene stove is taken as 40% and the heat energy of kerosene as 10 300 kcal/kg [91].

11. LPG Stove

The input to the LPG stove is kg of LPG fuel and the output is heat energy produced. The parameter defines the heat energy produced per kg of input fuel. The burner efficiency for an LPG stove is taken as 60% and the heat energy of LPG as 10 800 kcal/kg [91].

Environmental Resources

There are fourteen environmental resources input into the General Household System Model. The costs are specified by the user at the beginning of each scenario and the y through variables are calculated during the system simulation.

y_{e1} - kg cooked fodder	x_{e1} -Rs/ kg cooked fodder
y_{e2} - kg fresh fodder	x_{e2} - Rs/kg fresh fodder
y_{e3} - kg dry fodder	x_{e3} - Rs/kg dry fodder
y_{e4} - m^3 water	x_{e4} - Rs/m^3 water
y_{e5} - kg fuelwood (fw) purchased	x_{e5} - Rs/kg purchased fw
y_{e6} - kg fw own land	x_{e6} - Rs/kg fw own land
y_{e7} - kg fw tree plantation	x_{e7} - Rs/kg fw tree plantation
y_{e8} - kg fw gov't forest area	x_{e8} - Rs/kg fw gov't forest area
y_{e9} - kg fw panchayat forest area	x_{e9} - Rs/kg fw panchayat forest area
y_{e10} - kg fw roadside	x_{e10} - Rs/kg fw roadside
y_{e11} - kg fw other private sources	x_{e11} - Rs/kg fw other private sources
y_{e12} - kg crop residue	x_{e12} - Rs/kg crop residue
y_{e13} - kg kerosene	x_{e13}- Rs/kg kerosene
y_{e14} - kg lpg	x_{e14} - Rs/g LPG

Additionally, there are two environmental resource outputs:

y_{e01} - kg milk	x_{eo1} - sale price/kg of milk
y_{e02} - kg slurry	x_{e02} - sale price/kg of slurry

Component	Parameter	Y - Variables	X-Variables	Y - Process Equation	X - Process Equation
1. Ration	k_{11} - kg cooked fodder k_{21} - kg fresh fodder k_{31} - kg dry fodder	y_{11} - kg cooked fodder y_{21} - kg fresh fodder y_{31} - kg dry fodder y_{01} - # of feed rations	x_{11} - Rs/kg cooked fodder x_{21} - Rs/kg fresh fodder x_{31} - Rs/kg of dry fodder x_{01} - Rs/food ration	$y_{11} = k_{11} * y_{01}$ $y_{21} = k_{21} * y_{01}$ $y_{31} = k_{31} * y_{01}$	$x_{01} = -k_{11}x_{11} - k_{21}x_{21} - k_{31}x_{31} - f_1(y_{01})$
2. Shed	k_{12} - # rations k_{22} - l water	y_{12} - # of rations y_{22} - l of water y_{02} - # of buffaloes	x_{12} - Rs/ration x_{22} - Rs/l of water x_{02} - Rs/1 buffalo	$y_{12} = k_{12} * y_{02}$ $y_{22} = k_{22} * y_{02}$	$x_{02} = -k_{12}x_{12} - k_{22}x_{22} - f_2(y_{02})$
3. Buffalo	k_{13} - # buffaloes k_{23} - kg milk	y_{13} - # of buffaloes y_{23} - kg of milk y_{03} - kg of dung	x_{13} - Rs/ 1 buffalo x_{23} - Rs/kg of milk x_{03} - Rs/ kg of dung	$y_{13} = k_{13} * y_{03}$ $y_{23} = k_{23} * y_{03}$	$x_{03} = -k_{13}x_{13} - k_{23}x_{23} - f_3$(y03)
4. Divide Dung	w_{14} - % of dung for dung cakes for hara chulha w_{24} - % of dung input into biogas plant w_{34} - % of dung for dung cakes for tmc / ics w_{44} - % of dung for manure	y_{14} - kg for dung cakes for hara chulha y_{24} - kg input into biogas plant y_{34} - kg for dung cakes for tmc / ics y_{44} - kg for manure y_{04} - total kg of dung	x_{04} - Rs / total dung x_{44} - Rs / total dung	$y_{14} = w_{14} * y_{04}$ $y_{24} = w_{24} * y_{04}$ $y_{34} = w_{34} * y_{04}$ $y_{44} = w_{44} * y_{04}$	$x_{04} = x_{44}$
5. Hara Chulha	k_{15} - kg dung req'd / 1 kcal heat energy	y_{15} - kg dung cakes y_{05} - kcals heat energy	x_{15} - Rs/kg dung cake x_{05} - Rs/total heat energy	$y_{15} = k_{15} * y_{05}$	$x_{05} = -k_{15}x_{15} - f_5(y_{05})$
6. Biogas Plant	k_{16} - kg dung k_{26} - l water k_{36} - kg slurry	y_{16} - kg dung y_{26} - l water y_{36} - kg slurry y_{06} - m^3 biogas	x_{16} - Rs/kg dung x_{26} - Rs/l water x_{36} - Rs/kg slurry x_{06} - Rs/m^3 biogas	$y_{16} = k_{16} * y_{06}$ $y_{26} = k_{26} * y_{06}$ $y_{36} = k_{36} * y_{06}$	$x_{06} = -k_{16}x_{16} - k_{26}x_{26} - k_{36}x_{36} - f_6(y_{06})$
7. Biogas Stove	k_{17} - m^3 biogas req'd/ 1 kcal heat energy	y_{17} - m^3 biogas y_{07} - kcals heat energy	x_{17} - Rs/m^3 of biogas x_{07} - Rs/total heat energy	$y_{17} = k_{17} * y_{07}$	$x_{07} = -k_{17}x_{17} - f_7(y_{07})$
8. Decision to Collect Fuelwood	w_{18} - % purchased w_{28} - % own land w_{38} - % tree plantation w_{48} - % government forest area w_{58} - % panchayat forest area w_{68} - % roadside w_{78} - % other sources	y_{18} - kg purchased y_{28} - kg own land y_{38} - kg tree plantation y_{48} - kg gov't forest area y_{58} - kg panchayat forest area y_{68} - kg roadside y_{78} - kg other sources y_{08} - total kg all sources	x_{18} - Rs/kg purchased x_{28} - Rs/kg own land x_{38} - Rs/kg tree plant x_{48} - Rs/kg gov't forest area x_{58} - Rs/kg panchayat forest area x_{68} - Rs/kg roadside x_{78} - Rs/kg other sources x_{08} - Rs/total kg	$y_{18} = w_{18} * y_{08}$ $y_{28} = w_{28} * y_{08}$ $y_{38} = w_{38} * y_{08}$ $y_{48} = w_{48} * y_{08}$ $y_{58} = w_{58} * y_{08}$ $y_{68} = w_{68} * y_{08}$ $y_{78} = w_{78} * y_{08}$	$x_{08} - -w_{18}x_{18} - w_{28}x_{28} - w_{38}x_{38} - w_{48}x_{48} - w_{58}x_{58} - w_{68}$x68 - $w_{78}x_{78} - f_8(y_{08})$
9. TMC/ICS Stove Decision	w_{19} - % dung cakes w_{29} - % fuelwood w_{39} - % crop residues (used in stove) k_{19} = kg dung k_{29} = kg fuelwood k_{39} = kg crop residues (required to produce 1 kcal heat energy)	y_{19} - kg dung cake y_{29} - kg fuelwood y_{39} - kg crop residue y_{09} - kcals heat energy	x_{19} - Rs/kg dung cake x_{29} - Rs/kg fuelwood x_{39} - Rs/kg crop residue x_{09} - Rs/ kcal heat energy	$y_{19} = k_{19} * y_{09}$ $y_{29} = k_{29} * y_{09}$ $y_{39} = k_{39} * y_{09}$	$x_{09} = -k_{19}x_{19} - k_{29}x_{29} - k_{39}x_{39} - f_9(y_{09})$
10. Kerosene Stove	$k_{1\,10}$ - kg kerosene required to produce 1 kcal heat energy	$y_{1\,10}$ = kg kerosene $y_{0\,10}$ = kcals heat energy	$x_{1\,10}$ = Rs/kg kerosene $x_{0\,10}$ = Rs/ kcal heat energy	$y_{1\,10} = k_{1\,10} * y_{0\,10}$	$x_{0\,10} = -k_{1\,10}x_{1\,10} - f_{10}(y_{0\,10})$
11. LPG Stove	$k_{1\,11}$ - kg LPG required to produce 1 kcal heat energy	$y_{1\,11}$ = kg LPG $y_{0\,11}$ = kcals heat energy	$x_{1\,11}$ = Rs/kg LPG $x_{0\,11}$ = Rs/ kcal heat energy	$y_{1\,11} = k_{1\,11} * y_{0\,11}$	$x_{0\,11} = -k_{1\,11}x_{1\,11} - f_{11}(y_{0\,11})$

Table 6.2 - General Household Subsystem Model Parameters, Variables, and Equations

Component	Parameter	Value
1. Ration	k_{11} k_{21} k_{31}	= 1 kg = 30 kg = 7.5 kg
2. Shed	k_{12} k_{22}	= 1 ration = 35 l water
3. Buffalo	k_{13} k_{23}	= 1/20 = 6/20
5. Hara Chulha	k_{15}	= 1 /(3140 * 0.08)
6. Biogas Plant	k_{16} k_{26} k_{36}	= 25 kg = 25 l = 25 kg
7. Biogas Stove	k_{17}	= 1 / 4700 * 0.45
9. TMC/ICS	k_{19} k_{29} k_{39}	= w_{19} * 1 / 3140 * [0.10 (tmc) or 0.15 (ics)] = w_{29} * 1 / 4500 * [0.10 (tmc) or 0.15 (ics)] = w_{39} * 1 / 3900 * [0.10 (tmc) or 0.15 (ics)]
10. Kerosene Stove	$k_{1\ 10}$	= 1 / (0.4 * 10300)
10. LPG Stove	$k_{1\ 11}$	= 1 / (0.6 * 10800)

Table 6.3 - Parameter Values

Cooking Demands

The cooking energy demands will vary depending on the scenario being investigated. The user must specify two different aspects of the cooking demand. First, the quantity of each food cooked per day for the household must be given in kg, or set to zero if that particular food is not consumed. Then the stove which is used for each cooking task must be specified, e.g. simmering milk and cooking fodder on a hara chulha; making roti and heating bathing water on a traditional mud chulha or an improved chulha; making subji, dal and tea on a biogas, LPG, or kerosene stove.

Currently seven different cooking tasks or demands are considered in the model: making subji (a potato and vegetable curry); making dal (lentils); making tea; making roti (North Indian flat bread, similar to Mexican tortillas but made with wheat flour); heating bathing water; simmering milk (for preservation, due to lack of refrigeration facilities); and cooking fodder (an enriched grain mash/feed usually fed to milching buffaloes). These seven tasks have been chosen based on their dietary predominance in the study area in Haryana State; subji, dal, and roti constitute the main food elements of a north Indian diet in this region. In other regions of the country, such as in Kerela

State in the south, roti are not eaten as frequently and rice is a main dietary staple. Thus the cooking demands specified would be different for other regions of the country.

These cooking tasks are essentially low temperature tasks where thermal energy is required to reach the boiling point of water; where upon additional heat is required only to maintain the temperature (by compensating for heat losses) and to complete the cooking function through some chemical change in the food item [87]. This energy requirement may be defined in several different ways. In this work, the useful energy required for cooking, in terms of kcals required to cook one kg of food is used. The useful energy is defined after Sinha and Kandpal [87], as the sum of the energy required for the sensible heating of the food to the desired cooking temperature, the energy required for the chemical changes essential for the cooking process, and the energy losses during the cooking time. As Sinha and Kandpal discuss in detail, the theoretical calculation of the useful energy required for the sensible heating of food items is essentially straightforward, unlike that for determining the energy required for the chemical change of the food item. In fact, no convenient method currently exists for determining this latter requirement. Two other factors which strongly influence the energy requirement for cooking processes which involve the boiling of water are the water to food ratio and the fate of the excess water. Depending on the initial temperature of the water, every kilogram of decanted water will waste approximately 300 KJ of thermal energy, and each kilogram of water to be evaporated will require about 2750 KJ of energy which must be transferred to the water-food mixture [87]. Consequently, there are many factors involved in determining the energy requirement for cooking. Because very little empirical data of this nature is currently available in the literature and any calculations of the energy requirements necessitate approximations, the values used in the model should be regarded as indicative rather than definitive.

Some of the useful cooking energy requirements used in the model then, are taken from data reported in Sinha & Kandpal [87]. For cooking tasks such as simmering milk and cooking fodder on hara chulhas, cooking experiments were conducted by Teri in the field in Dhanawas to provide an estimate for these energy requirements. Additional cooking experiments were conducted to estimate the useful energy requirement for making rotis on a traditional mud chulha and preparing subji on a biogas stove, however, these data were not used, as the results reported in Sinha and Kandpal are considered to be more accurate. The useful energy requirement values used in the model are given in Table 6.4 below.

Food Cooked	Energy Required (kJ/kg)	Energy Required (Kcal/kg)
Subji	1315	313
Dal	3073	732
Tea (water)	576	137
Bathing water	576	137
Roti	3342	796
Simmering Milk	693	165
Cooking Fodder	1348	321

Note: 1 kcal = 4.2 kJ

Table 6.4 - Useful Cooking Energy Requirement for Different Foods

Sinha and Kandpal also offer a second method for determining the specified daily energy demand, using the normative value. The Advisory Board on Energy recommended, and the most often quoted, normative value in India is 520 kcal of useful thermal energy per person per day. The level of consumption, as indicated by the NCAER [67] domestic fuel survey is approximately 270 kcal of useful energy per person per day, based on 1979 data. Because the model deaggregrates the cooking tasks into specific fuel, stove, and task combinations, such a normative value could only be used if only one stove was to be used for all cooking tasks in the household.

The user of the model must specify the amount (kg) of each food item consumed by the household per day. This is done by defining the following seven variables:

amt1 = total subji / day
amt2 = total dal / day
amt3 = total tea / day
amt4 = total roti / day
amt5 = total bathing water heated / day
amt6 = total milk simmered / day
amt7 = total fodder cooked / day

Using the useful heat energy required to cook each food item (given in Table 6.4 above) the model calculates the actual cooking energy demands, given by the variables y_{d1} - y_{d7}. For the final demands used in the model simulation, the user must specify the allocation of cooking tasks for each stove. These stove allocation demands are assigned the following variables:

hara_dem = total kcals food cooked on hara chulha per day per household
biogas_dem = total kcals food cooked on biogas stove per day per household
tmc_ics_dem = total kcals food cooked on TMC / ICS per day per household
kero_dem = total kcals food cooked on kerosene stove per day per household
lpg_dem = total kcals food cooked on lpg stove per day per household

For example: if all cooking tasks are performed on the TMC then the total kcal demand would be tmc_ics_dem = d1 + d2 + d3 + d4 + d5 (and biogas_dem = 0, hara_dem = 0, kero_dem = 0, and lpg_dem = 0); or if a biogas stove is used for making subji, dal and tea, with a hara chulha used for simmering milk and cooking fodder, and a TMC used for making roti and heating bathing water; then the biogas_dem = d1 + d2 + d3, hara_dem = d6 + d7, and tmc_ics_dem = d4 + d5.

Finally, the demand for dung for manure fertiliser must be specified in kg:

manure_demand = quantity of dung needed for manure per day

6.2.2 The Agricultural Subsystem

The purpose of the agricultural subsystem is to model the crop production of a household's agricultural land. The cultivation of three different crops is modelled: mustard, wheat, and guar, and the crop production may be investigated from three different points of view. In the first case the user specifies the amount, in kg, of desired crop and crop residue yield. For example, a user may wish to model a situation where the farmer knows he can sell mustard crop at Rs 10 per kg and to meet his expenses for the coming year he needs Rs 10 000, thus he needs a crop yield of 1000 kg. The model is run with this demand specified and the model will calculate the field size in hectares which needs to be planted and the inputs in terms of seed, water and fertiliser which needs to be purchased. In the second case, the user specifies the amounts of inputs which are available to the farmer. For example, a farmer may know that he can purchase x kg of mustard seed, y kg fertiliser, and has a pumping capacity for z m^3 of water. Given these inputs the model then calculates the field size which can be planted and the resulting crop and crop residue yield. Finally, in the third case, the desired field size for a particular crop is specified, e.g. if a farmer wants to plant 3 acres wheat, 4 acres mustard, and 2 acres guar, and the model calculates the amount of inputs which need to be purchased (kg of seed, kg of fertiliser, and m^3 of water which must be available) and the crop yield (kg of crop and kg of crop residue).

A second feature of the subsystem model is the 'decision web' which allows the user to specify preferences for either how the crop and the crop residue should be allocated if the inputs are specified, or where the demands are specified, to more specifically describe the demands in terms of end uses. The decisions are specified in terms of percentage weightings (splitter decision processes). For example, the crop can be divided between being sold or saved for consumption by the household, and this decision is input into the model by specifying the decision parameters as 50% ($w_1 = 0.5$) of the crop output allocated for sale and 50% ($w_2 = 0.5$) of the crop to be saved for household consumption. The crop residue is divided first as fodder or non-fodder crop residue. The non-fodder crop residue is subdivided between non-fodder crop residue to be used as fuel and non-fodder crop residue to be used as building material. The fodder crop residue is further divided into fresh Vs dry fodder. The fresh fodder is then divided into fresh fodder for sale or fresh fodder for feeding the household's animals. The dry fodder is divided between dry fodder for sale, dry fodder to be used for cooked fodder for feeding the household's animals and dry fodder to be directly used as animal feed.

For computational ease, the components of the agricultural subsystem are divided into two sections - the '2 Process' section and the Decision Web, illustrated in Figures 6.20 and 6.21 respectively. The '2-Process' section contains two material transformation components:

1. Field
2. Crop

The Decision Web consists of six splitter decision process components:

3. Division of crop
4. Division of crop residue between fodder and non-fodder
5. Division of non-fodder crop residue between fuel and building material
6. Division of fodder between fresh and dry fodder

7. Division of fresh fodder between sale and animal feed
8. Division of dry fodder between sale, cooked fodder, and dry animal feed

A description of the component parameters, variables, and equations is given in Table 6.5 below. The components are defined in general terms - for each crop grown by the household a separate subsystem may be described, where the structure in terms of the components does not change, rather the parameters which specify the system change for each crop.

In addition to the three cases which may be investigated as described above, six different fertiliser scenarios may be investigated and the user must select one of the six. These scenarios define the set of parameters to be used for the three fertiliser inputs to the field - commercial fertiliser, dung, or slurry. The six cases are:

100% Slurry
100% Dung
100% Commercial Fertiliser
50% Slurry / 50% Dung
50% Slurry / 50% Commercial Fertiliser
50% Dung / 50% Commercial Fertiliser

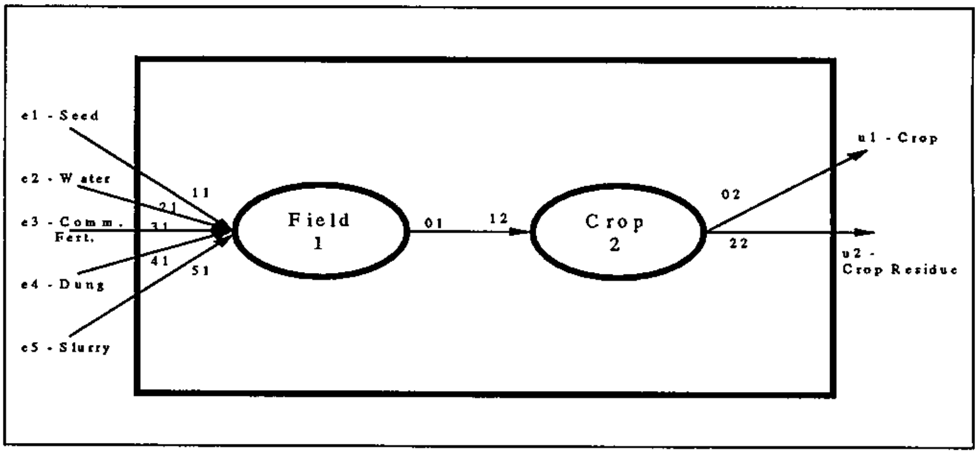


Figure 6.20 - Agricultural Subsystem - 2-Process Section

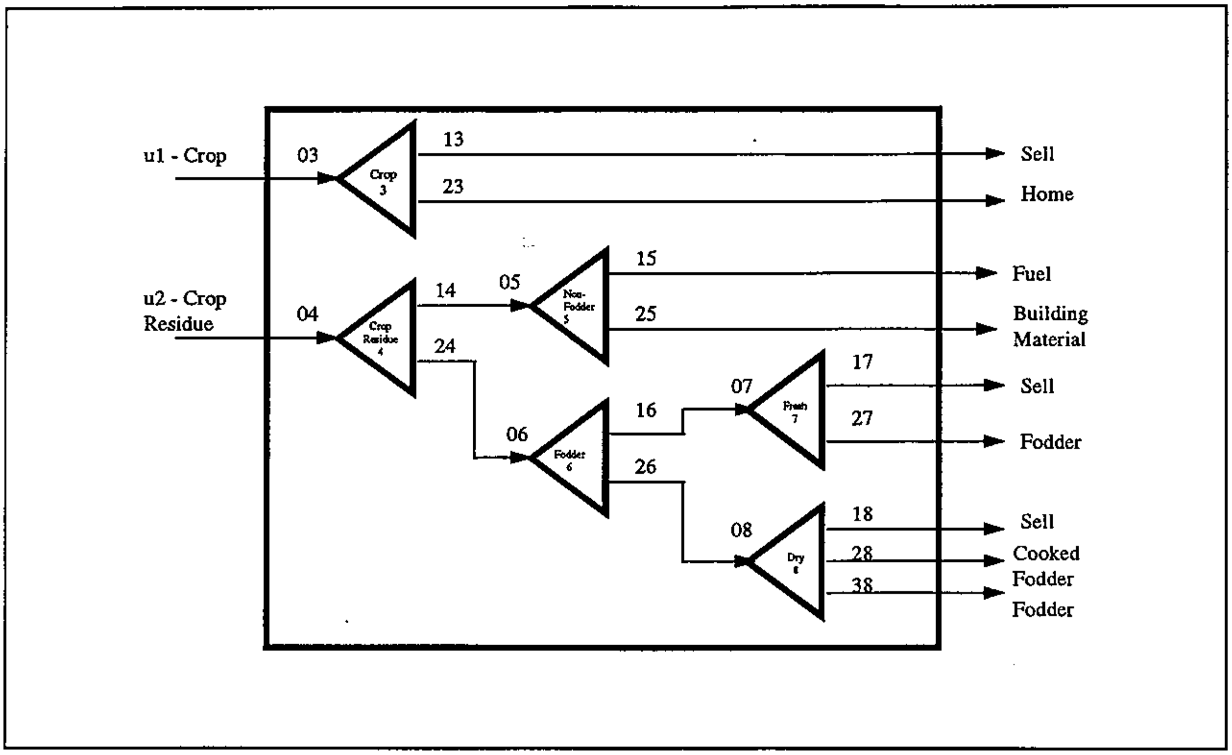


Figure 6.21 - Agricultural Subsystem - Decision Web

1. Field

The inputs to the field process are seed, water, commercial fertiliser, dung, and slurry and the output is hectares of planted field. The k parameter values define the amount of each input (kg or m^3) required to plant one hectare of crop.

2. Crop

The crop process is modelled using a 2-demand-driver component. The input to the crop process is ha of field planted, the primary output is kg of crop harvested, and the secondary output is kg of crop residue. Similar to the 'Buffalo' component, the primary output (which determines the expression of the k parameters) is somewhat convoluted, in that generally one would think of the ha of field to be the principle output and then the parameters expressed as kg of crop and kg of crop residue per ha. Because crop is the primary output, however, the k parameters are expressed as ha of field or kg of crop residue to required to produce (or produced with) one kg of crop.

3. Division of Crop

Of the total crop harvested, the decision must be taken as to how much should be sold and how much should be saved and consumed by the household.

4. Division of Crop Residues

The total crop residues must be divided into Fodder and Non-Fodder crop residues.

5. Division of Non-Fodder Crop Residues

The total non-fodder crop residues must be divided into a fraction used as fuel and a fraction used as building material.

6. Division of Fodder Crop Residues

The total fodder crop residues must be divided into fresh fodder and dry fodder.

7. Division of Fresh Fodder

The fresh fodder must be divided into a fraction which is sold and a fraction which is used as feed for the household animals.

8. Division of Dry Fodder

The dry fodder must be divided into a fraction sold, a fraction used as cooked fodder (animal feed), and a fraction used as dry fodder (animal feed).

Environmental Resources

There are five Environmental resources input into the 2- Process Section of the Agricultural model with the following associated costs:

y_{e1} - kg seed	x_{e1} - Rs/ kg of seed
y_{e2} - m^3 water	x_{e2} - Rs/m^3 of water
y_{e3} - kg commercial fertiliser	x_{e3} - Rs/ kg of commercial fertiliser
y_{e4} - kg dung	x_{e4} - Rs/kg of dung
y_{e5} - kg slurry	x_{e5} - Rs/kg of slurry

Additionally, because the crop and crop residue actually represent two specified demands driving the crop process (where normally only the primary output is associated or driven by a specified demand) an environmental slack variable must be introduced to account for any differences in the specified demands for crop and crop residue; i.e. the crop component is a 2-demand-driver component as opposed to a generic material transformation component. The slack will be identically zero in Case 2 and 3, since in these cases the demand is unknown. In Case 1, however, the environmental slack variable may have a value if , for example, the demand for crop residue is greater than the crop residue produced to meet the demand for the crop. The cost of the environmental slack is always specified as zero.

y_{eos1} - environmental slack - surplus / deficit crop residue
x_{eos1} - cost of 1 unit of environmental slack (Rs 0.00)

The two environmental resources input into the Decision Web are the outputs of the 2-Process section:

y_{eu1} - kg crop	x_{eu1} - Rs/ kg crop
y_{eu2} - kg crop residue	x_{eu2} - Rs/kg crop residue

Demands

The demands or outputs of the 2-Process section become the inputs to the Decision Web section. Depending on the Case being investigated, these demands will be specified / known (Case 1) or unknown and calculated (Case 2 and 3). The two demands and Decision Web demands or outputs are:

y_{u1} - kg crop	x_{u1} - Rs/ kg crop
y_{u2} - kg crop residue	x_{u2} - Rs/kg crop residue
y_{d1} - kg crop for sale	x_{d1} - Rs to produce crop for sale
y_{d2} - kg crop for household use	x_{d2} - Rs to produce crop for household use
y_{d3} - kg non-fodder crop residue for fuel	x_{d3} - Rs to produce non-fodder crop residue for fuel
y_{d4} - kg nfcr for building material	x_{d4} - Rs to produce nfcr for building material
y_{d5} - kg fresh fodder crop residue for sale	x_{d5} - Rs to produce fresh fodder crop residue for sale
y_{d6} - kg fresh fodder for animal feed	x_{d6} - Rs to produce fresh fodder for animal feed
y_{d7} - kg dry fodder for sale	x_{d7}- Rs to produce dry fodder for sale
y_{d8} - kg dry fodder for cooked fodder	x_{d8} - Rs to produce dry fodder for cooked fodder
y_{d9} - kg dry fodder for animal feed	x_{d9} - Rs to produce dry fodder for animal feed

Component	Parameter	Y-Variables	X-Variables	Y-Process Equation	X-Process Equation
1. Field	k_{11} - kg seed/ha k_{21} - m^3 water/ha k_{31} -kgcom. fert/ha k_{41} - kg dung/ha k_{51} - kg slurry/ha	y_{11} - kg seed y_{21} - m^3 water y_{31} - kgcom. fert. y_{41} - kg dung y_{51} - kg slurry y_{01} - ha field	x_{11}- Rs/kg seed x_{21}- Rs/m^3 water x_{31}-Rs/kgcom. fert. x_{41}Rs/kg dung x_{51}- Rs/kg slurry x_{01}- Rs/total field	$y_{11} = k_{11} * y_{01}$ $y_{21} = k_{21} * y_{01}$ $y_{31} = k_{31} * y_{01}$ $y_{41} = k_{41} * y_{01}$ $y_{51} = k_{51} * y_{01}$	$x_{01} = -k_{11}x_{11} - k_{21}x_{21} - k_{31}x_{31} - k_{41}x_{41} - k_{51}x_{51} - f_1(y_{01})$
2. Crop	k_{12} - ha field req'd to be planted to yield 1 kg crop k_{22}- kg cr/kg crop	y_{12} - ha field y_{22}- kg crop residue y_{02} - kg crop	x_{12} - Rs/ha field x_{22} - Rs/kg crop residue x_{02} - Rs/total crop	$y_{12} = k_{12} * y_{02}$ $y_{22} = k_{22} * y_{02}$	$x_{02} = -k_{12}x_{12} - k_{22}x_{22} - f_2(y_{02})$
3. Decision to Divide Crop	w_{13} - % of crop allocated for sale w_{23} - % of crop allocated for household consumption	y_{13}- kg crop for sale y_{23} - kg crop for household y_{03}- kg crop	x_{c3} - Rs to produce crop x_{03} - Rs to produce total crop	$y_{13} = w_{13} * y_{03}$ $y_{23} = w_{23} * y_{03}$	$x_{03} = x_{c3}$
4. Decision to Divide Crop Residue	w_{14} - % non-fodder crop residue w_{24}- % fodder crop residue	y_{14} - kg non-fodder crop residue y_{24} - kg fodder crop residue y_{04} - kg cr	x_{c4} - Rs / to produce crop residue x_{04} - Rs / to produce cr	$y_{14} = w_{14} * y_{04}$ $y_{24} = w_{24} * y_{04}$	$x_{04} = x_{c4}$
5. Decision to Divide Non-Fodder Crop	w_{15} - % of non-fodder crop residue allocated for fuel w_{25} - % of nfcr allocated as building material	y_{15} - kg crop for fuel y_{25} - kg crop for building material y_{05}- kg crop	x_{c5} - Rs to produce non-fodder crop residue x_{05} - Rs to produce non-fodder crop residue	$y_{15} = w_{15} * y_{05}$ $y_{25} = w_{25} * y_{05}$	$x_{05} = x_{c5}$
6. Decision to Divide Fodder Crop	w_{16} - % fodder crop residue allocated as fresh fodder w_{26} - % fodder crop residue allocated as dry fodder	y_{16} - kg fresh fodder y_{26} - kg dry fodder y_{06}- kg fodder	x_{c6} - Rs to producefodder crop residue x_{06} - Rs to produce fodder crop residue	$y_{16} = w_{16} * y_{06}$ $y_{26} = w_{26} * y_{06}$	$x_{06} = x_{c6}$
7. Decision to Divide Fresh Fodder	w_{17} - % fresh foddercrop residue allocated for sale w_{27} - % fresh fodder crop residue allocated as animal feed	y_{17} - kg fresh fodder sold y_{27} - kg fresh fodder for animal feed y_{07} - kg fresh fodder	x_{c7} - Rs to produce fresh fodder crop residue x_{07} - Rs to produce total fresh fodder crop residue	$y_{17} = w_{17} * y_{07}$ $y_{27} = w_{27} * y_{07}$	$x_{07} = x_{c7}$
8. Decision to Divide Dry Fodder	w_{18} - % dfcr allocated for sale w_{28} - % dfcr allocated as cooked fodder w_{38} - % dfcr allocated as dry animal fodder	y_{18} - kg dry fodder for sale y_{28} - kg dry fodder to be used in cooked fodder y_{38} - kg dry fodder for animal feed y_{08} - kg dry fodder	x_{c8} - Rs to produce dry fodder crop residue x_{08} - Rs to produce dry fodder crop residue	$y_{18} = w_{18} * y_{08}$ $y_{28} = w_{28} * y_{08}$ $y_{38} = w_{38} * y_{08}$	$x_{07} = x_{c7}$

Table 6.5 - Agricultural Subsystem Parameters, Variables and Equations

Parameter Specification for the Agricultural Subsystem

In northern India there are three distinct agricultural seasons:

Kharif - the rainy season from mid-June - October
Rabi - the cold season from November - February
Fallow / No Cultivation - the hot season from March - mid-June

In the Dhanawas region of Haryana the three predominant Rabi crops are Mustard, Wheat, and Barley while the three predominant Kharif crops are Guar (Cluster Bean), Bajra (Brushed, Spiked or Pearl Millet), and Jowar (Sorghum {great millet sorghum}). The crop seed parameter data are taken from typical quantities of seed planted per acre in this region and the cost per kg of seed as given in Table 6.6 below.

Crop	Quantity of Seed (kg / acres)	Average Quantity of Seed (kg / ha)	Cost (Rs / Kg)
Mustard	4 - 5	11.115	12
Wheat	40 - 50	111.15	4.20
Guar	8 - 10	22.23	10
Bajra	4 - 5	11.115	8
Jowar	20 - 25	55.6	8

[Reference: Pers. Comm. S.N. Srinivas]

Table 6.6 - Crop Input Requirements

The irrigation data are based on average estimates for Dhanawas. Typically, a farmer in this region will irrigate his crop six times per growing season, at a rate of eight hours per irrigation session per acre. A typical 5 hp pump will deliver 14 litres of water per second or 50 400 l/hr, or 50.4 m^3/hr. For each 8 hour irrigation session then, 8 * 50.4 = 400 m^3 / acre / irrigation session or 988 m^3 / ha / irrigation session of water is used. Consequently over the six irrigation sessions per crop 6 * 988 m^3 / ha = 5928 m^3 / ha / crop of water is required [reference: personal communication with S.N. Srinivas]. The farmers are charged a flat rate of Rs 50 / hp / year for water. Thus for a farmer with a 5 hp irrigation pump, the annual water charges would be Rs 250.

The agricultural data used in the model for the slurry, dung, and commercial fertilisers and the crop and crop residue yields are taken from a series of experiments conducted in Dhanawas by Teri from June 1989 to July 1991 and reported in Sharma [86]. The experiments were conducted to determine the relative fertility of digested slurry as compared to non-digested manure. More specifically, the three experiment objectives were to:

1. Determine the effect of biogas slurry on crop yield
2. Determine the effect of biogas slurry on soil fertility and productivity
3. Determine the relative advantage of biogas slurry in comparison to compost and chemical fertiliser yields.

The experiments were conducted on three acres of land with three different crops from June 1989 to July 1990 and then from July 1990 to July 1991 on two acres. Thirteen different treatment combinations of slurry, compost and fertiliser were applied to the land, as detailed in Table 6.7 below.

Treatment #	Composition of Treatment
1	0 (no treatment)
2	50 s
3	100 s
4	150 s
5	50 c
6	100 c
7	150 c
8	50 f
9	100 f
10	150 f
11	s + f
12	f + c
13	s + c

Note: s = biogas slurry - 100 % slurry is 112 kg of slurry
c = compost - 100 % compost is 144 kg of compost
f = fertiliser - 100 fertiliser is 1.5 kg of IFFY NPK with a ration of 12:36:16.

Table 6.7 - Fertiliser Treatments

The fertiliser parameters used in the model for one ha of field were then based on this data, as given in Table 6.8 below.

Fertiliser Combination	Quantity (kg) / ha
slurry	112 kg/100m^2 = 11 200 kg/ha
dung (compost)	144 kg/100m^2 = 14 400 kg/ha
commercial fertiliser	1.5 kg/100m^2 = 1500 kg/ha
slurry + dung	5600 kg slurry & 7200 kg dung
slurry + commercial fertiliser	5600 kg slurry & 750 kg comm. fert.
dung + commercial fertiliser	7200 kg dung & 750 kg comm. fert.

Table 6.8 - Fertiliser Combinations

Each field area of 4000m^2 was divided into 40 100 m^2 plots and each treatment was replicated 3 times on the 39 plots. Due to complications described in the report, data were only available for crop yields planted in relatively good soil for: Wheat in Rabi 1990 and Rabi 1991; Mustard in Rabi 1990; and Guar in Kharif 1990. The total crop, grain, and straw/residue yields, and grain to residue/straw rations are given in Tables 6.9 - 6.13 below, where total = green moist crop; grain = after air drying; and straw/residue = after air drying.

	Wheat Rabi 1990			
Fertiliser Combination	**Total Crop Yield (Kg/100 m^2 area)**	**Grain**	**Straw**	**Straw:Grain Ratio**
100 s	99.3	48.8	50.5	1.03
100 C	95.1	46.8	48.3	1.03
100 F	89.3	44.5	44.8	1.01
s + c	97.3	47.8	49.5	1.04
s + f	113.5	54.2	59.3	1.09
c + f	101.3	49.3	52.0	1.05

Table 6.9 - Wheat Yield Rabi 1990

Wheat Rabi 1991				
Fertiliser Combination	**Total Crop Yield (Kg/100 m^2 area)**	**Grain**	**Straw**	**Straw: Grain Ratio**
100 s	72.2	36.5	35.5	0.97
100 C	69.5	35.4	34.1	0.96
100 F	63.5	31.5	32.0	1.02
s + c	69.0	34.5	34.5	1.00
s + f	72.3	36.3	36.0	0.99
c + f	70.3	36.2	36.2	1.00

Table 6.10 - Wheat Yield Rabi 1990

Wheat Average Rabi 1990 & Rabi 1991				
Fertiliser Combination	**Total Crop Yield (Kg/100 m^2 area)**	**Grain**	**Straw**	**Straw: Grain Ratio**
100 s	85.8	42.7	43.0	1.01
100 C	82.3	41.1	41.2	1.00
100 F	76.4	38.0	38.4	1.01
s + c	83.2	41.2	42.0	1.02
s + f	92.9	45.3	47.7	1.05
c + f	85.8	42.8	44.1	1.03

Table 6.11 - Wheat Average Yield Rabi 1990 and Rabi 1991

Mustard Rabi 1990				
Fertiliser Combination	**Total Crop Yield (Kg/100 m^2 area)**	**Grain**	**Residue**	**Residue: Grain Ratio**
100 s	52.0	14.0	39.0	2.8
100 C	54.0	13.0	41.0	3.2
100 F	50.0	16.0	38.0	2.4
s + c	34.0	8.0	25.0	3.1
s + f	64.0	16.0	48.0	3.0
c + f	58.0	15.0	44.0	2.9

Table 6.12 - Mustard Yield Rabi 1990

Guar Kharif 1990				
Fertiliser Combination	**Total Crop Yield (Kg/100 m^2 area)**	**Grain**	**Residue**	**Residue: Grain Ratio**
100 s	69.0	11.0	27.0	2.5
100 C	64.0	10.0	31.0	3.1
100 F	53.0	8.0	28.0	3.5
s + c	68.0	10.0	32.0	3.2
s + f	66.0	8.0	27.0	3.4
c + f	63.0	9.0	29.0	3.2

Table 6.13 - Guar Yield Kharif 1990

For the crop component, the parameter values are based on the grain and residue yields per hectare. Specifically, where the grain yield is considered to be the primary output of the component, the parameter associated with the input (hectares of field planted) is given by 1 / grain yield (column 3 of tables) and the parameter associated with the secondary output (crop residue yield) is given by the Residue: Grain Ratio (column 4 of Tables 6.9 - 6.13).

6.3 Detailed Household Model Example

Prior to presenting an example of how the model can be used in a policy planning exercise; an example of the model results for one household is given to demonstrate the use of the mass-energy model for understanding the baseline household energy scenario and investigating intervention alternatives. The data used in this example are taken from the survey conducted in the 'typical' household in Dhanawas, described in Section 6.1.1. The purpose of this example is more specifically to demonstrate the potential of the model to answer different questions pertaining to the household energy system. In terms of the cooking subsystem the following questions will be investigated:

- What are the current (pre-intervention) resource use levels?
- What is the nature of the interactions among the system components?
- How does the adoption of an improved chulha affect the resource use levels?

- How does the adoption of biogas further affect these resource use levels?
- What other intervention options are illuminated by the model results?

and in terms of the agricultural subsystem the following two questions will be investigated:

- How can the model be used to gain an understanding of the baseline agricultural scenario?
- How does the model aid in clarifying the impact biogas adoption has on the household system?

6.3.1 Example Scenario Description

In this example three different household cooking scenarios and four different agricultural scenarios are created for comparison purposes. In the first cooking scenario, the baseline household model results are calculated. In the second an improved cooking stove is introduced into the household system, and in the third both an improved cooking stove and biogas plant are included. The first two agricultural scenarios complement or complete the household description simulated in the first and second cooking scenarios. Specifically, the farmer is using dung only as a fertiliser in the first agricultural scenario and dung and commercial fertiliser in the second. The third and fourth agricultural scenarios complete the household description simulated in cooking scenario three. In the third agricultural scenario the farmer uses only slurry from the biogas plant as fertiliser and in the fourth the farmer uses both slurry and commercial fertiliser.

Household Description

The family size is taken to be six adults. The farmer owns 7 acres of land and thus is considered to be a large farmer. The farmer also owns 3 buffaloes.

Cooking Scenario Data

The specific details of the fuel / stove / task combinations used for the example are given in Table 6.14 below.

Scenario #	Fuels	Stoves	Cooking Demands
1	dung cakes crop residues fuelwood kerosene	hara chulha tmc kerosene	hara_dem = simm. milk & cooking fodder tmc_ics_dem = subji, dal, tea, roti, water kero_dem = subji, dal, tea, roti
2	dung cakes crop residues fuelwood kerosene	hara chulha ics kerosene	hara_dem = simm. milk & cooking fodder tmc_ics_dem = subji, dal, tea, roti, water kero_dem = subji, dal, tea, roti
3	dung cakes crop residues fuelwood kerosene biogas	hara chulha ics kerosene biogas	hara_dem = simm. milk & cooking fodder tmc_ics_dem = roti, water kero_dem = subji, dal, tea, roti biogas_dem = subji, dal, tea

Table 6.14 - Example Cooking Data

As described above, the model simulates the resource consumption to meet the cooking demands for one day, and in order to estimate the total annual resource consumption for the household, model runs which illustrate typical seasonal "days" are combined to develop a yearly profile. In the baseline scenario #1, the family uses the traditional mud chulha: for making subji, dal, tea, and roti for eight months of the year; for making subji, dal, tea, roti and heating bathing water for three winter months of the year (December - February); and the kerosene stove for all five tasks for a period of one month total during the monsoon season. In the second scenario, the improved chulha is used in place of the traditional chulha. Whereas in the third scenario the biogas stove is used for making subji, dal, and tea, while the improved stove is continued to be used for making roti and heating bathing water. Even when the family has a biogas plant the kerosene stove will still be used during the monsoon season on days when the gas production is low due to inadequate feeding of the biogas plant (because of the rains the amount of dung actually collected is reduced).

Household Decisions

Dung Allocation - the three buffaloes owned by the household are tethered in the homestead area, consequently, 100% of the dung is assumed collected. Because of the predominance of crop residues available to the household, dung cakes are only used in the hara chulha. Consequently, the household allocates 10% of the daily dung production to making dung cakes and 90% to manure for the field.

Fuelwood Collection - The household does not choose to use a great deal of fuelwood because of the availability of crop residues. Any fuelwood needed is collected from sources on the household's own land.

Fuel For TMC / ICS - As explained above, the household chooses to use crop residues for the majority - 90% - of the cooking on the TMC/ICS and fuelwood for 10% of the cooking time.

Cooking Demands

The amount of each type of food cooked in a "typical" day for the family is based on estimates given by the study household. The quantities given represent the total amount of each food type cooked for both meals in the day. The total quantity of water heated for bathing is assuming that each family member uses 8 litres of hot water for a daily bath. In each scenario, the following cooking demand quantities are used:

subji - 2.5 kg per day
dal - 0.5 kg
tea - 2 kg (of water)
roti - 3 kg (of uncooked dough)
bathing water - 48 kg
simmering milk - 4 kg
cooked fodder - 3 kg

Manure Demands

The value for the demand for manure for fertiliser is chosen based on the manure requirement calculated in the agricultural subsystem model. In the first cooking scenario the demand is based on the maximum manure demand calculated from agricultural scenario # 1, where dung is the only fertiliser used. In the second cooking scenario, the manure demand is based on the minimum dung demand calculated from agricultural scenario # 2, where both dung and commercial fertiliser are used for fertiliser. In cooking scenario # 3 the manure demand for fertiliser is zero, as the farmer is using slurry and commercial fertiliser (agricultural scenarios # 3 and # 4) for fertilisers. The manure demand values are given below.

Scenario #	Manure Demand (per day)
1	128 kg
2	64 kg
3	0 kg

Costs

As described in the previous section, the only costs which are considered are the monetary costs. Because this typical household collects the majority of their resources "free" from the environment, only the unit (market) cost of kerosene and LPG for the Dhanawas area are considered.

Fuel	Market Price in Dhanawas
Kerosene	Rs 3.5 / l or Rs 4.025 / kg
LPG	Rs 120 / 14.5 kg or Rs 8.3 / kg

For comparison purposes, the Indian market and economic (without subsidy) prices of kerosene and LPG are given below.

Fuel	Market Price	Economic Price
Kerosene	Rs 3.135 / kg	Rs 6.465 / kg
LPG	Rs 5.742 / kg	Rs 9.813 / kg

Source: Table 3.6.1 p. 43 "Strategy for Rational Integrated Energy Pricing Policy". Teri Report No. 93EM62. Submitted to the Confederation of Indian Industry, May 1995.

Agricultural Scenario Data

As described in the previous section, three different cases may be investigated using the agricultural subsystem. In case I, the demands are specified, in case II the inputs are specified, and in case III the field size is specified. For demonstration purposes, the four scenarios considered in this example are case III examples. Table 6.15 below indicates the field size and fertiliser case used in each of the four scenarios. As discussed above, mustard and wheat are grown in the Rabi cropping season and guar in the Kharif season. The household owns a 5 hp irrigation pump.

Crop and Crop Residue Allocation Decisions

The household decides to sell 95% of the mustard crop for profit and keep 5% for consumption in the home; 100% of the mustard crop residue (mustard stalk) is allocated by the household for use as fuel. The household decides to sell 50% of the wheat crop yield for profit and keep 50% for consumption in the home. All of the crop residues are allocated to be used as dry fodder; with 35% sold for profit and 65% kept as dry fodder for the three buffaloes. For the guar crop, the household decides to sell 25% of the crop and keep 75% for consumption in the household. All of the guar crop residues are kept as dry fodder for the animals.

Scenario #	**Field Size**	**Fertilisers Used**
1	Mustard = 3 acres Wheat = 4 acres Guar = 1 acre	Dung
2	Mustard = 3 acres Wheat = 4 acres Guar = 1 acre	Dung + Commercial Fertiliser
3	Mustard = 3 acres Wheat = 4 acres Guar = 1 acre	Slurry
4	Mustard = 3 acres Wheat = 4 acres Guar = 1 acre	Slurry + Commercial Fertiliser

Table 6.15 - Agricultural Scenario Data

6.3.2 Cooking Subsystem Results

Cooking Scenario # 1 - Baseline Energy System

The daily and annual environmental resource requirements are given in Table 6.16 below.

Resource	**Run #1 - No Bathing Water Heating - Daily (per capita)**	**Run # 1 - Annual (8 months / 242 days)**	**Run #2 - Heating Bathing Water Daily (per capita)**	**Run # 2 - Annual (3 months / 92 days)**	**Run # 3 - Kerosene Only Daily (per capita)**	**Run # 3 - Annual (1 month / 31 days)**
FW - Own Land	0.9 (0.14)	205.7	2.3 (0.4)	212.5	0	0
Crop Residues	8.8 (1.5)	2127.2	23.97 (4)	2205.2	0	0
Dung Cakes	6.5 (1.1)	1563.3	6.5 (1.1)	594.3	0	0
Kerosene	0	0	0	0	0.9 (0.15)	28.7

Table 6.16 - Cooking Scenario # 1 - Results

The total annual resource use for the household is thus given in Table 6.17 below:

Resource	**Annual Quantity (kg)**	**Annual per capita (kg)**
Fuelwood	418.2	69.7
Crop Residues	4332.4	722.1
Dung Cakes	2157.6	359.6
Kerosene	28.7	4.8

Table 6.17 - Total Annual Resource Use - Scenario # 1

The costs incurred to meet the cooking demands are given in Table 6.18, these costs are identical for each of the three cooking scenarios, thus the results are only given once here.

Cooking Demand	Run # 1 Daily / Annual	Run # 2	Run #3
Hara Chulha	0/0	0/0	0/0
TMC	0/0	0/0	0/0
Kerosene Stove	0/0	0/0	Rs 0.001/0.365

Table 6.18 - Total Costs - Scenario # 1

To feed the household's buffaloes the following amounts of fodder and water are required, given in Table 6.19 below.

Resource	Daily Quantity (kg)	Annual Quantity (kg)
Cooked Fodder	3	1095
Fresh Fodder	90	38850
Dry Fodder	22.5	8212.5
Water (l)	105	38325

Table 6.19 - Scenario # 1 - Feed and Water Requirements for Buffaloes

Every day (assuming all three buffaloes are milching) 18 kg of milk is produced, the family uses 4 kg of milk for simmering and has 14 kg of milk left over for sale.

The manure demand for fertiliser was specified as 128 kg. The household allocates 54 kg of dung for manure, indicating a deficit of 74 kg per day. Additionally, the household has only allocated 6 kg of dung for dung cakes, but requires 6.5 kg to meet the hara chulha demands.

Cooking Scenario # 2 - Improved Chulha

The daily and annual environmental resource requirements are given in Table 6.20 below.

Resource	**Run #1 - No Bathing Water Heating - Daily (per capita)**	**Run # 1 - Annual (8 months / 242 days)**	**Run #2 - Heating Bathing Water Daily (per capita)**	**Run # 2 - Annual (3 months / 92 days)**	**Run # 3 - Kerosene Only Daily (per capita)**	**Run # 3 - Annual (1 month / 31 days)**
FW - Own Land	0.6 (0.1)	135.5	1.5 (0.3)	141.7	0	0
Crop Residues	5.9 (0.1)	1418.1	16 (2.7)	1472.2	0	0
Dung Cakes	6.5 (1.1)	1563.3	6.5 (1.1)	594.3	0	0
Kerosene	0	0	0	0	0.9 (0.15)	28.7

Table 6.20 - Cooking Scenario # 2 - Results

The total annual resource use for the household is thus given in Table 6.21 below:

Resource	**Annual Quantity (kg)**	**Annual per capita (kg)**
Fuelwood	277.2	46.2
Crop Residues	2890.3	481.7
Dung Cakes	2157.6	359.6
Kerosene	28.7	4.8

Table 6.21 - Total Annual Resource Use - Scenario # 2

In this scenario, the feed requirements for the animals are identical to those of scenario # 1. The demand for manure is only 64 kg. However, the household is still only allocating 54 kg of dung for manure and 6 kg for dung cakes. Thus, a deficit still exists both for dung for manure and dung for dung cakes of 10 kg and 0.5 kg respectively.

__Cooking Scenario # 3 - Biogas Plant and Improved Chulha__

The daily and annual environmental resource requirements are given in Table 6.22 below.

Resource	**Run #1 - No Bathing Water Heating - Daily (per capita)**	**Run # 1 - Annual (8 months / 242 days)**	**Run #2 - Heating Bathing Water Daily (per capita)**	**Run # 2 - Annual (3 months / 92 days)**	**Run # 3 - Kerosene Only Daily (per capita)**	**Run # 3 - Annual (1 month /31 days)**
FW- OwnLand	0.4 (0.1)	84.7	1.3 (0.2)	122.4	0	0
Crop Residues	3.7 (0.6)	888.1	13.8 (2.3)	1269.6	0	0
Dung Cakes	6.5 (1.1)	1563.3	6.5 (1.1)	594.3	0	0
Biogas	0.7m^3(0.1)	162.1	0.7m^3(0.1)	61.6	0	0
Kerosene	0	0	0	0	0.93 (0.15)	28.7

Table 6.22 - Cooking Scenario # 3 - Results

The total annual resource use for the household is thus given in Table 6.23 below:

Resource	**Annual Quantity (kg)**	**Annual per capita (kg)**
Fuelwood	207.1	34.5
Crop Residues	2157.7	359.6
Dung Cakes	2157.6	359.6
Biogas	223.7	37.3
Kerosene	28.7	4.8

Table 6.23 - Total Annual Resource Use - Scenario # 3

6.3.3 Agricultural Subsystem Results

For comparison and discussion purposes, the results from each of the four scenarios for each crop are presented together in the tables below. Table 6.24, 6.27, and 6.30 describe the inputs which must be purchased or available to the household in each of the four scenarios for Mustard, Wheat, and Guar respectively. Tables 6.25, 6.28, and 6.31 describe the total crop and crop residue yields for Mustard, Wheat and Guar respectively. Finally, Tables 6.26, 6.29, and 6.32 present the crop and crop residue allocations for each of the three crops respectively.

Input	Scenario # 1		Scenario # 2		Scenario # 3		Scenario # 4	
	Quantity (kg)	Cost (Rs)	Quantity (kg)	Cost (Rs)	Quantity (kg)	Cost (Rs)	Quantity (kg)	Cost (Rs)
Seed	13.5	135	13.5	135	13.5	135	13.5	135
Water		250[a]		250[a]		250[a]		250[a]
Com. Fert.	0	0	910.9	2277.3	0	0	910.9	2277.3
Dung	17489.9	0	8744.9	0	0	0	0	0
Slurry	0	0	0	0	13603.2	0	6801.6	0

a - Water purchased at a flat rate of Rs 5/hp/year. Farmer has a 5 hp pump, therefore charged a flat rate of Rs 250 per year.

Table 6.24 - Mustard Crop Inputs

Yield	Scenario # 1	Scenario # 2	Scenario # 3	Scenario # 4
	Quantity (kg)	Quantity (kg)	Quantity (kg)	Quantity (kg)
Total Crop	1578.9	1821.9	1700.4	1943.3
Total Crop Residue	5052.6	5283.4	4761.1	5830

Table 6.25 - Total Mustard Crop and Crop Residue Yields

Demand	Scenario # 1	Scenario # 2	Scenario # 3	Scenario # 4
	Quantity (kg)	Quantity (kg)	Quantity (kg)	Quantity (kg)
Crop for Sale	1500	1730.8	1615.4	1846.2
Crop for Home	78.9	91.1	85.0	97.2
Fuel	5052.6	5283.4	4761.1	5830
Building Material	0	0	0	0
Fresh Fodder-Sale	0	0	0	0
Fresh Fodder-Home	0	0	0	0
Dry Fodder-Sale	0	0	0	0
Dry Fodder-Cooked	0	0	0	0
Dry Fodder-Home	0	0	0	0

Table 6.26 - Mustard Crop and Crop Residue Distribution

Input	Scenario # 1		Scenario # 2		Scenario # 3		Scenario # 4	
	Quantity (kg)	Cost (Rs)	Quantity (kg)	Cost (Rs)	Quantity (kg)	Cost (Rs)	Quantity (kg)	Cost (Rs)
Seed	180	756	180	756	180	756	180	756
Water		250[a]		250[a]		250[a]		250[a]
Com. Fert.	0	0	1214.6	3036.4	0	0	1214.6	3036.4
Dung	23319.8	0	11659.9	0	0	0	0	0
Slurry	0	0	0	0	18137.7	0	9068.8	0.00

a - Water purchased at flat rate Rs 5/hp/year. Farmer has 5 hp pump, charged flat rate of Rs 250 per year.

Table 6.27 - Wheat Crop Inputs

Yield	Scenario # 1	Scenario # 2	Scenario # 3	Scenario # 4
	Quantity (kg)	Quantity (kg)	Quantity (kg)	Quantity (kg)
Total Crop	6655.9	6931.2	6915	7336.0
Total Crop Residue	6655.9	6931.2	6915	7336.0

Table 6.28 - Total Wheat Crop and Crop Residue Yields

Demand	Scenario # 1	Scenario # 2	Scenario # 3	Scenario # 4
	Quantity (kg)	Quantity (kg)	Quantity (kg)	Quantity (kg)
Crop for Sale	3327.9	3465.6	3457.5	3668.0
Crop for Home	3327.9	3465.6	3457.5	3668.0
Fuel	0	0	0	0
Building Material	0	0	0	0
Fresh Fodder-Sale	0	0	0	0
Fresh Fodder-Home	0	0	0	0
Dry Fodder-Sale	2329.6	2425.9	2420.2	2567.6
Dry Fodder-Cooked	0	0	0	0
Dry Fodder-Home	4326.3	4505.3	4494.7	4768.4

Table 6.29 - Wheat Crop and Crop Residue Distribution

Input	**Scenario # 1**		**Scenario # 2**		**Scenario # 3**		**Scenario # 4**	
	Quantity (kg)	**Cost (Rs)**	**Quantity (kg)**	**Cost (Rs)**	**Quantity (kg)**	**Cost (Rs)**	**Quantity (kg)**	**Cost (Rs)**
Seed	9	90	9	90	9	90	9	90
Water		250[a]		250[a]		250[a]		250[a]
Com. Fert.	0	0	303.6	759.1	0	0	303.6	759.1
Dung	5830	0	2915	0	0	0	0	0
Slurry	0	0	0	0	4534.4	0	2267.2	0.00

a - Water purchased at a flat rate of Rs 5/hp/year. Farmer has a 5 hp pump, therefore charged a flat rate of Rs 250 per year.

Table 6.30 - Guar Crop Inputs

Yield	**Scenario # 1**	**Scenario # 2**	**Scenario # 3**	**Scenario # 4**
	Quantity (kg)	**Quantity (kg)**	**Quantity (kg)**	**Quantity (kg)**
Total Crop	404.9	364.4	445.3	323.9
Total Crop Residue	1255.1	1166	1113.4	1101.2

Table 6.31 - Total Guar Crop and Crop Residue Yields

Demand	**Scenario # 1**	**Scenario # 2**	**Scenario # 3**	**Scenario # 4**
	Quantity (kg)	**Quantity (kg)**	**Quantity (kg)**	**Quantity (kg)**
Crop for Sale	101.2	91.1	111.3	81
Crop for Home	303.6	273.3	334.0	242.9
Fuel	0	0	0	0
Building Material	0	0	0	0
Fresh Fodder-Sale	0	0	0	0
Fresh Fodder-Home	0	0	0	0
Dry Fodder-Sale	0	0	0	0
Dry Fodder-Cooked	0	0	0	0
Dry Fodder-Home	1255.1	1166	1113.4	1101.2

Table 6.32 - Guar Crop and Crop Residue Distribution

6.3.4 Discussion of Example Results

The primary intent of this example is to provide a demonstration of the general methodology underlying the mass-energy model and to illustrate the potential utility of the model both for better understanding the nature of the rural domestic cooking energy system and for investigating alternative intervention options.

Data Limitations

The results obtained from the model are most useful for indicating relative system performance, as opposed to providing an absolute indication of resource use and energy consumption. The primary reasons for this are due to both the poor availability of data in general for the rural energy sector and inaccuracies in the data which is accessible. Collecting extensive rural sector data is inhibited due to the cost of data collection. When the data is collected it is difficult to accurately assess resource use; many rural people have a very limited concept of conventional units of measurement and resource use may be under or over estimated by the rural people, depending on the response which they believe the interviewer 'expects' to hear. Possible inaccuracies in the values used for the useful energy requirement to cook different food items were elaborated in section 6.2.1.

Domestic Cooking Energy Subsystem

Scenario # 1 - Baseline Energy System

The first case investigated for the domestic cooking energy system defines the baseline energy scenario for the household prior to undertaking any intervention initiatives. Careful examination of the component interactions in this baseline scenario helps to illustrate the underlying nature of the system. In Table 6.16, the results for the three runs of the model are given; the daily household and per capita resource consumption levels are indicated in addition to the contribution of each to the annual resource demand. Table 6.17 indicates the total annual household and per capita consumption of fuelwood, crop residues, dung cakes, and kerosene. Given the cooking energy demands, the household is using 418 kg of fuelwood, 4332 kg of crop residues, 2158 kg of dung cakes, and 29 kg of kerosene. Of significance is the increase in fuelwood and crop residue consumption during the winter months for water heating; 2.7 times as much fuelwood and crop residues are used. If the household also required space heating during the winter months (most predominant in the rural areas in northern India, particularly in the Himalayas) then fuelwood consumption would increase even further during this time.

In order to assess the relative accuracy of these results, consumption information collected for the village of Dhanawas by Teri in a comprehensive 1987 village survey is given in Table 6.33 below. Limitations of these survey results are discussed in detail in Puri [76].

Farmer Class	Fuelwood (Logs) Per Capita (kg month/day)	Fuelwood (Twigs) Per Capita (kg month/day)	Crop Residues Per Capita (kg month/day)	Dung Cakes Per Capita (kg month/day)	Kerosene per hh/month (per capita/ month) (kg)
Big	0.17 (0.01)	3.45 (0.11)	35.2 (1.13)	104.6 (3.4)	0.23 (0.03)
Medium	-	-	28.8 (0.93)	131.6 (4.2)	1.4 (0.17)
Small	3.24 (0.10)	8.9 (0.29)	29.03 (0.94)	87.9 (2.8)	0.09 (0.01)
Marginal	-	4.08 (0.13)	28.7 (0.93)	76.1 (2.5)	0.12 (0.02)
Landless	1.45 (0.05)	19.1(0.62)	21.2 (0.68)	73.3 (2.4)	1.02 (0.17)
All	1.04 (0.03)	9.1 (0.3)	27.7 (0.89)	90.1 (2.9)	0.61 (0.09)

Note: big - >10 acres, medium - 5-10 acres, small 2.5-5 acres, marginal 0-2.5 acres.

Table 6.33 - Dhanawas Resource Consumption Data

The survey data for Dhanawas are given as annual monthly averages and no seasonal information is included. The average daily per capita fuel consumption (calculated from the annual per capita in Table 6.17) for the study household is 0.19 kg/capita of fuelwood, 1.98 kg/capita of crop residues, 0.99 kg/capita of dung cake, and 0.013 kg/capita of kerosene. According to the survey farmer classification, the study household is of the medium land holding class. Comparing the example results to the Dhanawas survey data we see that the study household is using more fuelwood and crop residues and less dung cakes than the average medium farmer in Dhanawas. The reason for this difference would be due to the decision allocation for the three biomass fuels for the traditional mud chulha. For this example, no dung cakes were allocated for use in the traditional mud chulha, fuelwood was used 10% of the time and crop residues 90%. In general, fuelwood resources in Dhanawas are scarce. The study household, however, has access to limited fuelwood resources on their own property, which would account for the increased fuelwood consumption in comparison to the Dhanawas medium farmer average. The fuelwood consumption does, however, lie well within the range of averages given for all land holding classes in the village.

The greatest discrepancy between the Dhanawas survey data and the example results lie in the annual consumption of kerosene. According to the model, the household would consume 28.8 kg of kerosene per year, if the kerosene stove is used for all cooking tasks for 31 days of the year. According to the Dhanawas survey data, a household of the medium land owing class consumes on average 16.8 kg of kerosene a year for cooking with an overall village average (across all land holding classes) of 7.3 kg/year. Unfortunately, the standard deviation for this data is not given in the report. In the survey conducted for the collection of data for this example, the household indicated that they use between 10-15 l or 8.3 - 12.5 kg of kerosene a year. Using the daily per capita consumption level calculated by the model for the baseline scenario (0.93 kg/hh/day), this translates into 9 to 14 days of kerosene use per year. Consequently, the conclusion which may be drawn with respect to the model results is that 31 days per annum of kerosene use is a high estimate and the actual use is more likely to be for only 15 days. Of course, this would also depend on the weather conditions for a given year, as kerosene is used as a replacement fuel for cooking (in the absence of a biogas plant) when the traditional sources are too wet to effectively burn.

The daily and annual feed and water requirements for the household's three buffaloes are given in Table 6.19. Assuming all three buffaloes are milching, 18 kg of milk are produced daily, with the family consuming 4 kg of milk and 14 kg are available for sale. This surplus of milk indicates a possible income generating opportunity for the household. The logistics of which a planner may want to investigate with members of the household. The three buffaloes also produce 60 kg of dung per day.

The allocation of dung illustrates the utility of the slack variables for better understanding how preferences affect the system function and for identifying points of stress or unsustainable levels of resource consumption. The household has decided to allocate 90% of the dung for manure and 10% for making dung cakes. The slack variable associated with the quantity of dung allocated for manure indicates that a deficit of 74 kg exists. That is, the difference between the manure demand calculated in the agricultural subsystem scenario #1 and the quantity of dung allocated to manure is 74 kg. The household has decided to allocate 10% or 6 kg of the daily dung total for making dung cakes. The slack variable associated with this quantity of dung indicates a 0.5 kg deficit or 6.5 kg of dung are needed to meet the cooking requirements on the hara chulha (the only stove in which dung cakes are used in this scenario). The two slack variables indicate that while the household is essentially allocating a sufficient quantity of dung for making dung cakes, not enough dung is produced daily to meet the manure demand. Consequently, the household must choose to either accept a lower crop yield due to the decrease in fertiliser, or supplement the organic manure with inorganic commercial fertilisers (as discussed in greater detail in the agricultural subsystem results.)

The quantity of each of the three renewable biomass resources required annually may be compared to the sustainable supplies available to the household. The stress on a biomass resource may be computed as:

$$\text{Stress} = \frac{\text{Total biomass consumption}}{\text{Sustainable biomass supply}} \qquad [6.1]$$

A stress value of unity would indicate that biomass consumption is equal to the sustainable supply; a value greater than unity would indicate that the biomass resource is being consumed at an unsustainable rate [48]. The stress on the biomass supply may also be analysed in qualitative terms [48] by assessing the relationship between the most preferred biomass fuel species and those actually being burnt, the canopy density, and the type of biomass being used for fuelwood. In regions with acute fuelwood scarcities, households would have already consumed to essential extinction the preferred fuelwood species and now instead either be using lower grade fuel species or those preferred for fodder or timber. The level of deforestation and denudification of the landscape would also provide a qualitative indication of the stress on the biomass resource base. Finally, in areas with historically significant forest cover, the switch to dung cakes or other woody biomass resources e.g. shrubs would indicate considerable biomass stress.

The stress on cow dung production is incorporated into the model via the slack variables associated with the divide dung splitter component, as described above. The stress on the agricultural crop residues appears in two different aspects of the model, the demand for crop residue for cooking and the demand for fodder for the buffaloes. Currently, this stress factor must be calculated manually. The quantity of crop residues produced in the agricultural subsystem is given both as an aggregate annual total and disaggregated based on the allocation preferences of the household. To compute the stress factor on the crop residue supply for fuel the total annual demand for crop residues as fuel is equated against the total annual quantity of crop residues allocated by the household for fuel (in the agricultural subsystem). For example, in the case of the baseline scenario for our study household, 4332 kg of crop residues are required to meet the annual cooking demand with the specified fuel allocation preferences. Of the three crops considered in the agricultural subsystem in scenario # 1, only 100% of the mustard crop residues were allocated for use as fuel. The total quantity of mustard crop residue produced in scenario # 1 was 5053 kg, indicating a *surplus* of 721 kg of mustard crop residue. The surplus of crop residues, and hence their abundant and easy availability, helps to understand the preference of the household women for cooking with crop residues, despite the smoke they generate while burning. Any alternative fuel must be able to compete with crop residues in terms of availability.

To compute the stress factor on the crop residue supply for dry fodder, the difference between the quantity of dry fodder required annually to feed the household's animals and the total quantity of crops and crop residues allocated for dry fodder in the agricultural subsystem is taken. In this example, the 8213 kg of dry fodder must be available annually to feed the three buffaloes and 65% or 4326 kg of the wheat crop residues and 100% or 1255 kg of the guar crop residues, equalling a total of 5581 kg, are allocated by the household for dry fodder use. This would indicate that a *deficit* of 2632 kg exists and the household must either purchase the additional dry fodder or allocate the dry fodder resources differently. Specifically, the household has decided to sell 35% of the wheat dry fodder instead of using it for fuel and this decision may have to be altered. As indicated earlier,guar is just one of several fodder crops usually grown; in reality the household may grow other fodder crops during the Kharif season. These would supplement the dry fodder supply base, however, both for simplicity and due to data limitations only guar is included in the model at this time.

Similarly, the stress on the fresh and cooked fodder resources may calculated by equating the annual requirements for fresh and cooked fodder to feed the household's animals against the crop and crop residues allocated for fresh and cooked fodder consumption in the agricultural subsystem

In order to calculate the stress on the fuelwood biomass the sustainable supply from all possible sources available to the household must be calculated. The stress factor for each source could then be assessed using the fuelwood resource demands found by the model. A method for the calculation of sustainable yield is given in Joshi et. al. [48]. The technique, however, requires time consuming measurements of both tree basal area and crop height. This information was not available for Dhanawas. Consequently, for the fuelwood use by the household, the stress on the biomass supply can only be analysed from a qualitative point of view. The 1987 survey in Dhanawas indicated that fuelwood scarcity was already a significant problem at that time, as evidenced by the relatively low consumption of fuelwood as compared to crop residues and dung cakes. The consumption of fuelwood by the example household mirrors this general lack of fuelwood resources. The quantitative calculation of the stress on the household fuelwood supply could easily be incorporated into the model were the data for assessing the sustainable yield available. These sustainable yield values would be set as fixed environmental resource inputs to the 'decision to collect fuelwood' joiner decision component. Any difference between the quantity of fuelwood required to meet the cooking demands and the sustainable yield would be registered by the slack variables associated with the joiner edge. A zero slack variable would indicate that sustainable supply and demand are in equilibrium, whereas a negative value would indicate that the environmental resource is being used in an unsustainable manner.

The reliance of the household on low grade biomass resources (crop residues and dung cakes), in conjunction with the scarcity of fuelwood would indicate the potential for alternative energy interventions. To assess the potential of two such technologies to positively impact on the household resource use two different scenarios were created. In the first the traditional mud chulha is replaced with an improved chulha and in the second a both a biogas plant and an ICS are adopted by the household.

Scenario # 2 - Improved Chulha

In the results for this second scenario we see the positive impact an improved chulha has on the resource consumption of the household. Table 6.21 gives the annual total and per capita requirement for fuelwood, crop residues and dung cakes, given the same cooking demands as in scenario # 1. Compared to scenario # 1, 23.5 (1.1 x 10^5 kcal) fewer kg of fuelwood and 240.4 (9.4 x 10^5 kcal) fewer kg of crop residues are consumed when the improved chulha is adopted by the household. Because the dung cakes are only used in the hara chulha in this example, the quantity of dung required for cooking by the household remains the same across the two scenarios. Also, the kerosene demand does not change. The feed and water requirements for the buffaloes also does not change, however, if the minimum dung for manure demand is used (calculated in agricultural scenario #2), the deficit of dung is reduced to 10.46 kg.

Scenario # 3 - Improved Chulha and Biogas Plant

The results for the third scenario indicate the additional positive impact the adoption of a biogas plant has on the household resource consumption. In this scenario, the biogas plant is used for making subji, dal, and tea, the improved chulha for making roti and water heating, and the hara chulha for simmering milk and cooking fodder. The kerosene stove is still used for a total of one month during the monsoon season. From Table 6.23 we see that with this stove and task allocation the consumption of fuelwood and crop residues have further decreased by 11.7 kg (5.5 x10^4 kcals) and 122.1 kg (4.8 x10^5 kcals) respectively. The savings in fuelwood and crop residue, compared to scenario # 1 are 35.2 kg and 362.5

kg respectively, or a 50% reduction in the amount of both fuelwood and crop residues used by the household.

The model calculates the household biogas consumption at 0.7 m^3 / day. This result compares very favourably to the daily gas consumption value estimated by the household in the survey. A properly functioning biogas stove consumes between 200 - 450 l of biogas per hour of operation [55]. The household stated that they use the biogas stove for 3 hours a day (1 hour of cooking three times a day), which translates into 600 - 1350 l/day or 0.6 - 1.35 m^3 per day. The capacity of the household's biogas plant is 2m^3. This means that, under ideal operating conditions, 2m^3 of biogas are produced each day. The household may in fact be using additional biogas to fuel a biogas lamp, or excess gas may bubble out of the digester via the inlet and outlet openings. If the household is not using biogas for lighting and excess gas is being wasted, then this would indicate that the household is inefficiently using their biogas stove. Accordingly, additional training or information may be required for the women of the household to improve her efficiency of use of the technology; for example, teaching her how to make rotis on the biogas stove instead of on the TMC/ICS. Currently, resource consumption to meet household lighting needs is not included in the model. If the household is using biogas for lighting, then they may indeed be consuming the full 2m^3 of biogas per day. A gas lamp (equivalent to a 60W bulb) consumes 120-150 l/hr or 0.12 - 0.15 m^3/hr. The example household would then have 2-0.67 = 1.33m^3 or sufficient biogas for nine hours of lighting.

The results of the agricultural subsystem scenarios # 3 and 4 indicate that a maximum of 99 kg and a minimum of 50 kg of slurry would be required to meet the household's fertiliser needs, if the acreage for all three crops are fertilised (these results are discussed in more detail in the next section). The model indicates that 16.8 kg of slurry are produced each day, or 6132 kg/year. Because of the structure of the mass-energy material transformation components, the slurry production is calculated based on the demand for biogas as opposed to the supply of dung and water. If the biogas plant is operating under ideal conditions, 50 kg of slurry would be produced daily. This quantity would be sufficient to meet the minimum slurry fertiliser demand of scenario #4.

Therefore, the results of the cooking subsystem model, under the three scenarios, indicate that the adoption of an ICS and a biogas plant will have a very positive impact on the resource use levels in the household. The results from the three scenarios also illuminate another possible area for appropriate technology intervention. In each scenario, a constant quantity of dung was allocated for making dung cakes for the hara chulha, 359.6 kg annually. This indicates two things; first that the household has a significant preference for performing the allocated tasks on the hara chulha (simmering milk and cooking fodder), and second that since these tasks are performed daily a genuine opportunity may exist for a renewable energy technology. A policy planner should interpret this result as an opportunity for action.

Agricultural Subsystem

At the beginning of this example an explicit decision has been taken by the farmer; in using the case III simulation situation, the number of acres under each crop is specified. The crops grown in Rabi are generally grown for profit, whereas the Kharif crops are predominantly fodder crops [59]. In the Rabi season, the decision to put greater acreage under mustard or wheat depends largely on the prevailing weather conditions. Mustard is more hearty than wheat in terms of its ability to survive in drought conditions and it requires less investment and has higher rates of return, however, it is more prone to diseases and hence can involve greater risk of crop failure. Consequently, mustard is preferred in the case of low rainfall during the monsoon, whereas wheat is preferred when sufficient irrigation can be ensured [59]. The cultivation of land in Kharif also has a bearing on the type of crop to be sown in Rabi. Because the harvesting of Kharif crops and the sowing of mustard seed both occur in the month of October, the area to be put under mustard is generally left fallow in Kharif [59]. Plowing and sowing of wheat is done after the harvesting of the Kharif crops.

The results from the simulation of the agricultural subsystem may be interpreted from several different points of view. As indicated above, we are interested in the model's ability to answer a number of questions which would aid in policy planning activities. Specifically, in this example we are interested in using the model to establish a baseline situation for agricultural production and to investigate the possible positive impact biogas slurry may have on agricultural production.

Crop Yields

Tables 6.24, 6.27, and 6.30 indicate the total crop and crop residue yields for mustard, wheat, and guar respectively under each of the four fertiliser scenarios. For both mustard and wheat, a consistent trend is realised, the application of 50% slurry and 50% commercial fertiliser produces the greatest yield (scenario #4); the combination of commercial fertiliser and dung produce the second greatest yield (scenario #2); the application of slurry alone produces third greatest yield (scenario #3); while the application of dung alone results in the smallest yield (scenario #1). Interestingly, the results for the guar crop differ in that the application of commercial fertiliser, in addition to either slurry or dung, appears to negatively affect crop yields. Specifically, for the guar crop the maximum yield is achieved with slurry only (scenario #3), followed by dung only (scenario #1), commercial fertiliser and dung (scenario #2), and finally the minimum yield with slurry and commercial fertiliser (scenario #4). The reasons for this decrease in crop performance under the application of commercial fertiliser are not known.

The most important result obtained from the four agricultural subsystem scenarios is the increased crop yield obtained from the use of digested slurry as a fertiliser instead of dung. The first scenario indicates both the amount of dung which would be required to fertiliser all seven acres of the farmer's land and the corresponding crop yields. These crop yield values provide a useful baseline indication of agricultural production. The study has three buffaloes and consequently the maximum amount of dung which would be produced by the animals annually is 20 * 3 * 365 = 21 900 kg. The results of scenario #1 indicate that a maximum of 46 640 kg of dung would be required to achieve the calculated crops yield of 1580 kg of mustard, 6656 kg wheat, and 405 kg of guar, which is more than double the amount of dung annually available to the household. The actual amount of dung required could be lower, however, depending on one of several options the farmer could take. Mustard and wheat are Rabi crops and guar is a Kharif crop. Accordingly, for example, the acreage which is planted with mustard and fertilised with dung, may not need to be fertilised with dung for the second crop of the year - i.e. guar. The farmer may also be willing to accept a lower crop yield of wheat for example, by not fertilising those acres dedicated to that crop. The farmer would have approximately sufficient dung to fertilise 3 acres of mustard (17490 kg dung) and 1 acre of guar (5830 kg of dung) or 4 acres of wheat. Nonetheless, the baseline 'dung only' scenario indicates that some level of intervention would be necessary, since the farmer does not have near the quantity of manure to adequately fertilise his fields.

The second scenario indicates the crop yield achievable when a combination of dung and commercial fertiliser is used. The increase in total crop yield for mustard and wheat, over the baseline scenario #1 yields, are 13% and 4% respectively. In the case of guar, a 10% decrease in crop yield is seen in scenario # 2. In this scenario, the total maximum amount of dung required to fertiliser the acreage for the three crops is 23 320 kg. The farmer would have approximately sufficient dung produced from his three buffaloes to meet this demand.

The third scenario indicates the crop yields achievable when slurry alone is used as a fertiliser. The increase in crop yield over the baseline scenario for mustard, wheat, and guar is 7%, 4%, and 9% respectively. The total slurry requirement is 36 275.3 kg, however, the total annual amount of slurry produced from an optimally operating 2m^3 biogas plant is 18 250 kg. Thus, the farmer would not be able to meet the total slurry demand for all three crops. Since wheat has the lowest increase in yield resulting from the application of slurry, the farmer may want to apply the available slurry only to the acreage under mustard and guar. In this case, he would need 18 138 kg of slurry, a requirement he could meet if his biogas plant is maintained in optimal condition.

In the fourth scenario, we see the increase in crop yield due to the combined application of slurry and commercial fertiliser. For mustard and wheat the increased yield is 19% and 9.3% respectively. For guar crop a 20% decrease in yield is calculated. The most significant yield increase is seen for the mustard crop. As mustard is a commercial crop, the farmer may want to spend the extra money on the commercial fertiliser to achieve the maximum yield.

If the 1994 market prices for each crop, as collected in the household survey, are used to calculate the maximum profit for each crop yield, a strong case for the use of slurry as a fertiliser is further established. The data collected from the farmer in Dhanawas on crop yields, seed, irrigation, and fertiliser use, and market prices for 1994 are given in Table 6.34 below.

Using these market sale prices the possible maximum profit for the household may be calculated (if the total crop yield were sold). These profits are compared to the cost of fertiliser for each scenario as calculated by the model, in Table 6.35 below.

Crop	**Seed/Acre (kg)**	**Water/Acre (#irrigation times)**	**Fertiliser/Acre**	**Crop Yield (kg)**	**Market Price (Rs/kg)**	**Crop Residue Yield (kg)**	**Market Price (Rs/kg)**
Mustard	1.5	4	slurry	1200	10.5	-[a]	-
Wheat	50	12	100 kg (urea)	5600	3.5	7000	0.75
Guar	4	0	5 kg (urea)	200	6.0	200	-

a - not given in survey data

Table 6.34 - Agricultural Costs - Survey Data

Crop	**#1 - Profit (Rs)**	**#1 - Fert. Cost (Rs)**	**#2 - Profit (Rs)**	**#2 - Fert. Cost (Rs)**	**#3 - Profit (Rs)**	**#3 - Fert. Cost (Rs)**	**#4 - Profit (Rs)**	**#4 - Fert. Cost (Rs)**
Mustard	16580	0	19131	2277	17850	0	20402	2277
Wheat	23296	0	24259	3036	24203	0	25676	3036
Guar	2430	0	2184	759	2670	0	1944	759

Table 6.35 - Example Household Profits

Since mustard is predominantly grown as a cash crop (95% of crop is allocated by study household for sale) and the greatest % increase in yield resulting from the application of slurry is achieved with mustard let us consider it as an example. The household's maximum profit under scenario # 1 would be Rs 16 580. The net profit under scenario # 2 would be Rs 17 850, or an increase of Rs 996. This increase in net profits could be used to pay for the installation of the biogas plant. If commercial fertiliser is also purchased (scenario #4) then the net profit is increased to Rs 18 125, or an increase of Rs 1545.

Crop Residue Yields

The changes in the crop residue yield are most significant when interpreted in relation to the household's demand for fuel and fodder. Mustard crop residue is exclusively used in the study household (and in most households in Dhanawas) as fuel. As discussed above, a maximum quantity of 4332 kg of crop residues are demanded by the household for fuel. Under each of the four fertiliser scenarios a surplus of crop residue would be available to the household, ranging from 429 kg to 1498 kg. The existence of this surplus would indicate to a policy planner an opportunity for intervention. These extra crop residues could either be shared with a landless household for fuel directly, or they could be contributed to a village level crop residue fuel briquetting programme, for example.

Wheat and guar crop residues are used by the household for fodder. The ability of the household to meet their fodder crop demands from the crop residues produced from wheat and guar has been discussed in the previous section. Specifically, it was noted that a deficit of 2632 kg would exist for dry fodder.

The levels of crop and crop residue yields calculated by the model should be interpreted as maximum quantities. A farmer could choose to use less seed or fertiliser and thus have a lower yield for each of the three crops. Also, as discussion in Section 6.2.2, the crop and crop residue yields are based on a limited sample of data. Therefore, the model provides a relative indication of yield as opposed to an absolute. Additionally, the farmer may plant other crops, particularly in the Kharif season (such as Tinda, Bajra or Jower) and these would contribute to the total quantity of fodder available to the household.

In terms of practical usefulness for an intervention planning exercise, the model results illustrate an economical advantage of biogas adoption. The male head of the home may not be convinced of the utility of biogas for reducing the drudgery caused by fuel procurement for his wife, however, the potential of increased crop yield and subsequent profits from a 'free', organic fertiliser would certainly hold significant sway. The model results do certainly provide a clear indication of the increase crop yield which may be achieved with the application of biogas slurry.

Input Requirements

The fertiliser input requirements have already been discussed above. The seed and irrigation requirements remain consistent for all four scenarios for each of the crops, helping to illustrate the effectiveness of slurry, in particular, for increasing crop yields. In reality, the water requirement for guar and other crops grown in Kharif may be less; since these crops are planted in the rainy season often no irrigation is required. The annual irrigation requirements for each crop are in reality difficult to accurately estimate; since the amount of irrigation required is seasonally dependant. A key fact highlighted by the model, however, is the fact that for the farmer, the cost of running an irrigation pump is essentially free and is not dependant on the amount of water used, but rather on the horsepower of his pump. Because of the low price of electricity for irrigation pumps farmers are neither encouraged to use water resources wisely or to invest in alternative power sources e.g. solar water pumps.

Distribution of Yields

In Tables 6.25, 6.28, and 6.31 above, the actual distribution of mustard, wheat, and guar crop and crop residues among the possible end use options are given, respectively. Most significantly, we see that the survey household has not chosen to allocate any of the three crop residues for fresh or cooked fodder. Consequently, the household must either purchase these inputs or grow other crops for these uses.

In this chapter, we have discussed the evolution of the mass-energy model from a convenient conceptual configuration to a useful mathematical form. The particulars of the mathematical structure have been discussed in detail and a very thorough example of how the model may be used both to understand the energy situation for a rural household and for intervention design has been presented. In the next chapter, we extend the example of the application of the model to intervention planning to village level scenarios.

Chapter 7

Model Application For Village Level Energy Planning

Energy policy planning in India is increasingly moving from the sphere of centralised, hierarchical decision making to that of decentralised, holistic planning. In order for policy planning to be effective at the local (village) level, various mechanisms are required for investigating alternative policy options. The mass-energy model of the domestic cooking energy system, developed in the previous chapter, provides such a tool for use by planners to facilitate village level energy intervention design. Consequently, in this chapter a detailed examination of the application of the model to village level policy planning is undertaken.

In Chapter 2, the fuelwood crisis was presented as a crisis of choice in which household members are faced with a number of possible decision options given the shortage of safe and feasible supplies of fuelwood. Three different approaches were outlined for understanding the underlying nature of the problem or the root of the crisis (i.e. efficiency problems, fuel poverty problems, and gender inequality problems). To demonstrate how the model could be used in a policy planning exercise, a village level problem scenario is proposed and these choices are translated into several solution alternatives. Before describing the problem scenario, a brief revision of the three different approaches for defining the nature of the woodfuel crisis and the related suggested policy options is given. Very briefly, the policy options suggested by Pearson and Stevens [75] are discussed, with the aim of selecting one policy option upon which to focus this detailed example.

Efficiency Problems

Efficiency problems reflect uninternalised costs of environmental externalities which lead to high fuel consumption and low fuel prices. Pearson and Stevens suggest three policy options: the first option would be extremely difficult to realise in the rural Indian context; a form of the second has previously been attempted in India with very limited success; and, the Government of India has just recently begun to investigate forms of the third option. Specifically, the three options are:

(i) Taxation of wood to raise its price: For the vast majority of rural villagers, fuelwood is collected outside of the commercial market at a 'zero cost'. Accordingly, a direct tax on the price of wood would be an entirely ineffective mechanism for inducing change in the rural energy scenario. Taxes on fuelwood could only be effective where fuelwood is purchased, such as in the urban or peri-urban areas.

(ii) Regulations to control consumption: Such an option has already been tried, and failed to make a positive impact on the fuelwood consumption patterns in rural India. Indian regulations exist, in terms of the classification of forest land, which were put in place in colonial times in an attempt to restrict the access by unregulated actors, such as village women, to the fragile forest resources. Specifically, laws made under British rule in 1865 and 1878 effectively granted the government control of all forest areas. The 1878 law divided the forests into three categories: unclassified, protected, and reserved, with the latter being the most regulated and restricted. Today, 97% of India's forest land is publicly owned and 85% is managed by state forestry departments[98]. Historically, the state forest officials have tried to limit rural people's access to the forests and they have mainly concentrated on timber extraction for commercial uses. Local inhabitants have nonetheless desired and required access to the forests for fuelwood and other resources and thus have been in conflict with the officials over access rights. In the 1970's and 1980's the Government of India initiated social forestry programmes. However, these encouraged private farms and community wood lots, focusing on increasing the supply of timber, construction material, and pulp. Because of problems both with difficulties in policing the forest areas by the roughly 100

000 government forest officers [98] and the lack of viable fuelwood supply alternatives, especially for the poorest 300 million rural Indians living officially in poverty, the enforcement and success of these regulations have been weak.

(iii) Redefinition of property rights: Recognising the failure of strict regulations to control fuelwood consumption, in the late 1980's and early 1990's the Government of India modified its approach to forestry management to include greater participation from the local village communities[98]. Specifically, the 1990 Guidelines to the 1988 National Forest Policy Act support a number of measures intended to ensure genuine public participation, including forming partnerships between communities and forest departments; granting forest access and benefits to communities involved in forest regeneration; and, giving communities rights to all non-wood forest products and a share of the tree harvest. Consequently, between 1987 and 1993, eleven states passed orders and resolutions to provide greater authority and rights to communities that protect public forest land [98]. These attempts at participatory forestry management are not without difficulty, however, given the political complexity of Indian villages. The unique cultural traditions, various castes, and division of labour between the genders and among subgroups translate into serious obstacles to effective communication and co-operation.

Fuel Poverty Problems

Fuel poverty problems are marked by the inability of poorer members of the village social system to obtain adequate supplies of fuelwood at appropriate prices. Three policy options are suggested, the latter of which is the most easily and accurately assessed using the mass-energy model.

(i) Raise incomes directly: As discussed in Chapter 2, raising the income of the male head of the household has been shown *not* to translate into increased wealth for the family, because of the nature of male spending patterns. While women would invest an increase in income into the household, most women do not work in the formal economy for traditional wages. Thus, beyond direct handouts to women it would be very difficult to affect the incomes of households in the short term. In the long term, genuine employment opportunities for women in the rural areas would need to be created. This, however, is a complex issue, far beyond the scope of this thesis.

(ii) Increase supply of safe and feasible wood: As discussed above, the Government of India is attempting to increase the supply of fuelwood and other forest resources by rehabilitating local forest areas, with the help and partnership of local communities. The supply of safe and feasible wood available to households which must choose fuelwood as a fuel option could also be increased by encouraging those families who can afford it to adopt alternative renewable energy technologies.

(iii) Decrease demand for wood: The demand for fuelwood would be reduced if rural households were provided with genuine opportunities for adoption renewable energy technologies, such as improved cooking stoves, biogas plants, or solar cookstoves.

Gender Inequality Problems

As emphasised earlier in Chapter 2, a central tenant of this thesis is that the fuelwood crisis is equally a crisis of women's time. Consequently, any policy option must consider how the local women will be affected by the policy choice. Any rural energy policy option must fundamentally incorporate means of reducing drudgery for women, increasing time saving, or providing a beneficial change (as defined by the women) in the women's lives. Also, the implementation schemes devised for these policy options must include women as genuine participants in all phases of the project cycle.

At the local village level, the options which would have the greatest opportunity for directly impacting on the lives of the rural villagers are increasing the supply of safe and feasible wood and decreasing demand for fuelwood. Consequently, the problem scenario discussed in this chapter will concentrate on examining options for increasing supply of and decreasing demand for fuelwood.

The intent of this example is to demonstrate how the mass-energy model could be used as a tool for rural energy planning. The utility of the model lies in its ability to allow planners to better understand the rural energy system and to investigate 'what if' scenarios. In this example, the energy system for a hypothetical village in Haryana state is examined through four different resource scenarios. For each scenario, the knowledge which a planner could acquire from the interpretation of the model results and the policy indicators which emerge from these results are discussed. A hypothetical case is used instead of a real situation for two reasons. A complete set of required village level energy data was not available. Consequently, the 'hypothetical' village description was established based on partial information available from Dhanawas and Gari Natthe

Khan, and as well, the village description was based on 'typical' characteristics for a village in Haryana state. Also, since the intent of this example is to demonstrate the strength of the model as a training and planning tool, a simple scenario, which illustrates these features was selected for implementation.

In the case examined in the first scenario, the village is assumed to have access to an abundant safe and feasible fuelwood supply. All households are using fuelwood as the only major cooking fuel in a traditional mud chulha. This scenario gives an estimate of the annual fuelwood consumption for the village as a whole and by land holding class. It is then assume that the safe, feasible supply of fuelwood has been severely degraded such that it is now both unsafe and infeasible. The second through fourth scenarios investigate the possible consequences of several different policy options. In the second scenario, the option of the entire village moving down the energy ladder to crop residues and dung cakes is investigated. In the third scenario, the option of the entire village moving up the energy ladder to kerosene, a non-renewable, commercial fuel is examined. Finally, in the fourth scenario, a mixed policy option is investigated, with the large land holding class installing biogas plants, the small and landless farmers purchasing improved chulhas, and the landless households employed in the service sector, moving up the energy ladder to using LPG. In this example, how the model may be used for examining the potential impact, in terms of resource and energy savings of demand management policies, is considered. The model results also provide an indication of how the model could be used to establish the level of fuelwood consumption; which can be used for devising supply management policies by indicating the level of safe and feasible fuelwood supply which would be required of a village tree plantation, for example.

7.1 The Problem Scenario

In this example, a village composition typical of the state of Haryana, India is considered. The village contains one hundred households, classified into four categories:

15% landless farm labourers
65% small farmers, owing 1 buffalo and less than 5 acres of land
15% large farmers, owing 3 buffaloes and 5 or more acres of land

5% landless families, who are employed in the government service sector.

Each family is assumed to have an average of 6 adult members.

In the first scenario, every household is modelled as using a traditional mud chulha for all cooking tasks, with fuelwood as the only fuel. The landless farmers choose to collect 80% of their fuelwood from the government forest area and 20% from the roadside. The small farmers collect 90% from the government forests and 10% from their own land and the large farmers collect 80% from the government forests and 20% from their own land. In the second scenario the case where all households are forced to move down the energy ladder to crop residues and dung cakes for fuel, in a ratio 75% and 25% respectively, using the traditional mud chulha is considered. In the third scenario the policy option of all families moving up the energy ladder to kerosene for all of their cooking tasks is investigated. In the fourth scenario, a mixed policy option is considered. The large farmers all install biogas plants and use biogas for all their cooking tasks. The landless and small farmers purchase improved chulhas (20% efficiency), using fuelwood and the landless, service employed families moved up the energy ladder to LPG for all cooking tasks. Additionally, in each scenario, both the small and large farmers use some of the dung from their animals to make dung cakes to fuel a hara chulha which is used for simmering milk and cooking fodder. The small farmers decide to allocate 20% of the dung for making dung cakes and 80% of the dung for manure, while the large farmers choose to allocate 10% of the dung for dung cakes and 90% for manure.

7.1.1 Cooking Demands

Each scenario is run using three different cooking demand cases. In case one, the quantities of food cooked are specified and the required useful energy calculated for the demand, using the useful energy requirement per kg of food item to be cooked, as described in the example in the previous chapter. In the second case, the ABE normative value for India is used to calculate the total demand for the family - 520 kcals/person/day. In the third case, the NCAER estimate is used - 270 kcals/person/day. These three cases essentially provide a high, medium, and low estimate of the cooking energy demands for each household. The quantities of food cooked for each land holding class, used in case one, are given in Table 7.1 below.

Land Holding Class	Subji	Dal	Tea	Roti	Water Heating	Simmering Milk	Cooking Fodder
Landless	1 kg	0.5 kg	2 kg	3 kg	48 kg	0 kg	0 kg
Small	2 kg	0.5 kg	2 kg	3 kg	48 kg	4 kg	1 kg
Large	2.5 kg	0.5 kg	2 kg	3 kg	48 kg	4 kg	3 kg

Table 7.1 - Cooking Food Item Quantities

7.1.2 Manure Demand

The dung requirements calculated in the agricultural subsystem are used to determine the daily manure demand for the small and large farmers. These values are given in Table 7.2 below.

Land Holding Class	Manure Demand (kg / day)
Small Farmer	16 kg
Large Farmer	40 kg

Table 7.2 - Manure Demand

7.1.3 Agricultural Subsystem

In this example, the principal concern is with examining the policy options available to an energy planner for a village which is suffering from a lack of safe and feasible fuelwood supplies. Consequently, the aspects of the agricultural subsystem of greatest interest are the crop residue quantities which would be available for fuel and the quantities of dung and slurry required to fertilise the crops. As mustard crop residues are the principal residues used for fuel, only the acreage under mustard crop is modelled for this example. The small farmers are assumed to plant, on average, 2 acres of mustard and the large farmers are assumed to plant, on average, 5 acres. The small farmers are assumed to be using a mixture of dung and commercial fertilisers for all scenarios. The large farmers are assumed to use dung and commercial fertiliser for the first three scenarios, while in the fourth scenario slurry alone and slurry and commercial fertiliser combinations are investigated.

7.2 Results

As described above, four different cooking energy scenarios are investigated in this example. The results for each of these are first presented, followed by the agricultural subsystem results for the small and large farmers.

7.2.1 Scenario # 1 - Baseline Fuelwood Case

The results of this first scenario present what may be considered to be a baseline view of the village energy consumption under conditions of abundant supply of safe and feasible wood. For this first case it is assumed that commercial fuels are not available to the villagers and no dissemination attempts for improved chulhas or biogas plants have been previously undertaken. The hypothetical daily and annual fuelwood and dung consumption for one household in each of the land holding classes are given in Table 7.3 below. In Table 7.4, the total annual consumption of fuelwood, for the entire village, by land holding class is given.

The small farmers allocate 20% of the dung for making dung cakes and 80% for manure. The manure demand for fertiliser is calculated in the agricultural subsystem to be 16 kg/day and 16 kg/day of dung are allocated by the household for manure. A surplus of 0.095 kg of dung for dung cakes results due to the household's allocation decision. The large farmers allocate 10% of the dung for making dung cakes and 90% for manure. The manure demand for fertiliser is calculated in the agricultural subsystem to be 40 kg/day and, 54 kg/day are allocated by the household, resulting in a 14 kg surplus. A 0.5 kg deficit of dung for dung cakes results from the household's allocation decision.

For this example it is assumed that the small farmer land holding class has on average one buffalo and the large farmer land holding class has, on average three buffaloes. In Table 7.5, both the daily and annual quantities of fodder and water required to feed the buffaloes and the quantities of milk and dung produced are given. These results are identical for each of the four cooking scenarios; consequently, they are only reproduced once here.

		High Energy Useful Demand		**Medium Useful Energy Demand**	**Low Useful Energy Demand**
Land Holding Class	**Resource**	**Run # 1 - No Bathing Water (daily / annual per hh in kg)**	**Run # 2 - Bathing Water Heating (daily / annual per hh in kg)**	**One Demand All Year**	**One Demand All Year**
Landless	Fuelwood - gov't	5.9 (1621.6)	17.6 (1622)	5.6 (2025.8)	2.9 (1051.2)
	Fuelwood - roadside	1.5 (404.0)	4.4 (405.7)	1.4 (507.4)	0.7 (262.8)
Small	Fuelwood - gov't	7.3 (1995.6)	20.5 (1886)	6.2 (2277.6)	3.2 (1182.6)
	Fuelwood - own land	0.8 (221.1)	2.3 (211.6)	0.7 (255.5)	0.4 (131.4)
	Dung	3.9 (1067.4)	3.9 (359.7)	3.9 (1427.2)	3.9 (1427.2)
Large	Fuelwood - gov't	6.8 (1848.2)	18.5 (1472)	5.6 (2025.8)	2.9 (1051.2)
	Fuelwood - own land	1.7 (461.4)	4.6 (425.0)	1.4 (507.4)	0.7 (262.8)
	Dung	6.5 (1763.6)	6.5 (594.3)	6.5 (2357.9)	6.5 (2357.9)

Note: high useful energy demand: run # 1 - 3341 kcal/hh/day (ll), 3654 kcal/hh/day (sf), 3811 kcal/hh/day (lf); run # 2 - 9917 kcal/hh/day (ll), 10230 kcal/hh/day (sf), 10386 kcal/hh/day (lf). medium useful energy demand: 3120 kcal/hh/day. low useful energy demand: 1620 kcal/hh/day.

Table 7.3 - Fuelwood Consumption

Land Holding Class	**Resource**	**High Useful Energy Demand (kg)**	**Medium Useful Energy Demand (kg)**	**Low Useful Energy Demand (kg)**
Landless	Fuelwood - gov't	64871.6	40515.0	21024
	Fuelwood - roadside	16195.2	10147.0	5256
Small	Fuelwood - gov't	252306.0	14804.4	76869
	Fuelwood - own land	28127.5	16607.5	8541
	Dung	92768.0	92768.0	92768
Large	Fuelwood - gov't	49803.2	30386.3	15768
	Fuelwood - own land	13296.2	7610.3	3942
	Dung	35368.5	35368.5	35368.5

Table 7.4 - Total Village Level Annual Consumption

Resource	Small Farmer		Large Farmer	
	Daily Quantity (kg)	Annual Quantity (kg)	Daily Quantity (kg)	Annual Quantity (kg)
Cooked Fodder	1	365	3	1095
Fresh Fodder	30	10950	90	38850
Dry Fodder	7.5	2737.5	22.5	8212.5
Water (l)	35	12775	195	38325
Milk	6	2190	18	6570
Dung	20	7300	60	21900

Table 7.5 - Buffalo Subsystem Results

7.2.2 Scenario #2 - Moving Down the Energy Ladder

In the second scenario, all of the households in the village move down the energy ladder to using crop residues and dung cakes in the traditional mud chulha. The decisions to divide the dung among: dung cakes for the hara chulha, dung cakes for the traditional mud chulha, and dung for manure, taken by the small and large land holding classes for each cooking demand case, are given in Table 7.6.

Land Holding Class	**High Useful Energy Demand**		**Medium Useful Energy Demand**	**Low Useful Energy Demand**
	Run #1	**Run #2**		
Small	20% - Hara 15% - TMC 65% - Manure	20% - Hara 40% - TMC 40% - Manure	20% - Hara 15% - TMC 65% - Manure	20% - Hara 15% - TMC 65% - Manure
Large	10% - Hara 15% - TMC 80% - Manure	10% - Hara 15% - TMC 80% - Manure	10% - Hara 15% - TMC 80% - Manure	10% - Hara 15% - TMC 80% - Manure

Table 7.6 - Dung Allocation Decisions

The daily and annual resource consumption per household by land holding class is given for the three cooking energy demand cases in Table 7.7 and the annual village level consumption is given in Table 7.8.

		High Energy Useful Demand		Medium Useful Energy Demand	Low Useful Energy Demand
Land Holding Class	**Resource**	**Run # 1 - No Bathing Water (daily / annual per hh in kg)**	**Run # 2 - Bathing Water Heating (daily / annual per hh in kg)**	**One Demand All Year**	**One Demand All Year**
Landless	Crop Residues	6.4 (1755.4)	19.1 (1757.2)	6.0 (2190)	3.1 (1138.8)
	Dung	2.7 (737.1)	7.9 (726.8)	2.5 (905.2)	1.3 (470.9)
Small	Crop Residues	7.0 (1919.2)	19.7 (1812.4)	6.0 (2190)	3.1 (1138.8)
	Dung	6.8(1859.1)	12.1 (1113.2)	6.4 (2336)	5.2 (1898)
Large	Crop Residues	7.3 (2001.1)	20.0 (1837.2)	6.0 (2190)	3.1 (1138.8)
	Dung	9.5 (2590.8)	14.7 (1355.2)	9.0 (3266.8)	7.8(2828.8)

Note: high useful energy demand: run # 1 - 3341 kcal/hh/day (ll), 3654 kcal/hh/day (sf), 3811 kcal/hh/day (lf); run # 2 - 9917 kcal/hh/day (ll), 10230 kcal/hh/day (sf), 10386 kcal/hh/day (lf). medium useful energy demand: 3120 kcal/hh/day. low useful energy demand: 1620 kcal/hh/day.

Table 7.7 - Crop Residue and Dung Cake Consumption

Land Holding Class	**Resource**	**High Useful Energy Demand (kg)**	**Medium Useful Energy Demand (kg)**	**Low Useful Energy Demand (kg)**
Landless	Crop Residues	70251.8	43800	22776
	Dung	29278	18104	9417
Small	Crop Residues	242553.4	142350	74022
	Dung	193201.5	151840	123370
Large	Crop Residues	57575	32850	17082
	Dung	59189	49001.3	42431.3

Table 7.8 - Village Level Annual Crop Residue and Dung Consumption

In each of the four runs of the cooking system model, the dung decision allocation for the small farmer results in a 0.095 kg surplus of dung for the hara chulha and for the traditional mud chulha a surplus in all but run # 2 of the high demand level (0.091 kg, 0.52 kg, and 1.71 kg for cases I, III and IV, respectively). In the latter case, a 0.145 kg deficit of dung results. In terms of the dung allocated for manure, in the first, third and fourth cooking demand cases 13 kg of dung are allocated for manure, resulting in a 3 kg deficit. In the second cooking demand case, only 8 kg are allocated for manure, resulting in an 8 kg deficit. A similar trend is seen in the results for the large farmer, in terms of the dung allocation for the traditional mud chulha. A small surplus of dung is allocated to the TMC in the first, third and fourth cases (2.96 kg, 3.52 kg, and 4.71 kg), with a deficit of 2.3 kg in the second case. In all four cases a small deficit of 0.5 kg results for the dung allocation for the hara chulha. The manure demand for fertiliser for the large farmer is calculated in the agricultural subsystem to be 40 kg/day and 48 kg/ day are allocated by the household, resulting in a 8 kg surplus.

7.2.3 Scenario #3 - Moving Up the Energy Ladder

In the third scenario, the option of the entire village moving up the energy ladder to kerosene is considered. The daily and annual kerosene consumption per household by land holding class is given for the three cooking energy demand cases in Table 7.9 below and the annual village level kerosene consumption is given in Table 7.10.

The allocation of dung for making dung cakes for the hara chulha and for manure is identical to the first scenario for both the small and large farmers.

		High Energy Useful Demand		Medium Useful Energy Demand	Low Useful Energy Demand
Land Holding Class	**Resource**	**Run # 1 - No Bathing Water (daily / annual per hh in kg)**	**Run # 2 - Bathing Water Heating (daily / annual per hh in kg)**	**One Demand All Year (daily / annual per hh in kg)**	**One Demand All Year (daily / annual per hh in kg)**
Landless	Kerosene	0.8 (221.1)	2.4 (221.7)	0.8 (277.4)	0.4 (142.4)
Small	Kerosene	0.9 (243)	2.5 (228.2)	0.8 (277.4)	0.4 (142.4)
	Dung	3.9 (1067.4)	3.9 (359.7)	3.9 (1427.2)	3.9 (1427.2)
Large	Kerosene	0.9 (253.9)	2.5 (231.8)	0.8 (277.4)	0.4 (142.4)
	Dung	6.5 (1763.6)	6.5 (594.3)	6.5 (2357.9)	6.5 (2357.9)

Note: high useful energy demand: run # 1 - 3341 kcal/hh/day (ll), 3654 kcal/hh/day (sf), 3811 kcal/hh/day (lf); run # 2 - 9917 kcal/hh/day (ll), 10230 kcal/hh/day (sf), 10386 kcal/hh/day (lf). medium useful energy demand: 3120 kcal/hh/day. low useful energy demand: 1620 kcal/hh/day.

Table 7.9 - Household Level Kerosene Consumption

Land Holding Class	**Resource**	**High Useful Energy Demand (kg)**	**Medium Useful Energy Demand (kg)**	**Low Useful Energy Demand (kg)**
Landless	Kerosene	8857	5548	2847
Small	Kerosene	30623.5	18031	9252.8
	Dung	92768	92768	92768
Large	Kerosene	7286	4161	2135.3
	Dung	35368.5	35368.5	35368.5

Table 7.10 - Annual Village Level Kerosene Consumption

7.2.4 Scenario #4 - Biogas, Improved Chulha, and LPG Mixed Option

In this final scenario, the 15 landless farm labourer families and the 65 small farmers switch to using improved chulhas, while the large farmers adopt biogas plants and the 5 landless service sector employed families switch to using LPG. The daily and annual fuelwood consumption for the landless and small farmers, LPG consumption for the service households, and biogas consumption for the large framers are given in Table 7.11. The village level annual resource consumption for each land holding class is given in Table 7.12.

		High Energy Useful Demand		**Medium Useful Energy Demand**	**Low Useful Energy Demand**
Land Holding Class	**Resource**	**Run # 1 - No Bathing Water (daily / annual per hh in kg)**	**Run # 2 - Bathing Water Heating (daily / annual per hh in kg)**	**One Demand All Year (daily / annual per hh in kg)**	**One Demand All Year (daily / annual per hh in kg)**
Landless - Labourer	Fuelwood - gov't	3.0 (810.8)	8.8 (811.4)	2.8 (1011.1)	1.4 (525.6)
	Fuelwood - roadside	0.7 (202.0)	2.2 (202.4)	0.7 (251.9)	0.4 (131.4)
Landless - Service Sector	LPG	0.6 (152.9)	1.6 (145.4)	0.5 (175.2)	0.3 (91.3)
Small	FW - gov't	3.7 (1010.1)	10.2 (941.2)	3.1 (1138.8)	1.62(591.3)
	FW - own land	0.4 (111.9)	1.1 (104.9)	0.4 (127.8)	0.2 (65.7)
	Dung	3.9 (1067.4)	3.9 (359.7)	3.9 (1427.2)	3.9 (1427.2)
Large	Biogas (m^3)	1.8 (492)	4.9 (450.8)	1.5 (540.2)	0.8 (281.1)
	Dung	6.5 (1763.6)	6.5 (594.3)	6.5 (2357.9)	6.5(2357.9)

Note: high useful energy demand: run # 1 - 3341 kcal/hh/day (ll), 3654 kcal/hh/day (sf), 3811 kcal/hh/day (lf); run # 2 - 9917 kcal/hh/day (ll), 10230 kcal/hh/day (sf), 10386 kcal/hh/day (lf). medium useful energy demand: 3120 kcal/hh/day. low useful energy demand: 1620 kcal/hh/day.

Table 7.11 - Household Level Daily and Annual Resource Consumption

Land Holding Class	Resource	High Useful Energy Demand (kg)	Medium Useful Energy Demand (kg)	Low Useful Energy Demand (kg)
Landless - Farm Labourers	Fuelwood - gov't	24333.8	15165.8	7884
	Fuelwood - roadside	6066.3	3777.8	1971
Landless - Service Sector	LPG	1491.2	876	456.5
Small	Fuelwood - Gov't	126831.9	74022	38434.5
	Fuelwood - own land	14092.7	8303.8	4270.5
	Dung	92768	92768	92768
Large	Biogas (m^3)	14141.3	8103	4216.5
	Dung	35368.5	35368.5	35368.5

Table 7.12 - Annual Village Level Resource Consumption

The allocation of dung for making dung cakes and for manure is identical to the first and third scenarios for the small farmer land holding class. In this fourth case, the large farmer is using all of the dung for the biogas plant and the digested slurry is applied to the field for fertiliser. For the high, medium and low useful cooking energy demands, 45.0, 36.9, and 19.2 kg of slurry are produced daily, respectively.

7.2.5 Agricultural Subsystem Results - Small Farmer

For each of the four cooking scenarios, the average small farmer is assumed to be planting 2 acres of mustard crop, using a combination of manure and commercial fertilisers. The crop inputs which need to be purchased or available are given in Table 7.13 and the total yield and distribution are given in Table 7.14.

	Scenario # 1 - 4	
Input	**Quantity (kg)**	**Cost (Rs)**
Seed	9	90
Water	4800	250
Comm. Fert.	607.3	1518.22
Dung	5829.96	0
Slurry	0	0

Table 7.13 - Mustard Crop Inputs - Small Farmer

The dung requirement is divided into a daily quantity to give the manure demand for the cooking scenarios - 5830 / 365 = 16 kg /day.

		Scenario # 1-4		
Yield	**Total (kg)**	**Crop for Sale (kg)**	**Crop for Household (kg)**	**Crop Residue for Fuel (kg)**
Crop	1214.6	1153.9*	60.7	-
Crop Residue	3522.3	-	-	3522.3

* Note: 95% of crop allocated for sale, 5% for household, 100% crop residues allocated for fuel.

Table 7.14 - Total Mustard Crop & Crop Residue Yield & Distribution

7.2.6 Agricultural Subsystem Results - Large Farmer

For the first three cooking scenarios, the average large farmer is assumed to plant 5 acres of mustard crop, using a combination of manure and commercial fertilisers. For the fourth cooking scenario, the large farmer uses slurry instead of manure, in addition to the commercial fertilisers. The crop inputs which need to be purchased or available for scenarios 1-4 are given in Table 7.15. The total yield and distribution are given in Tables 7.16, 7.17, and 7.18.

	Scenario # 1-3		Scenario #4			
			Slurry Only		Slurry & Comm. Fert.	
Input	**Quantity (kg)**	**Cost (Rs)**	**Quantity (kg)**	**Cost (Rs)**	**Quantity (kg)**	**Cost (Rs)**
Seed	22.5	225	22.5	225	22.5	225
Water	12000	250	12000	250	12000	250
Comm. Fert.	1518.2	3795.6	0	0	1518.2	3795.6
Dung	14574.9	0	0	0	0	0
Slurry	0	0	22672.1	0	11336	0

Table 7.15 - Mustard Crop Inputs - Large Farmer

The dung requirement is divided into a daily quantity to give the manure demand for the cooking scenarios - 14575 / 365 = 40 kg /day.

		Cooking Scenario # 1-3		
Yield	**Total (kg)**	**Crop for Sale (kg)**	**Crop for Household (kg)**	**Crop Residue for Fuel (kg)**
Crop	3036.4	2884.6*	151.8	-
Crop Residue	8805.7	-	-	8805.7

* Note: 95% of crop allocated for sale, 5% for household, 100% crop residues allocated for fuel.

Table 7.16 - Total Mustard Yield & Distribution - Manure & Commercial Fertiliser

		Cooking Scenario # 1-3		
Yield	**Total (kg)**	**Crop for Sale (kg)**	**Crop for Household (kg)**	**Crop Residue for Fuel (kg)**
Crop	2834.0	2692.3*	141.7	-
Crop Residue	7935.2	-	-	7935.2

* Note: 95% of crop allocated for sale, 5% for household, 100% crop residues allocated for fuel.

Table 7.17 - Total Mustard Yield & Distribution - Slurry Only

		Cooking Scenario # 4		
Yield	**Total (kg)**	**Crop for Sale (kg)**	**Crop for Household (kg)**	**Crop Residue for Fuel (kg)**
Crop	3238.87	3076.92*	161.9	-
Crop Residue	9716.6	-	-	9716.6

* Note: 95% of crop allocated for sale, 5% for household, 100% crop residues allocated for fuel.

Table 7.18 - Total Mustard Yield & Distribution - Slurry & Commercial Fertiliser

7.3 Discussion

The four cooking energy scenarios have been created to illustrate how the mass-energy model may be used for intervention policy planning. The first scenario outlines the baseline energy situation for the village and the second to fourth scenarios illustrate the impact which various intervention alternatives might have on resource consumption. Since this example is based on a hypothetical situation, and a number of assumptions, particularily regarding the allocation of resources, have been made in order to create the scenarios, the results must be interpreted as demonstrative and indicative, rather than absolute.

7.3.1 Scenario # 1 - The Baseline Energy Scenario

The results from the baseline energy scenario are given in Tables 7.3 - 7.5. The total fuelwood consumption for the entire village may be calculated from Table 7.4. Table 7.4 indicates the total annual fuelwood consumption would range from 424 600 kg (high estimate) to 131 400 kg (low estimate), with 366 981 kg (113 661 kg) being collected from the government controlled forest areas; 41 242 kg (12483 kg) from the private homestead lands; and 16195 kg (5256 kg) from the roadside. Thus, the village forest areas must be able to sustainably provide up to 425 tonnes of fuelwood annually, in order for this fuelwood demand to be met in a safe and feasible manner.

The total annualvillage level dung consumption for cooking would be 128 137 kg. The small farmers require 92 768 kg of dung for cooking and 378 950 kg of dung for manure. The total quantity of dung available to this land holding class is 474 500 kg. Thus, the land holding class would have a surplus of 2782 kg of dung. The large farmers require 35 369 kg of dung for cooking and 218 625 kg of dung for manure. The total annual quantity of dung available to this land holding class is 328 500 kg. Therefore, the large farmer land holding class would have a surplus of 74 506 kg of dung. This surplus quantity of dung would thus be available for fertiliser for other crops grown by the households.

For the hypothetical village, it is next considered that the village forest areas are no longer able to provide sources of safe and feasible fuelwood to the village. As described above, three different intervention options are investigated and the results in terms of the feasibility of each for the village are discussed.

7.3.2 Scenario # 2 - Moving Down the Energy Ladder

In this second scenario, the entire village moves down the energy ladder to use 75% crop residues and 25% dung cakes for all cooking tasks, in a traditional mud chulha. The results for this scenario are given in Tables 7.7 and 7.8. Table 7.8, indicates that the landless farmer land holding class would require a total annual maximum(minimum) of 70 252 (22 776) kg of crop residues and 29 278 (9417) kg of dung cakes to meet their collective cooking energy demands. Since these households neither grow their own crops nor have their own animals, all of these fuel resources would have to be collected or purchased from surplus supplies in the village. The crop residues may be received as payment in kind for labour services rendered to the large farmer land holding class. If the resources must be purchased, then this would represent an increased cost for the landless households, where they were previously collecting their fuelwood for free.

The results from the agricultural subsystem simulations indicate the total quantity of crop residues available to the entire village. Each small farmer would produce 3522 kg of mustard crop residues or 228 930 kg for the land holding class. Table 7.8, however, indicates that the small farmer land holding class requires an annual maximum of 242 553 kg of crop residues for fuel. This means that a deficit as great as 13 623 kg of crop residues could exist each year. Each large farmer would produce 8806 kg of mustard crop residues or 132 090 kg total for the land holding class. Again, Table 7.8 illustrates that this land holding class demands a maximum of 57 575 kg of crop residues for fuel and thus among these households there exists a 74 515 kg surplus of crop residues. The combined unmet demand for crop residues from the landless and small land holding classes is 83 875 kg. Thus, even if some crop sharing mechanisms were worked out between the large and small and landless land holding class households, there does not exist among the total crop residues produced in the village a sufficient quantity to meet the entire village level demand.

The small farmer land holding class has a total of 474 500 kg of dung available on an annual basis. Table 7.8 indicates that a maximum total of 193 201 kg of dung is required for cooking and, from the agricultural subsystem, 378 950 kg of dung are required for manure, for a total of 572 151 kg of required dung. Therefore, the land holding class would have an annual deficit of 97 651 kg of dung. The large land holding class has a total of 328 500 kg of dung for use on an annual basis. These households require a maximum total of 59 189 kg of dung for meeting the cooking demands and 218 625 kg for manure demands. Therefore, the land holding class would have a surplus of 50 686 kg of dung. Unfortunately, this surplus is not sufficient to meet the combined unmet demands of the landless and small land holding classes, which need 126 930 kg of dung to meet their collective cooking and manure demands.

Therefore, this first option, moving down the energy ladder, is not feasible for the village since the total amount of crop residues and dung available to all households in the village is insufficient to meet the demands. Furthermore, were the resources available, such an option would require sharing of resources among households of different land holding classes and such arrangements may be problematic due to cultural barriers on inter-household interactions. Additionally, the use of up to 281 668 kg of dung for cooking fuel represents a significant loss of nutrients to the village agricultural land. Also, using such resources implies an increased burden on the village women, both in terms of increased fuel collection time and increased exposure to smoke filled kitchens. Thus, such an option would be undesirable, considering only the impacts on the village women. Given that moving down the energy ladder is not a feasible option for the village, the possibility of moving up the energy ladder to commercial fuel consumption is next considered.

7.3.3 Scenario # 3 - Moving Up the Energy Ladder

In this third scenario the option of the entire village using kerosene for all of its cooking tasks is examined. The results for this scenario are presented in Tables 7.9 and 7.10. Table 7.10 indicates that the total annual village level consumption of kerosene would range from 46 767 kg of kerosene to 14 235 kg. Ravindranath and Hall [80] give an estimate of 18 000 kg of kerosene required to meet the total annual demand for kerosene for a village of 600 persons. Thus, the estimates given by the model using the medium useful energy demand value are perhaps the most accurate for this scenario. Nonetheless, using the maximum consumption levels to provide a conservative estimate, such a kerosene consumption would require a total village investment of Rs 188 237, using the market cost (purchase price in the commercial market) of Rs 4.025/kg of kerosene. At the economic price (actual cost of fuel, excluding subsidies and local market competitive forces) of Rs 6.5/kg, a village level investment of Rs 303 986 would be required. On a household level, the financial cost would be:

Land holding Class	Annual Demand	Cost [market (economic)]
Landless	443 kg	Rs 1783 (2880)
Small	471 kg	Rs 1896 (3062)
Large	486 kg	Rs 1956 (3159)

These costs exclude the additional financial burden of purchasing kerosene for lighting. Currently, the lighting demands in the rural areas are predominantly met by kerosene. According to the NCAER 1985 survey Rs 5.1 l/capita/year are required in the rural areas for lighting.

The dung requirements of the small and large households for meeting cooking demands on the hara chulhas do not change (from the baseline scenario) under this energy option. This is because these households are still simmering milk and cooking fodder on a hara chulha even when the kerosene stove is used for other cooking tasks.

Given the financial requirements, is kerosene a viable village level option? The benefits of using kerosene lie in several areas. Since kerosene is already used predominantly in the rural areas for lighting, the rural people are familiar with the fuel. Additionally, because of its use for lighting, a distribution network already exists in the rural areas. A kerosene stove requires an investment of approximately Rs 100 [80] and these stoves are available in small towns adjacent to the rural areas. However, the use of kerosene as the principal cooking fuel for all households in the village represents a significant financial investment both at the local and national level. Currently, 40 % of India's total oil use is imported [80]. If the rural people were to adopt kerosene as a fuel en masse, then large imports and outflows of foreign exchange would be required. At the local level, a significant portion of the households would not be able to afford to purchase the kerosene. Certainly, the landless farmers, who often do not work within the cash economy, would be hard pressed to acquire the financial resources to purchase the fuel. For all of the households, the switch to kerosene represents an increase in spending on cooking fuel, relative to the baseline scenario, where all of the fuelwood was collected. While switching to kerosene would certainly represent a reduction in daily work burden and drudgery for the rural women, in the long term this is not a truly viable option, as kerosene is a non-renewable source of fuel.

To close this chapter, a third intervention alternative, which contains a mixture of alternative, biomass, and commercial fuel use, is lastly examined.

7.3.4 Scenario # 4 - Biogas, Improved Chulha, and LPG Mixed Option

In this final scenario, we investigate the option of the large farmers adopting biogas plants, the small and landless labourers adopting improved chulhas, and the landless households employed in the service sector adopting LPG stoves. The results for this scenario are presented in Tables 7.11 and 7.12. Table 7.12 indicates that the landless labourer households are using a total of between 30 400 kg and 9855 kg of fuelwood; 24334 (7884) kg collected from government forest areas and 6066 (1971) kg collected from the roadside. The small farmer land holding class is requiring between a total of 140 925 kg and 42 706 kg of fuelwood, collecting 126 832 (38435) kg from the government forest areas and 14 093 (4271) kg from their own lands. Thus, the total village level fuelwood use ranges from 171 325 kg to 52 561 kg. This represents a maximum savings of 253 275 kg of fuelwood (and a minimum of 78 839 kg) for the village, or a 60 % reduction in the total village level consumption, from the baseline scenario. This symbolises a very significant fuelwood savings. This consumption demand requirement is also useful for planners, as it gives an indication of the sustainable supply which must be available from the government forest areas. Thus, this may be used in setting rehabilitation and reforestation targets for village level social forestry programmes. For the women of these land holding classes, the adoption of the improved chulhas translates both into time savings and drudgery reduction (in terms of reduced fuelwood collection) and decreased exposure to hazardous smoke (since improved chulhas are, generally, smokeless).

The landless households employed in the service sector are using LPG in this scenario. A total of 1491 kg of LPG is required at the village level, or 298 kg per household per annum. This would require a financial investment of Rs 1699 at the market price (Rs 5.7 / kg) for LPG to Rs 2920 at the economic price (Rs 9.8 / kg) for LPG. An investment is also required for the LPG stove and for the 14.2 kg LPG cylinder. Additionally, because of the poor penetration of LPG into the rural areas, no distribution network currently exists for LPG. Since these households are employed in the government service, however, at least one household member would be travelling daily to the urban or peri-urban areas and as such would have access to supplies of LPG. Since biogas is not an option for these households, due to their lack both of space for the plant and buffaloes to provide dung, LPG represents a viable option to the consumption of unsafe and infeasible fuelwood. Certainly, moving up the energy ladder to LPG represents a beneficial change in the lives of the women of this land holding class, both in terms of time saving and drudgery reduction.

The households in the large land holding class are adopting biogas plants in this scenario. This translates into fuelwood savings and nutritional benefits to the soils (from the slurry fertiliser). Additionally, a significant time savings and drudgery reduction for the women in this land holding class are beneficial changes induced by this option. If each household in this land holding class installs a 2m^3 biogas plant, and assuming optimal operating conditions, then 10 950 m^3 of biogas would be available in the village annually and 18250 kg of slurry would be produced per household or 273 750 kg of slurry for the entire village. Table 7.12, examined for the biogas requirements to meet cooking demands indicates that between 14 141 m^3 and 4217 m^3 are needed to meet the village level cooking demands. Thus, an insufficient quantity of biogas would be available to meet the high useful energy cooking demand level. Closer inspection of Table 7.11 reveals that only during the winter months, when water heating for bathing is required, does the total daily household demand level exceed 2 m^3. Thus, if the useful energy requirements are similar to the high demand levels, an alternative resource/ stove combination must be used for the water heating task. Consequently, the biogas supply is sufficient to meet the village level cooking demands.

While a detailed cost analysis of biogas adoption is not included in the model, the cost of a biogas plant in Haryana in 1985-1986 prices is Rs 4790 [55]. The government of India also provides a number of incentives for constructing biogas plants. The exact subsidy rates vary depending on the size of the biogas plant installed, the region, and the social class of the farmer. However, the entire amount needed for construction is available as a soft loan. Furthermore, this amount minus the subsidy is repayable over seven years [55]. Using the 1994 market price for mustard crop (Rs 10.5/kg as given in Chapter 6), the household profits may be calculated. Before biogas adoption., when a mixture of dung and commercial fertilisers is used, the annual net profit to the household would be Rs 28 082 (3036 kg * 10.5 Rs/kg = Rs 31 878 minus the cost of the commercial fertiliser, Rs 3796 = Rs 28 082). The annual net profit if only slurry were used as fertiliser would be Rs 29 757. However, an insufficient quantity of slurry is produced to meet the total slurry demand. Consequently, some commercial fertiliser would have to be purchased. Tables 7.15 and 7.18 indicate that the total cost of commercial fertiliser, in this case is Rs 3796 and the total profits from the sale of the mustard crop, Rs 34 010, result in a annual net profit of Rs 30 214. Consequently, the large farmer would increase net profits by at least Rs 2132 and this amount would easily cover the loan payment for the biogas plant. Thus, we see that biogas is a feasible option for the large farmer.

In summary, the results from the first cooking scenario provided a baseline fuelwood consumption level. The second scenario investigated the policy option of moving down the energy ladder to crop residues and cow dung for fuel. This option was revealed by the model results to not be feasible for the village. The third scenario investigated the policy option of moving up the energy ladder to a commercial fuel, kerosene for the entire village. This option is not feasible in financial terms, nor from an ecologically sustainable point of view. The fourth scenario investigated a mixed alternative option. In this scenario, significant fuelwood savings are realised in the village, and sustainable alternative renewable energy options are utilised. This fourth scenario, then illustrates a viable policy option for the village, when faced with a shortage of safe and feasible fuelwood supplies.

In this application example, a hypothetical village scenario, based on a combination of known village level data and average or typical village characteristics, has been considered. The hypothetical case was chosen because it very clearly illustrates the utility of the model for understanding the village level energy system scenario and investigating different policy options. Because the application scenario is hypothetical, however, the results cannot be intrepreted as definative, but rather they must be understood to be demonstrative of the capabilities of the modelling tool. In order to create the four scenarios examined in the example, a number of assumptions had to be made. Specifically, the resources available, such as land and cattle holdings, the allocation of the resources, such as dung allocation, and the decisions to use the various resources, such as the percentage of crop residue and dung cakes used in the second scenario, were all assumed based on known practises in Dhanawas and surrounding villages. As these assumptions were based on known data, they are considered to be valid and representative of the village level reality. If these values were significantly altered, the results of the model would obviously be changed. This type of sensitivity analysis was not undertaken, as the application example is inteneded simply to demonstrate the modelling methodology.

Also, because this application is intended to demonstrate the range of capabilities of the model as opposed to providing a concrete policy initiative for alternative energy options, the four scenarios considered in this example are simple cases. In reality, it is unlikely than an entire village would simultaneously move either up or down the energy ladder to using commercial fuels or crop residues / dung cakes, respectively. These simple cases were selected in order to demonstrate in a straightforward manner, how different policy options, such as those suggested by Pearson and Stevens, might be translated into various modelling scenarios.

In Chapter 3 of this work, the stages which comprise a systems approach for intervention design were presented. In Chapters 4 through 7, the mass-energy model was developed and demonstrated as one tool to be used as an integral part of the systems approach. In the following chapter, a detailed example of the systems approach to intervention design is given, based on an actual intervention design exercise conducted in the village of Gari Natthe Khan, Haryana.

Chapter 8

An Application of the Systems Approach For Rural Energy Intervention Design

In this chapter, the synthesis of the mass-energy model and the systems approach to intervention design is presented, based on village level planning and implementation experience gained from an intervention design activity undertaken as part of the joint UW-Teri project in the village of Gari Natthe Khan, Haryana. The Systems Approach to Intervention Design was described in detail in Chapter 3 and the mass-energy model was presented and discussed in Chapters 4 - 7. The example in this chapter illustrates each step of the intervention design process as it has been used in a real world situation. Before discussing the example, some key elements from theory on diffusion of innovations, intervention design, and user acceptance are presented, highlighting the factors which most influence user acceptance of a new technology.

8.1 The Innovation-Development Process

Any rural energy programme is an exercise in diffusing an innovation. For example, the NPIC and NPBD are fundamentally concerned with diffusing specialised energy innovations: an improved chulha and a biogas plant/stove, respectively. The diffusion of an innovation, however, is actually only one phase in a larger sequence of events which may be called the innovation-development process. Broadly speaking, the innovation-development process consists of the stages which an innovation passes through from (i) the initial perception of a problem or need; (ii) basic and applied research into the problem and investigation of solutions; (iii) development of the most feasible solution; (iv) commercialisation of the innovation; (v) diffusion and adoption of the innovation; and finally (v) the impact of the consequences of adoption [83]. Consequently, to be effective a rural energy programme should follow a comprehensive innovation-development process. Moreover, as discussed in detail in Chapter 2, a serious flaw in past attempts to disseminate rural energy interventions such as biogas plants and improved chulhas was the fact that these initiatives often started in the 'middle' of the innovation-development process - approaching a village with a pre-conceived solution, without taking the time to understand the nature of the localised energy problem and to tailor solutions to these local needs. The systems approach, outlined in detail in Chapter 3, is an example of a holistic innovation development process.

8.1.1 Diffusion of Innovations

Diffusion is the process by which an *innovation* is *communicated* through certain *channels* over *time* among the members of a *social system* [83]. The ultimate aim of innovation diffusion is to elicit change; a new idea is invented, diffused, adopted or rejected, leading to consequences which change the social system. Encompassed in the diffusion stage of the innovation-development process is the innovation-decision process. This process defines the series of decision stages experienced by a potential adopter (the village men and/or women) of a new innovation as they pass from first knowledge of, to the eventual decision to adopt and use, an innovation. The innovation-decision process is thus an information seeking and processing activity; rural villagers require information to reduce their uncertainty about the advantages and disadvantages of a new innovation. Uncertainty and information are intimately connected; in order to reduce uncertainty information is required.

To further illustrate the concept, the four main elements of diffusion (innovations, communication channels, time, social systems) are next examined in greater detail.

8.1.2 Innovations

Many of the solutions to rural energy problems involve disseminating or introducing a new innovation into the village system. What exactly is an innovation? An innovation is an idea, practice, or object perceived as new by an individual which typically creates uncertainty by presenting an individual with a new means of solving a problem. If a broad understanding of the word 'technology' is taken, then innovations may also be conceptualised as technologies. A technology has two different, complementary aspects: (1) a hardware aspect, consisting of the physical, material object; and (2) a software aspect, consisting of an information base, which provides answers to questions such as "What is the innovation?", "How does it work?", and "Why does it work?". Different technologies encompass different amounts of the two aspects. For example, the biogas technology consists of both the physical biogas plant and stove along with the related information detailing the operation, repair, and maintenance. Some technologies may consist entirely of 'software' for example, general pre- and post-natal health care methods for new mothers. Any innovation or technology may be defined further by its five primary features or characteristics: (i) Relative Advantage; (ii) Compatibility; (iii) Complexity; (iv) Trialability; and (v) Observability [83].

Relative Advantage

Relative Advantage is defined as the degree to which an innovation is perceived by the potential adopter as better than the idea it supersedes. In particular, the relative advantage of an innovation will be manifest in its technical and economic characteristics. As well, there are less tangible factors, such as the social prestige associated with the adoption of an innovation, the level of convenience of its use, and the personal satisfaction which the user gains from its adoption.

The technical characteristics of an innovation relate to the hardware aspects of the technology or the material and physical aspects of the innovation. These physical attributes influence the innovation's relative advantage in terms of the construction, maintenance, and repair.

In particular, in the rural Indian setting, an innovation which can be generated and adapted in the field rather than in the laboratory using locally available materials and local artisans, labours, or technicians will have a greater relative advantage compared to an innovation which uses imported materials and labour.

Three facets to the economic characteristics of an innovation determine its relative advantage: the form, i.e. financial vs. non-financial, in which costs are incurred and benefits received by the adopter; the level of these costs and benefits; and, the quickness with which these benefits are realised. Furthermore, the costs and benefits of the innovation may be private - relating to an individual, or social - relating jointly to a community of people. Different innovations will comprise different combinations of costs and benefits, i.e. private, financial, costs and benefits (mechanical agricultural equipment); private financial costs and private non-financial benefits (watches, radios); private financial and non-financial costs and private financial benefits (family biogas plant); social financial and non-financial costs and private financial benefits (irrigation canals); social financial and non-financial costs and private non-financial benefits (piped drinking water); or social financial and non-financial costs and private financial and non-financial benefits (contraceptives) [2]. An innovation which is perceived as having a direct, high, financial benefit in a relatively short period of time is more likely to be readily adopted than an innovation whose benefits to the individual would be indirect, non-financial, and often only realised after a considerable period of time. The former represents a much lower level of uncertainty to the potential adopter than the latter.

Compatibility

The compatibility of an innovation refers to the degree to which an innovation is perceived by the potential adopter as being consistent with existing values, past experiences, and needs. An innovation perceived as being compatible by a potential adopter will also be less uncertain or will inherently contain less uncertainty for the potential adopter. If an innovation is not compatible with the current socio-cultural values and beliefs then before diffusion can occur a new value system will need to be introduced and adopted. This is both a slow process and one of questionable merit; perhaps it is the innovation which needs to be changed and not the local value system. To judge the innovation, the potential adopter needs some point of reference and past experiences will provide a familiar standard for comparison. Finally, the more compatible an innovation is with the felt needs of the potential adopter the greater the likelihood of successful adoption.

Complexity

The complexity of an innovation refers to the degree to which the innovation is perceived as difficult to understand and operate. Innovations which are simple to understand and require few new skills to use and maintain will be more rapidly adopted than those more complex ones. The greater the complexity of the innovation the greater the uncertainty. Consequently, more information will be required by the potential adopter for the adoption of a complex innovation. Where an innovation is complex, and requires user education and training for its adoption, it is the responsibility of the change agent, as one aspect of communication of knowledge and information, to ensure that relevant and useful programs are provided to the potential adopters.

Trialability

The trialability of an innovation refers to the degree to which the innovation may be experimented with by the potential adopter on a limited basis before making final decision to adopt. A trialable innovation will represent less uncertainty to the potential adopter and thus innovations which can be investigated on a trial basis before adoption are more likely to be successfully diffused.

Observability

The observability of an innovation refers to the degree which the results or consequences of the innovation are readily visible to others. If the positive consequences of adoption are apparent to potential adopters, they are more likely to adopt; being able to view the consequences directly reduces some of the uncertainty surrounding the innovation. The observability of an innovation is often a function of the nature of the technology; the consequences of a technology which is primarily of a 'software' nature will often be more difficult to observe.

8.1.3 Communication Channels

Communication channels are the means by which messages or information pass from one individual to another. Since the innovation-decision process is a process of uncertainty reduction via information exchange between the potential adopter and the change agent, or the individual who is employed by the diffusion agency to diffuse the innovation, communication and means of communication are of critical importance. Communication channels may be categorised as interpersonal vs. mass media, and originating from local vs. cosmopolite sources [83]. The different communication channels will play varying roles in creating knowledge to reduce uncertainty and persuade individuals to change their attitudes towards an innovation. Mass-media channels, such as radio, television, and newspapers, reach a large audience quickly, are useful for creating knowledge and spreading information, and can lead to changes in weakly held attitudes and beliefs. On the other hand, interpersonal channels, which involve a face-to-face exchange between two or more individuals, are necessary for changing strongly held beliefs and attitudes. The mass-media channels are most important in quickly disseminating general knowledge and information. The interpersonal channels are necessary for providing a direct and two-way exchange of in depth information and details about an innovation. Cosmopolite communication channels are those which originate from outside of the social system of study; interpersonal channels can be either cosmopolite or local. In the rural areas of many developing countries, such as India, mass media channels play a very restricted role, due to the limited access of the local people to these channels. In these areas, interpersonal-cosmopolite channels of communication are the most important for generating first knowledge of an innovation, and interpersonal-local channels are most critical for communicating information to actually reduce technological uncertainty and influence decisions to adopt or reject an innovation.

8.1.4 Time

The importance of time is a subtle aspect of the innovation-diffusion process. The time dimension is involved in diffusion in three different ways [83]. First, in the innovation-decision process, the potential adopters do not make an instantaneous decision to adopt and use an innovation when they first learn about it. The process of deciding to use an innovation may take from days to weeks to months. Second, in the innovativeness of the individual adopter, that is the earliness or lateness with which an innovation is adopted in comparison with other members in the social system. And third, in terms of the rate of adoption of the innovation into a social system, generally measured by the number of adopters in the system in a specific period of time. An innovation with a rapid rate of adoption will have a large number of adopters, including the 'later' adopters, in a short period of time.

8.1.5 Social System

Diffusion of an innovation does not occur in an isolated environment, but rather occurs within a social system and the nature or structure of this system will have important consequences for the success of the diffusion process. As Agrawal [2] observed, the characteristics of the social system may be classified as cultural, infrastructional, or social. Each aspect will influence the potential adopter's attitude to change and willingness to adopt an innovation. The change agent responsible for introducing an innovation into a social system must be cognisant of and sensitive to the structure of the system if the diffusion is to be successful. Specifically, the change agent must understand the particular *cultural* context of the potential adopter's environment; attitudes, traditions, customs, taboos, religious beliefs and rituals will all influence the potential adopter's attitude to change. Additionally, the change agent must know which cultural customs are related to the economic and social standing of the individual, as these may vary across class and caste. As well, the past experiences of potential adopters both with different innovations and change agents, will influence their attitude towards the current innovation being introduced and the change agent responsible for its diffusion.

The public *infrastructure* extant in the social system serves three basic functions in the diffusion of innovations: in the development of the innovation; in the spreading of knowledge about the innovation to potential adopters via extension services; and in making it financially feasible for the potential adopter to acquire the innovation [2]. In terms of actual diffusion of innovations, the latter two functions are the most critical and the key issues are the biases that are present in the infrastructure. In particular, the change agent needs to be aware of the biases in the extension and credit services in the social system. For example, a tendency may exist to favour a particular economic or social group, e.g. the wealthy vs. the poor, high caste vs. low caste, or men vs. women.

In addition to cultural and infrastructure characteristics, the structure of the social system will also affect the success of the diffusion of an innovation. For example, inequalities in social status and the unequal nature of the balance of power among different castes or classes and between men and women will all influence the innovation diffusion process. As discussed in Chapter 2, the roles of men and women in the domestic cooking energy system, both in terms of tasks undertaken and decision-making responsibilities, are highly segregated. The status of women in the social system is often a key factor affecting the success of innovation diffusion. Women are often the potential beneficiaries of the innovations relating to rural development, such as cooking, family planning, education, and health care innovation. However, women seldom have access to information, to direct credit, or to independently disposable cash incomes. As well, the balance of power between different households in the rural village system, stemming from differences in ownership and control of material wealth and social status, will affect the ability of the potential adopter to access information on an innovation and to secure its purchase. Finally, the social hierarchies may present barriers to the formation of linkages between different groups which need to be involved for the successful diffusion of an innovation, such as the users, the artisans who will locally construct the innovation, and the extension workers.

8.1.6 The Innovation - Decision Process

The definitive success of any rural energy programme may be measured by the response of the potential adopters or rural villagers to the new innovation, which the programme ultimately attempts to promote. If the rural villagers not only enthusiastically adopt the new innovation but also genuinely integrate its use into their daily lives on a long-term basis, then the aims of the programme will have been met. In order for a rural energy programme to enjoy such success, the planners of such programmes need to understand the decision-making process undertaken by a rural villager or indeed any potential adopter of a new innovation. This decision-making processes, here called the innovation-decision process, is a procedure of uncertainty reduction, whereby the potential adopter seeks to gain information on the innovation to guide the decision to adopt. The process is characterised by a series of actions and decisions which may be categorised as [83]:

- *Knowledge* - occurs when an individual first learns of the existence of an innovation and gains some basic understanding on how it functions.
- *Persuasion* - occurs when an individual forms a favourable or unfavourable attitude towards the innovation.
- *Decision* - occurs when an individual engages in activities which lead to a choice to adopt or reject the innovation.
- *Implementation* - occurs when an individual puts the innovation to use.
- *Confirmation* - occurs when an individual seeks reinforcement of a decision to adopt or reject an innovation or reverses a previous decision, if exposed to conflicting messages concerning the innovation.

In the first stage, the potential adopter ideally attains three different types of knowledge awareness, each of which constitutes software information [83]. The first type of knowledge is "awareness knowledge" concerning the existence of the innovation. At this point of knowledge, uncertainty about the innovation will be very high. Next, the potential adopter may be motivated to seek "how-to knowledge", or information which describes how to use an innovation, thereby reducing uncertainty concerning its advantages and disadvantages. As the complexity of an innovation increases, so does the amount of how-to knowledge necessary for proper adoption and use. If an adequate amount of how-to knowledge is not attained before the adoption of an innovation, then rejection and discontinuance is likely to occur, as the potential adopter will not fully understand how to use or maintain and repair the innovation. The final type of knowledge is termed "principles knowledge" and comprises information dealing with the actual principles underlying how the innovation works. It is certainly possible to adopt an innovation without understanding all of the underlying scientific principles on which it is based. Depending on the type of innovation, however, a lack of some basic principles knowledge may lead to misuse and some may be essential for the correct use, repair, and maintenance of the innovation. Ideally, the potential adopter will have gained all three types of knowledge about an innovation before moving to the persuasion stage of decision, however, this is often not the case. Nevertheless, the greater the knowledge base of the potential adopters on the innovation, the lower their uncertainty will be over its advantages and disadvantages. In general, the potential adopter does not pass through the innovation-decision process in a linear fashion, completing one decision stage and then moving on to the next. Rather, the boundaries between the stages are blurred and some stages may be virtually skipped or an early stage may be 'revisited' later in the process.

In the second phase, persuasion, the potential adopters form a favourable or unfavourable attitude towards the innovation and seeks to increase their knowledge (how-to and principles) of the innovation. In this phase, the potential adopter is seeking innovation-evaluation information in an attempt to reduce uncertainty about the potential consequences of the innovation. Additionally, they will be learning about several of the characteristics of the innovation: its technical and economic relative advantage over the product it is to supersede; its compatibility with their existing values, past experiences, and needs; and the level of difficulty associated with understanding its use, or its complexity. The availability of a near peer, who can provide an opinion on the innovation based on their own experience with its adoption, can be critical to the formation of a favourable attitude towards the innovation, to the reduction of uncertainty, and to the decision to adopt. The formation of a positive attitude towards an innovation, however, does not guarantee its adoption.

In the third phase, the decision stage, the potential adopter engages in activities that lead to a choice to either adopt and make full use of an innovation or to reject the innovation. Before the decision to adopt the innovation is taken, a significant amount of uncertainty about the innovation's consequences will still exist. At this point, the trialability and observability characteristics of an innovation become very important. If a potential adopter can test the innovation in a low risk situation for a short period of time before committing to its adoption, the uncertainty about its consequences can be greatly reduced. For some potential adopters, trial by a near peer can serve as an adequate substitute. In this case, the degree to which the results of adoption are readily observable to others will be very critical. The rejection of an innovation by a potential adopter may be classified as one of two types of rejection: active rejection, where the potential adopter was considering adoption, perhaps even tried the innovation, but ultimately decides not to adopt; and, conversely, passive rejection or non-adoption, where at no point did the potential adopter ever seriously consider the use of the innovation.

The decision phase is followed by the implementation stage and it is at this point that the potential adopter actually puts the innovation to use. At this fourth stage, a degree of uncertainty about the expected consequences of the innovation will still exist in the mind of the potential adopter. If, however, the individual has had the opportunity to exchange a significant amount of relevant software and innovation-evaluation information with near peers and the change agent, and they have been able to either try the innovation themselves or haveobserved the results of a trial by a near peer, then the amount of uncertainty will be significantly reduced. At the implementation stage the role of the change agent is extremely important; they provide the potential adopter with the technical assistance to actually obtain, install, and operate the innovation. During implementation, the innovation may go through a process of re-invention, it may be changed or modified by the users so that it more closely suits their needs and environment. Re-invention, while sometimes viewed by a change agent as 'destroying their innovation', can be a very positive process. The change agent, however, needs to ensure that in the process of re-invention the innovation is not damaged or modified such that it ceases to function properly. Re-invention of a innovation may indeed make the innovation more closely meet the felt needs of the potential adopters. The process of actually adopting the innovation needs to be a flexible one and customisation of the innovation should be encouraged to the extent that the changes allow the innovation to fit more appropriately to the local situation.

The final stage in the innovation-decision process is confirmation. At this stage the individual, now either the adopter or rejecter of the innovation, seeks reinforcement of their decision. If the individual is exposed to conflicting messages regarding the innovation they may reverse the previously made decision to either adopt or reject. In particular, if an adopter of a innovation receives conflicting information concerning its advantages and disadvantages, thereby increasing uncertainty of its usefulness, they may decide to discontinue using the innovation. Specifically, discontinuance is the decision to reject an innovation after having previously adopted [83]. Two different types of discontinuance exist: replacement discontinuance - when the adopter replaces an innovation with a better one which supersedes the original innovation; and disenchantment discontinuance - where the innovation is rejected because the user is dissatisfied with its performance. In this stage it is the role of the change agent to ensure that adopters of the innovation receive positive, supporting messages confirming the decision to adopt.

Implicit to the concept of the innovation-decision process is communication among the change agent and the potential adopters; for the latter to acquire information requires genuine dialogue with the former. The more intimately the potential adopter is connected into the entire process of development of the innovation, the greater their exposure to information pertaining to that innovation. Consequently, if a change agent is serious about exchanging useful information with a potential adopter, then the potential adopter - the rural villager - must be provided with the opportunity for genuine participation in the innovation development cycle.

In order to demonstrate the concepts pertaining to the systems approach to intervention design, an example of an intervention design activity conducted in Gari Natthe Khan, Haryana is next presented. A much more detailed description of this example is given in [34].

8.2 Intervention Design in Gari Natthe Khan

In this section, the eleven stages of the systems approach for rural energy intervention are illustrated through an example which describes an energy intervention design activity conducted in Gari Natthe Khan, Haryana. For clarity, the eleven stages are grouped into four main phases: Problem Formulation, Alternative Solution Generation, Selection of the Best Solution, and Implementation, Assessment and Monitoring.

8.2.1 Problem Formulation

Identifying the Defect In the Environment

At the heart of the systems approach to rural energy intervention design lies the gathering, evaluation, and communication of information among the different actors in the design process. Consequently, even before the actual defect in the environment can be ascertained, the intervention agency must establish a comfortable rapport with the rural villagers. The members of the implementation agency are always 'outsiders', and as such it is extremely important for the agency workers to create a non-threatening atmosphere in which ideas and views can be freely expressed and a dialogue can be initiated among the potential participatory actors in the village. In intervention-diffusion terms, the intervention agency must establish cosmopolite-interpersonal communication channels between themselves and the villagers, and foster productive local-interpersonal communication channels among the village participants.

As a preparatory step to rapport establishment, the implementation agency must gain an understanding of the village level social dynamics, or in intervention-diffusion terms, must study the village social system. In particular, the implementation agency must gain a clear picture of the social and cultural history of the village, because this would condition the villagers' present behaviour and responses both in relation to each other and to an external agency.

As a first step in understanding the social dynamics of the village of Gari Natthe Khan, discussions were undertaken to establish who the opinion leaders in the village were, and to obtain the sanction of the local leaders to ensure an entry point into the village. In particular, in Gari Natthe Khan, two women leaders were initially identified; one was a representative on the village panchayat and another had previously received training in chulha construction. The sanction of these women was important because they would understand the significance of the intervention effort and effectively communicate with other women in the community. Also, in order to understand how the undercurrents of the past intervention experiences and the present relationships among people influence the villagers' opinions about their leaders, numerous discussions were held with different groups in the community.

Specifically, discussions revealed that the personal views of the people on the power status and role of the former sarpanch (elected village panchayat (council) leader and in this village belonging to a general caste category) and the present sarpanch (belonging to the scheduled caste category) were different. What emerged from theses discussions was the existence of socially and politically defined groups in the village community. For any intervention activity to be successful, it was critically important for the intervention agency to be aware of these strong power groups, their political affiliations, and the influence which they seemed to have on the social relationships and social status in the village. The agency had to systematically work with all groups separately but simultaneously, in order to ensure the participation of all groups while at the same time eliminating any blocks to participation.

Additionally, in order to establish the critical defects in the village environment, different interests groups had to be identified and the hierarchy of 'defects' for each group clarified. Specifically, the households in the main village of Gari Natthe Khan have a serious water problem, as the groundwater in the main village is saline and most of these households must rely entirely on the government water supply, which is erratic, unreliable and grossly inadequate to meet their needs. This problem, however, is not faced by villagers living on the outskirts of the village in the dhanis or hamlets in the agricultural fields. Similarly, only the poor and small farmers face a fuelwood problem, and thus have a direct interest in investigating immediate solutions.

Finally, in order to establish the views and perceptions of the women in the village, informal discussions were held with different groups of women, separate from the men.

In summary, four critical aspects of the village social dynamics were revealed during the rapport establishment phase of the intervention design process. First, the distinct division of the villagers along caste lines into two groups, those of the scheduled caste (Harijans) and those of the unscheduled castes. Second, a division along political affiliation, between those groups who supported the new sarpanch and those whose allegiance still remained with the old sarpanch. Third, the division depending on the household location, either within the village or outside in the dhanis; and fourth, differences of opinion based on gender.

Thus, through the process of rapport establishment and identification of the different interest groups in the village, a number of general 'defects in the village environment' were identified. Specifically, three general problem areas were illuminated: (1) the problem of access to a clean and reliable source of water for the households in the main village; (2) the problem of access to safe and feasible sources of biomass for fuel, for the poor and small farmers; and, (3) the general problem of lack of employment for young people in the village.

The final task in this phase of the systems approach to intervention design was to begin to establish a systems diagram of the village. Baseline information was used to establish both the structure of the village level energy system and the household level energy system. Both secondary information from the Block and District offices and primary information gathered using a number of different participatory rural appraisal techniques was collected in the village to develop this system profile.

Needs Assessment

The importance of a careful needs assessment can not be understated since a lack of consideration of the felt needs of the potential adopters is cited as the most common reason for the poor adoption of previously disseminated renewable energy technologies. In terms of the energy intervention design process, the first step in the needs assessment is to establish whether energy issues are a priority for any of the various groups in the village.

In Gari Natthe Khan, initial discussions with the various groups led to the assessment that energy was not the immediate priority of the villagers. Fuel scarcity was perceived as being a potential problem in the future, but not an issue that merited immediate and urgent attention.

In order to prioritise the felt needs of the people, further discussions were held with the various groups in the village. For groups which were not articulate or did not have a clear understanding of the issues, several tools were used in an attempt to draw out a priority ranking for the felt needs. Specifically, a time budgeting activity, where information is collected on how much time a woman spends on each daily activity and a flow movement activity, where the daily spatial movements of a women are traced, were used. Through these activities, several interesting and critical factors came to light. Most importantly, the women *did* acknowledge that biomass availability would become a problem in the future. In the past in Gari Natthe Khan, however, there had been several intervention attempts to disseminate improved cooking stoves and biogas plants. These technologies did not perform well, and therefore the women no longer considered those technologies to be potential solutions to their fuel problems. These negative opinions held by the women vis a vis the technology, especially biogas, were revealed to also be due to a lack of correct information. Consequently, in the absence of correct information, unfounded fears and doubts had arisen, causing the fuel problem to be pushed down the list of priorities.

For the men in the village, the problem of drinking water in the main village was the most important problem, followed by poor electricity supply for irrigation and a lack of employment opportunities in the village, and finally transportation needs. The problem of drinking water shortage was also accorded the highest priority by the women, while the lack of employment opportunities and health facilities were other concerns voiced. Despite the fact that the only current source of cooking fuel for the households was fuelwood collected from rapidly shrinking agricultural fields and households were having to resort to inferior fuels like wood from Neem trees and dung cakes, and the fact that most families could not afford commercial fuels like LPG or kerosene, neither the women nor the men accorded great significance to these issues.

Thus, the needs assessment revealed that the unfavourable past experiences with energy interventions had led to a number of misconceptions, knowledge gaps, and resistance in the people to any new energy intervention attempts. This had eclipsed their ability to foresee problems of fuel scarcity due to the unsustainable use of the available biomass resources. In this situation, it was then extremely important, as part of the needs assessment, to sensitise the people to the various energy problems and issues by providing them with the correct information pertaining to the technologies and to make them aware of new technologies and programmes. This was done via lectures, presentations, and demonstrations. In particular, demonstrating the use and maintenance of a properly functioning biogas plant.

Scope and Objectives

The needs assessment revealed various different issues of importance to the villagers. Before the problem to be addressed by the intervention design process could be defined, the scope and objectives of the intervention activity had to be confirmed. To do this several steps had to be taken. The scope of the problem had to be defined both in terms of the ability of the villagers to participate in the solution design process and in the ability of the intervention agency to address the problem. The objectives of the villagers for the intervention activity were established based on the priorities allotted to the felt needs. For the intervention agency, the mandate and areas of expertise inevitably mould their objectives for the intervention process. Because TERI had little expertise in employment generation and health-related issues, these had to be eliminated from the problem scope. Since the mandate of TERI reseted in energy intervention, the objective for the intervention activity became to integrate the water and energy problems.

Problem Definition

At this point in the cycle, the intervention design process bifurcated into two parallel problem definition activities. The first activity related to defining the water supply problem and the second related to the fuel supply problem. Although both activities were carried out in tandem, the remainder of this example will only focus on the latter, fuel supply problem. To be able to define the fuel supply problem, detailed information pertaining to the cooking energy system had to be collected. This activity, initiated as part of the system description, was enhanced at this point. Specifically, the following information was collected:

Baseline:

- types of fuels used and seasonality of use
- fuel availability and requirement, seasonality
- fuel sources and location
- fuel gathering practices
- time spent in fuel collection, preparation, and physical effort involved
- quantity of fuel consumed

Technical:

- stove design and measurements
- kitchen location
- study of stove design modifications and reasons for modifications
- types of briquettes available, features, benefits and limitations
- raw materials available: agricultural residues, cow dung
- requirement and demand for briquettes

Financial:

- current fuel costs
- current device costs
- willingness/ability to pay for new fuels and stoves
- market potential
- payment schemes

Infrastructure:

- availability of local artisans, masons etc.
- availability of land for biogas installation
- schemes for supporting various intervention activities

Socio-cultural:

- shifts in fuel use and reasons for
- cooking tasks and practices
- dietary habits and food
- vessels and equipment
- fuel preferences
- activity schedule of women
- decisions on purchase of fuel, vessels, device, efficient equipment, etc.
- features valued in traditional systems and changed desired

This information was used to develop a problem definition as follows:

"In light of the increasing fuelwood scarcity in Gari Natthe Khan, there is a need to find new, low cost, alternative, and sustainable local sources of energy to meet the cooking energy needs of the village women".

Constraints and Criteria

The constraints and criteria limiting potential solutions were established in consultation with the village women and men. The following table, Table 8.1 presents the list of criteria and constraints which the proposed solution must meet.

Criteria	Constraints
Availability: • Women should have access to information on the technology. • Technology should be available to women. • Technology should be financially affordable to women. • Technology should be cost effective.	Availability: • 'Software' aspect of solution must include discussions and physical demonstrations. • Expertise must be developed locally. • The costs must only include labour charges, provided raw material available. • Local materials and expertise must be used for the construction of technology.
Practicability: • Technology should blend with socio-cultural beliefs. • Technology should address some present need. • Technology should cater to some preference of the women for relief from cooking related burdens. • The men should feel it is a viable option. • The technology should be sustainable at the local level.	Practicability: • Alternative must be socio-culturally acceptable. • Fuel/technology must address need for alternative to fuelwood and dung cakes. • Fuel/technology must be smokeless to relieve women from burden of smoke from cooking fires. • Men must feel option is viable. • Technology must use local resources and local expertise.
Profitability: • Technology should include benefits for women? • Technology should be superior to traditional fuels. • Alternative should be financially profitable to community. • An existing market should exist for the new product.	Profitability: • Fuel (for technology) must take less than 2 hours to collect (time saving), be easily available in the village. • Fuel must burn cleanly (smokeless). • Fuel must cost less than Rs 70 per 40 kg. • Alternative must provide a local income generating activity for an entrepreneur.

Table 8.1 - Criteria and Constraints

8.2.2 Generation of Alternative Solutions

Once the problem had been carefully defined and the constraints and criteria established for evaluating potential solutions, the next step in the intervention design process was to generate alternative solutions to the fuel supply problem. The discussions held during the needs assessment had clearly indicated a lack of trust on the part of the villagers regarding many of the available renewable energy technologies. Although the problem sensitisation activities had helped to dispel most of this mistrust, the intervention design team felt that to gain the confidence of the villagers a solution had to be found which could be quickly disseminated and which would have very direct and visible benefits to the villagers. For this reason, the intervention design team did not seek to develop a 'new' technology, but rather examined off-the-shelf solutions and ways of improving and adopting currently existing solutions to meet the villagers constraints and criteria.

Consequently, relevant information was collected on all of the available potential technologies: costs, government programmes and financial schemes, construction procedures etc. These were discussed with the villagers and a list of potential solutions was devised consisting of:

- Solar Cookstoves
- Biogas Plants
- Biogas Rectification
- Crop Residue Briquettes

8.2.3 Selection of Best Solution

__Feasibilty Analysis__

Solar cookstoves were considered to be infeasible by the village women for a number of reasons. The most critical problems were the cost, the fact that the types of foods cooked by the women are not easily cooked on solar cookstoves, and because the solar cooking methods do not fit harmoniously with the village cooking traditions and preferences. The state of disrepair of the few biogas plants which had been previously disseminated in the village was such that biogas rectification was not a feasible alternative at the time of the study. The feasibility of installing biogas plants in those households which met the land and cattle requirements was assessed on an individual basis. To assess the feasibility of the crop residues briquettes, a technology trial was undertaken.

Prior to this intervention experience, the villagers had not heard of the crop residue briquetting technology. Consequently, to assess the feasibility of such an intervention, a three-day demonstration trial was undertaken. For this trial to be a success, it was essential that effective communication links be maintained between the trial households and the non-trial households, and with the Panchayat. Carefully considering the social and political divisions in the village, fourteen households were selected for the trial. Seven households were given 10 kgs of char (mustard straw) briquettes and seven were given 10 kgs of green mustard straw briquettes. The trial lasted three days and the fuel was used in the Hara Chulha (for simmering milk and cooking fodder). At this time, it was made clear to the villagers that the agency was not going to distribute the fuel free of cost on a regular basis, but rather that TERI would design an appropriate intervention strategy if the demonstration was considered a success. To assess the performance of the briquettes in the Hara chulha, field experiments were conducted in several of the households. This was done in order to determine whether (i) the use of briquettes led to a fuel savings, (ii) briquettes helped in smoke reduction, and (iii) briquettes burned easily and for a longer time as compared to the traditional fuel, in this case dung cakes. These experiments ensured that the alternative quantitatively met the solution constraints outlined earlier.

To gauge whether the trial had been a success and if the alternative did indeed represent a feasible solution, an assessment of the trial was undertaken. Focused interviews were undertaken with the villagers, both with those trial households and those who were observing the trial, to assess the features of the fuel that they liked/disliked, and to determine whether they would be willing to purchase the fuel if it was made available.

Optimisation

The results of the trial assessment were used optimise the crop residue briquette alternative, incorporating suggestions for fuel use and distribution.

Select Best Solution

At the conclusion of the technology trial, the crop residue briquettes were deemed to be the most feasible village level solution. The next step in the intervention design cycle was to develop and implement a longer three month trial period. The results of the three month trial period must be assessed in order to determine whether this indeed is a 'best' long-term solution and based on this assessment a final implementation scheme for a permanent solution must be established.

8.2.4 Implementation, Assessment, and Evaluation

Communication and Implementation

The villagers responded postitively to the three-day technology trial and expressed an interest in exploring the alternative further. Consequently, in light of this positive response of the villagers to the crop residue briquette alternative, a joint decision was taken by TERI and the villagers to design a village level intervention; first on a three month trial basis and depending on the success of the trial, later as a long-term solution.

Working with the villagers, an implementation scheme for the three month trial intervention was designed. Between the Panchayat and the villagers, one unemployed, low-income person in the village was to be identified as an entrepreneur to take up the production of the briquettes as a commercial venture. This person was to be trained by TERI on the briquetting machine for four days, as required to master the operation. TERI would provide the briquetting machine for the three month trial and the entrepreneur would be responsible for collecting the raw material for the briquette production. As of December 1996, however, the three month trial has not yet been undertaken. The reason for this is because funding is not available for financing the purchase of the briquetting machine at the end of the trial. As it was the desire of the intervention design team to implement a long-term solution, as opposed to just a three month demonstration, it was decided to postpone the three month trial until the financing for a briquetting machine could be secured. The problem of lack of financing for the briquetting machine was discussed in detail with the villagers, in order to ensure that the reason for the postponement of the implementation was clear and communicated to all villagers.

Establishment of Performance Standards, Monitor & Evaluation

When the three month trial is undertaken, the agency will monitor the operation of the briquetting machine and provided supervision and maintenance support during the course of the trial. At the conclusion of the three month trial period, a detailed impact assessment of the intervention will be undertaken. If the results of this assessment show that the intervention has been a success, measured by whether the villagers are indeed using the fuel on a daily basis and if the entrepreneur is able to profit from the venture, then financial assistance will be provided for the entrepreneur to purchase his own machine. Also, additional training will be given to the entrepreneur on how to develop markets and to sell his product. If the assessment reveals that the trial has been a failure, then the reasons for this failure must be understood and the problem must be re-evaluated.

Transfer to a More Detailed Phase

If the three month trial is a success, then the next phase in the intervention design cycle will be to identify a new defect in the environment. If the trial is found to be unsuccessful, then the design process must be revisited, to determine whether changes can be made to make the solution a viable option.

The exercise of designing the crop residue briquette alternative with the villagers of Gari Natthe Khan illustrates the potential of the systems approach as a tool for rural energy intervention design. In particular, the attention given to the problem formulation phase of the intervention design cycle ensured that effective communication links were established between the implementation agency and the villagers and among the different groups in the village. These communication links were crucial for establishing a clear picture of the needs of the villagers and for working with the villagers to identify and evaluate different solution alternatives. Through the use of the systems approach for rural energy intervention design, the villagers, in particular the rural women, were ensured a primary role in all phases of the design cycle. Through this intervention design activity, a viable sustainable energy alternative has been indentified with the villagers and an initial cycle of feasibility assessment and opitimisation of the alternative has been achieved.

Chapter 9

Conclusions

9.1 Conclusions

The two primary goals of this thesis have been one, to provide a methodology for rural energy intervention design based on the well-established principles of systems theory and two, to develop as an integral component of this approach, a mass-energy model of the rural domestic cooking energy system. The previous chapters have presented the problem, developed both the systems approach to rural energy intervention design and the mass-energy model of the domestic cooking energy system, and examined the results of both household and village level energy modelling scenarios. Additionally, the application of the design methodology to a real world village level intervention design exercise was presented. The various key aspects of the rural energy crisis were outlined; highlighting the rural energy scenario, the role of women in the domestic energy system, and a conceptual framework for understanding and framing policy options for addressing the fuelwood crisis. As well, a review of past Government of India intervention initiatives was presented, in conjunction with an assessment of the technical, economic, socio-cultural, and infrastructional reasons for the failure of these past programmes and projects to ameliorate the rural energy crisis. This analysis revealed at least two vital reasons for the failures of these past intervention activities: the lack of consideration of the felt needs of the potential beneficiaries coupled with the lack of a genuine participation by the rural women in the project development cycle; and an inability to conceive of the rural energy crisis from a systems perspective, or to realise the complex system structure of the rural energy crisis. This assessment then provided a framework of reference for the work presented here.

The stages in the systems approach for rural energy intervention design were then outlined and a detailed discussion on the need for modelling the rural domestic energy system given. This included a review of the various techniques previously employed for rural energy modelling. After presenting the necessary background theory for both the Graph Theoretic Method and mass-energy modelling, a mass-energy model of the rural domestic cooking energy system was developed, both as a conceptual model and a mathematical version. To incorporate the critical decisions made in the household, in terms of the decisions to use resources and technologies, four new decision components were developed in this thesis based on the mass-energy material transformation process component structure. The complete mathematical description was developed for each component and a simple example was given which illustrated how these components may be used within the rural energy system model. The utility of the mass-energy model was demonstrated first at the household and then at the village level of intervention planning and design. The systems approach for rural energy intervention design was also demonstrated through an example intervention planning activity conducted in the village of Gari Natthe Khan, Haryana.

The results of the model for the three cooking and four agricultural scenarios investigated for the study household in Dhanawas, Haryana indicate that a savings in biomass resources, specifically fuelwood and crop residues, may be realised by adopting an energy saving device such as an improved chulha. Even further fuel savings are possible when several technologies are used together, as was demonstrated by the increased savings achieved when both a biogas plant and an improved chulha are adopted by the household. The model results also indicated other avenues for intervention investigation. Particularly, the continued use of a hara chulha for simmering milk and cooking fodder translates into potential fertiliser being diverted away from the agricultural fields. The model results also provide justification for biogas adoption on economic grounds, which would be very useful and necessary for convincing male financial decision makers of the utility of the technology.

The results of the four model scenarios created to examine village level options when safe and feasible supplies of fuelwood are no longer available to the households indicate the advantages which a mixture of renewable energy technologies have for reducing demands on the village resource base. The model results show that moving down the energy ladder forces households to compromise their well-being in order to meet cooking energy fuel needs. Certainly, in many village situations, as in the example village, insufficient crop residue and dung resources would be available to meet the entire village level demand. Similarly, moving up the energy ladder to commercial fuels is infeasible for many households due to financial constraints.

The results of the crop residue briquetting intervention design exercise in the village of Gari Natthe Khan, Haryana, illustrated of the success which may be achieved when the systems approach for rural energy intervention design is employed. Through using the systems approach, a picture of the history and village level socio-cultural dynamics was first established at the beginning of the process. As well, sincere efforts were made to establish from the outset viable communication links with the various village interest groups. Consequently, the needs of the villagers were both articulated and communicated to the intervention design team. Working with the villagers, the energy problems were defined and alternative solutions investigated. A technology trial was designed and implemented to assess the feasibility and optimise a crop residue briquetting alternative fuel option. Upon the success of this trial a longer three month trial was established. The impacts, both positive and negative, of this trial will be assessed with the villagers to ascertain whether the innovation should be implemented in the long term.

9.2 Future Work

The mathematical mass-energy model developed in this thesis was implemented for testing purposes using Matlab, a mathematical simulation programme. In order for the model to be used effectively by policy planners, a version needs to be developed which incorporates an easy to understand and manipulate user interface for creating scenarios, entering parameter values, and examining the model output. One possibility would be to develop a spreadsheet-based version of the model, using a package such as Microsoft Excel. The advantages of such a spreadsheet-based application are that the software is widely available, even in developing countries such as India.

Consequently, planners and other individuals and groups involved in intervention design, who may not have a technical background, would likely be nonetheless familiar with its operation. The drawbacks to such an option are the limited mathematical processing capabilities of such a software programme. Such spreadsheets have limited abilities to solve matrices and these often cannot be user defined. This would limit the flexibility for creating new scenarios. A better software alternative would be a software package specifically designed for simulating systems models. Prosim, developed at the University of Waterloo WATSUN laboratory, is such a software package. Using Prosim, a software package could be created with all of the system components pre-defined in libraries. The user, however, would have the flexibility to create different scenarios by combining the components together into systems and then easily changing the parameter values and simulating the model. Thus, despite its newness, Prosim would provide an excellent software platform for developing a user friendly version of the model.

In order to make the mathematical model more robus,t a number of changes and additions are recommended. For the examples presented in this work, only the x-monetary costs were calculated. The reasons for this are largely due to data limitations. If the model could provide a direct indication of the amount of human labour (energy) required by different system configurations, this would be very useful for assessing the benefits to rural women of alternative technologies. Labour data are only available in terms of number of hours required to complete a task or number of hours spent on a task. For use in the model, data must be available in terms of number of hours per unit of material, i.e. while the amount of time taken each day to collect fuelwood is known, how this translates into labour per unit of fuelwood collected is not known. Thus, further quantification of the data in this area is required such that it may be included into the model. Also for the stove components, the only output currently included in the component characterisation is the output of heat energy. For each stove, however, a second very important secondary output is produced - combustion gases generally classified as 'smoke'. The quantity of 'smoke' produced by the combustion of the various fuels in the various stoves needs to be quantified, as well as the effects of this smoke on women's health, so that this data, and this important aspect of the system, can be included in the model. Finally, in order to better quantify the demands for cooking energy to cook one unit of the various food items most frequently consumed in the household, further in field testing must be done.

Two other improvements which should be investigated are the inclusion of an optimisation algorithm and stochastic data directly into the model. To facilitate decision making for policy planners, a linear programming algorithm could be included which would optimise, for example, cost or environmental resource use. Currently, the model uses only deterministic data. Parameters such as the quantity of dung or the amount of biogas produced daily could easily be specified as probabilistic or stochastic parameters, more realistically modelling the reality of the village resource availability. One advantage of the current structure of the model, however, is that users are forced to change the parameter values themselves, and then evaluate the results. This forces users to closely examine the household/village situation and can aid in learning about and understanding the system structure, which is one of the primary goals of the model.

The systems approach for rural energy intervention design proposed in this thesis has been developed for specific application within the Indian context. One of the primary benefits of this approach is its flexibility, as such it is suited to adapting to the wide range of differing socio-cultural conditions found across India. Consequently, in light of this flexibility, the intervention design approach and model would also be useful for intervention design and planning exercises in other developing nations, which face similar energy related development issues. As such, it is recommended that an avenue for future work exists in applying the methodology and model to energy development endeavours in other countries of the south, such as those in Sub-Saharan Africa. Also, the intervention design activities considered in this thesis were based at the village level. Since planning activities in India are increasingly being targeted to the block and district levels, the application and usefulness of the methodology to this level of the system hierarchy should be investigated.

9.3 Final Remarks

Energy is a critical input into the rural development process. If developing countries such as India are to meet the growing needs of the rural populace for energy, both for use in the domestic sector as well as for economic growth, long-term ecologically sustainable energy systems must be developed. Renewable energy technologies will have to be central to this sustainable energy system and women, as the primary managers and decision makers (in terms of resource use) in these systems, must not only be consulted but genuinely included in every phase of the development process. In order for these aims to be realised, useful planning approaches and tools must be developed to aid policy planners and facilitate rural energy intervention design. This thesis represents one possible intervention design approach, with a mathematical model of the rural domestic cooking energy system as a key tool to expedite both understanding of the structure and function of the system and investigating alternative intervention options. The results of this work indicate not only the potential of the model to facilitate intervention planning, but also the success which may be realised when village level rural energy interventions are designed and implemented using the systems approach.

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Appendix A

Model Questions and PRA Techniques

Cows and Buffaloes

1. How many animals does the household own?
   - Buffaloes - # of adult, # of young
   - Cows - # of adults, # of young

   Direct Question

2. Feeding Regime - for each animal need to know:
   - What type(s) of Purchased Feed is consumed?
   - What type(s) of Dry Fodder is consumed?
   - What type(s) of Cooked Fodder is consumed?
   - What type(s) of Fresh Fodder is consumed?

   Note: If a mixture of ex. dry fodder consumed = dry fodder #1 + dry fodder #2, then we need to know the type and amount of each given.

   - Does the feeding regime vary with season?
   - Is one type of feed preferred over others - what is the preference ranking for the different types of fodder?

Seasonality Chart to determine both the different types of fodder consumed by the animals and in which months the different fodder is fed to the animals. Direct Observations and measurement of the actual amounts fed to each animal. Priority ranking chart in terms of preferences of each type of fodder fed to the animals.

Animal	Consumption of Purchased Feed (kg/day)	Consumption of Grazed Fodder (kg/day)	Consumption of Dry Fodder (kg/day)	Consumption of Fresh Fodder (kg/day)	Consumption of Cooked Fodder (kg/day)	Consumption of Water (l/day)
Adult Buffalo						
Young Buffalo						
Adult Cow						
Young Cow						

Note: The consumption must be broken down by type as well as quantity.

3. Milk and Dung Production

- How much dung is produced per day per animal? (kg/day)
- How much milk is produced per day per animal? (l/day)
- Does the household rotate between which animal is milked? If so, in what months is each animal milked?
- How is the milk distributed: sold vs. self consumption and simmering vs. non-simmered?

Direct Question and observation/measurement. On the same seasonality chart as used for feeding regime, record the seasonality or rotation of milking the animals.

4. Dung Collection

- What percentage of the dung produced per animal is collected each day?

Direct Question and observation

5. Dung Distribution - Of the collected dung:

- How much (percentage of total collected) dung is sold?
- How much is put into biogas plant (%)?
- How much is made into dung cakes (%)?
- How much is directly used as fertiliser in the fields (%)?

Note: % sold + % biogas plant + % dung cakes + % fertiliser = 100%

Quantity Preference Exercise / "Stick Exercise." Use a pile of sticks to represent the total amount of dung collected, have the women divide this into piles representing the percentage sold/biogas plant/dung cakes/fertiliser. Record the amount in each pile to get a percentage. This should be done twice, once to show how they currently divide the dung, and once to see how they would if they had a biogas plant (awareness of benefit of biogas plant). Instead of sticks can also use the baskets in which the women collect the dung.

6. Human Labour Requirements

Activity	**Time Spent**	**Person Who Does Task**
Preparing Dry Fodder		
Preparing Fresh Fodder		
Preparing Cooked Fodder		
Preparing Purchased Feed		
Attending Grazing Animals		
Feeding Animals		
Fetching Water		
Milking Animals		
Collecting Dung		

Activity Schedule - use time as a base, get the women to suggest the activities these given are examples, but there may be more tasks which they do concerning the animals of which we are unaware - thus present them with the opportunity to describe these activities. The base should be one day, i.e. how much time is spent performing each activity.

Biogas Plant

1. What type of biogas plant does the family own?
2. What is the capacity of the plant?
3. For the biogas plant what is the theoretical gas production?

i.e. 1m3 biogas = x kg dung + y l water + z kg slurry produced.

- How much dung is fed into the plant each day (kg/day) ?
- How much water is fed into the plant each day (kg/day) ?
- How much slurry is produced per day (kg/day) ?

- How much biogas is produced per day (kg/day) ?

Direct questions and observation, once the type of biogas plant is known then the theoretical gas production may be calculated.

4. Division of Slurry - Of the slurry produced each day:

- How much slurry is sold (% of total produced)?
- How much slurry is used as fertiliser (%)?
- How much slurry is made into dung cakes (%)?

Note: % sold + % fertiliser + % dung cakes = 100%

"Stick Exercises" (same as for dung distribution) and Direct Observations / Questions

5. Human Labour Requirements

- Time taken to collect dung (hrs/day)?
- Time taken to fetch water (hrs/day)?
- Time taken to feed dung and water into digester (hrs/day)?
- Time taken to put slurry onto field (hrs/day) / frequency?
- Time taken to sell slurry (hrs/day)?
- Who performs each task?

Activity Schedule - activity based, for each activity give how much time is spent on that activity each day.

Dung Cakes

1. Making Dung Cakes

- How much dung is used to make dung cakes (kg/day)?
- How many dung cakes are made (#/day)?
- What is the weight of one dung cake (kg)?
- Of the total amount of dung used:
    - How much is collected as fresh dung (kg)?
    - How much is slurry from the biogas plant (kg)?
- Which dung source is preferred for making dung cakes and why?

Direct Questions and observation of the quantity of dung used (get the women to separate out from a pile of dung how much they would use in one day total and how much they use for one dung cake and take measurements of the weight of each pile). Open ended questions on the sources of dung for the dung cakes *and on the preference for the different sources (i.e. fresh dung vs. slurry). If a number of different sources are used for the dung then use the "Stick Exercise" to determine the percentage breakdown on how much dung comes from each source.*

2. Storage of Dung Cakes

- How long are the dung cakes stored for before being used for cooking fuel?
- Where are the dung cakes stored?
- Do the dung cakes change while being stored (deteriorate in anyway or improve in quality)?
- Why are they stored in piles?

Direct questions and observation, open ended question on why they stove them the way they do.

3. Human Labour Requirements

- How much time is spent collecting the dung to make dung cakes (hrs/day)?
- How much time is spent making dung cakes (hrs/day)?
- How much time is spent storing the dung cakes (stacking etc.) (hrs/day)?
- Who performs each task?

Daily activity schedule.

Fuelwood

1. Fuelwood Species

- What different species of fuelwood are collected?
- Which species is the most/least preferred?
- Why is one species preferred over another?

Species preference chart.

2. Sources of Fuelwood

- From where is the fuelwood collected - e.g. own land / government forest / government plantation / village plantation / common lands / purchased (etc.)?
- Which sources are preferred and why?

Species preference chart.

3. Collection of Fuelwood

- What is the frequency of collection of fuelwood (e.g. daily /weekly/monthly/yearly/not fixed) ?
- How much fuelwood is collected from each source (kg/day) ?
- How much of the collected fuelwood is used for cooking (kg/day)?
- What distance is travelled to collect the fuelwood (km)?
- How is the fuelwood transported to the household (e.g. carried/headload), cart, tractor etc.)?

"Resource Map" showing different sources, distance of source from household, method of transportation between source and household. "Stick Exercise" to show how much is collected from each source, include in this the preference for the quantity collected from each source (e.g. would prefer to collect all from own land but must purchase some.)

4. Storage of Fuelwood

- How long is the fuelwood stored for before being used for cooking?
- Where is the fuelwood stored (out in open & exposed to elements / covered and allowed to dry before using) ?
- While the fuelwood is stored does it change? i.e. does it dry out? become more wet? stay the same as when it is collected?

Direct question, observation, and open ended discussion on benefits of storing fuelwood to dry it.

5. Human Labour Requirements

Activity	**Frequency**	**Time Spent**	**Person Who Does Task**
Collection of Fuelwood			
Preparation of Wood for Transport to Household			
Transport of Fuelwood to Household			
Preparation of Wood For Storage			

Activity Schedule, activity based, how much time in each day is spent on each task.

Cooking and Water Heating - Fuel / Stove / Task Combinations

1. General Cooking Questions

- Where is the kitchen located (inside / outside) ?

- Who decides on the location of the kitchen?
- Who decides on the layout of the kitchen (stove location etc.)?
- Is the kitchen located in a pucca or kuccha structure?
- What secondary activities are carried out in the kitchen? i.e. what else do you use kitchen for?
- How many people are cooked for at each meal?
- How many meals a day are cooked?
- Is smoke a problem in the kitchen/ advantages from smoke?
- Are the cooking vessels difficult to clean?
- Is it difficult to keep the kitchen walls clean / is this a concern?

Direct questions and observations - in an open ended discussion about cooking and kitchens this information should be ascertained.

2. Fuels

- What fuels are used for cooking?
- What fuels are preferred and why?

e.g. smokiness, burning characteristics, cost, availability, taste given to food, convenience (etc.)?

Fuel preference chart.

3. Stoves

- How many different cookstoves are used?
- Which stove is most/least preferred and why?

Stove preference chart.

3. Tasks

- What are the major cooking tasks performed everyday?
- e.g. making subji, making tea, making roti, simmering milk, cooking fodder, heating water (etc.)?

Direct questions - but make a block to have something to represent each task.

4. Fuel / Stove / Task Combinations

- For each task:
    - Which stove is used?

  - Which fuel is used?
- What is the quantity of food/liquid cooked (kg/l / day)?
- How much fuel is used per day for each task (kg/day)?
- Why are the various fuel/stove/task combinations preferred?
- Is there any difference over season for the combinations?

Activity to show combinations - have different symbols (e.g. blocks), one for each stove, fuel, and task performed, and have the women club the fuel/stove/and tasks together as they use them and as they prefer them. Also if, for example, they may perform one task on a different stove or with a different fuel then need to do a priority ranking exercise on the different combinations.

Once the tasks are established, then by direct observation and measurement, the amount of food/liquid cooked for each task must be measured as well as the amount of fuel consumed by each task.

5. Human Labour Requirements

- How much time is spent on each cooking task (hrs/day)?
- How much time is spent collecting the water for heating (hrs/day)?

Activity Schedule (must be done after establishing the cooking tasks performed). Direct observation - monitor a cooking session.

Agriculture

1. General Questions

- How much total land is owned by the household?
- How is the land divided / land use pattern?

e.g.:

  - How many acres used for agriculture?
  - How many acres used for non-agriculture purposes?
  - How many acres left fallow?
  - How many acres used as grazing land?
  - How many acres used for tree plantations?

  i.e. General breakdown of land use pattern.

- How many distinct agricultural seasons are there in this region? (i.e. winter: October - March, summer: April- September)
- What crops are grown in the winter / summer?
- How many acres per crop?
- How is the land irrigated?

Land use map and direct observation for distribution of land. Seasonality chart for the different crops - when they are grown or direct questions - this will depend on the particular farmer and the ability to answer the question.

2. Planted Crop:

For EACH crop grown:

For each acres of crop harvested:

- How many kg of seed planted per acre?
- How many l of water per acre irrigated?
- How much commercial fertiliser is applied per acre?
- How much Slurry is applied per acre?
- How much Fresh Dung is applied per acre?

Direct Questions

3. Crop Processing (for each crop)

For each kg of harvested crop, when processed,

- kg of crop residue per kg of harvested crop?
- kg of "useful" crop per kg of harvested crop?

Bar Diagram / direct question / calculate

4. "Useful" Crop (for each crop)

- What percentage of this crop is sold?
- What percentage of this crop is saved for self consumption?

Note: % sold + % self consumption = 100%

Direct Question

5. Crop Residues (for each crop)

Of the total Crop Residues:

- What percentage is used as fodder?
- What percentage is used for non-fodder purposes?

Note: % fodder + % non-fodder = 100%

Pie Diagram / Direct Question

Non-Fodder Crop Residue

- How / where is this crop residue stored?
- Is it prepared before being stored?
- How long is it stored for before using?
- Does it "change" in any way while being stored?
- What percentage is used as fuel?
- What percentage is used for other uses such as construction material?

Note: % fuel + % construction material = 100 %

Table for first 4 questions and pie diagram for percentages.

Fodder Crop Residue

- What percentage of the fodder crop is used as fresh fodder?
- What percentage of the fodder crop is dried for later use?

Note: % fresh fodder + % dry fodder = 100 %

Pie Diagram / Direct Question

Fresh Fodder

- What percentage of the fresh fodder is sold?
- What percentage of the fresh fodder is fed to the animals?

Note: % sold + % animal feed = 100 %

Pie Diagram / Direct Question

Dry Fodder

- How / where is the dry crop stored?
- Is it prepared before storage?
- How long is it stored for before being used?
- Does it "change" in any way while it is stored?
- What percentage of the dry fodder is sold?

- What percentage is cooked and fed to the animals?
- What percentage is directly fed to the animals (not cooked)?

Note: % sold + % cooked fodder + % dry fodder = 100%

Table for first 4 questions. Pie Diagram for percentages / Direct Question

6. Human Labour Requirements

Activity	Hours/day	# of Days	# of Labours	Person Who Does Task
Seed Procurement				
Ploughing				
Planing				
Seeding				
Watering 1				
Watering 2				
Application of Commercial Fertiliser				
Application of Slurry				
Harvesting				
Threshing				
Preparation of Fodder for Storage				
Selling Crop				
Selling Fresh Fodder				
Selling Dry Fodder				

Activity Schedule - Activity based.

Summary of Data Collection Techniques

Observations	Direct Questions	Exercises	Discussions
Associated with the majority of the questions.	47	22	Associated with the majority of the questions. For certain questions in the interview guides or schedules will be required.

Appendix B

How to Run the Model

The model code is written in a text file which essentially contains a series of Matlab commands. All Matlab files have the extension .m. The text file is run in Matlab and the results are output to a second file, which may be then examined using a generic word processor. Two different versions of the General Household System Model are available for use. In the first version, the number of buffaloes in the household is taken to be an unknown value and thus given the dung demands, one of the outputs of the model is the number of buffaloes the family must have to meet these demands. This version of the model is found in the file:

model1.m

and the output is written into the file:

mod1out.m

In the second version of the General Household System Model the number of buffaloes owned by the household is taken to be a known value and using this information the amount of feed needed for the animals, the amount of dung and milk produced, and whether these amounts are sufficient to meet the specified demands are calculated as results. This version of the model is found in the file:

model2.m

and the output is written into the file:

mod2out.m

1. Starting Matlab

The first step in running the model is to open up the Matlab program. From the Windows Program Manager, select the AStudent Edition of Matlab@ icon to open the Matlab folder. To invoke Matlab, double click on the Matlab icon and the Matlab Command Window will open. The prompt in the Command Window is EDU>> and this is similar to the c:> dos prompt.

2. Running the Model

To run the model first change the directory to the model directory: EDU>> cd d:\cynthia\model [enter]. Then to run the model simply type EDU>> modlel[enter] (or model2 [enter]). When the prompt reappears the model has finished running (only a couple of seconds). The output can then be viewed in the Matlab Command Window by typing: EDU>> type mod1out.m (or mod2out.m).

3. Modifying the Model Parameters

Obviously, before running the model, the user will want to specify the specific parameters for the scenario to be investigated. To do this the model1.m (or model2.m) file has to be modified. To modify the file use the Notepad text editor available under the Accessories icon from the Program Manager of Windows. Once the Notepad editor is invoked, open the file d:\cynthia\model\model1.m. The changes that are to be made to create different scenarios are described step by step below. Once the changes have been made i.e. the new scenario is fully described, save the file. To run the model using these new parameter values follow the steps described in 2. Running the Model.

4. Setting Up a General Household System Model Scenario

Once you are into the Notebook editor with the newmod1.m file open you are ready to begin creating your scenario. A % sign at the beginning of a line indicates a comment this means that Matlab will skip over this line and not read it. Comments are generally used to provide description to the Matlab code.

1. General Household Information

The first step in creating a model scenario is to specify some general information about the household to be modelled. The following information must be entered:

Description	***Variable to be Modified***
number of family members	family_size

number of acres	acres
number of hectares	hec
number of buffaloes owned	buffalo
percentage of dung collected	collect
fuels used in the household	dungcake fuelwood crop_res biogas lpg kerosene
stoves used in the household	hara tmc ics biogas_stove lpg_stove kero_stove

The family_size is set equal to the number of people in the household. Only one of acres or hectares needs to be specified, the other is automatically calculated. This value should be the total land owned by the family,. not just agriculture land (as this value is used to determine landholding classification of the household). The buffalo is set equal to the total number of buffaloes and cows where a cow is considered to be half of a buffalo. The variables identifying the fuels and stoves used in the household must have a value of either zero or one, where a value of zero indicates the fuel / stove is not used by the household and a value of one indicates that the fuel / stove is used in the household. Because of the way in which the model is currently set up the model cannot be run with both a tmc and an ics specified. Thus if tmc = 1, ics must = 0 and vice versa. Additionally, the number of buffaloes cannot be zero. If the household has no animals then the landless farmer model should be used instead.

Model Parameter Section of Code

In general, the only model parameters which are modified by the user are the decision weightings. Other parameters will generally not be modified to create a scenario.

2. *Decision Weightings*

The decision weightings must be set by the user to reflect the material allocation preferences of the household. The decision weightings must be set for three components: the decision to divide the dung, the decision to collect fuelwood, and the decision to select fuel for the traditional mud chula / improved chula.

3. *Material Transformation Component Parameters*

The next step in the definition of a scenario is to specify the material transformation component parameters. In fact, these will often not be changed by the user. The Buffalo Subsystem Parameters are specified first. These values are for buffaloes in Haryana State, thus the values would be changed only if a different feeding regime is to be investigated, or the amount of milk and dung produced per animal is to be modified. The parameters for the Biogas Plant are given as >classical values=, these can be modified if the user wishes to investigate different gas production states, i.e. currently the values are set considering that to produce 1 m^3 of biogas requires 25 kg of dung, 25 kg of water, and produces 25 kg of slurry. In the Stove Parameters section, generally none of the values will be modified. For some scenarios, however, the user may want to specify a different stove efficiency or heat energy content of the fuel.

4. *Demands*

Once the model parameters are set the next step in defining the scenario is to specify the cooking energy demands. Currently seven different cooking tasks are considered: making subji, making dal, making tea, making roti, heating bathing water, simmering milk, and cooking fodder. For each of the cooking demands, the energy requirement in terms of kcals required to cook one kg of the food is given. In general these values will not be modified by the user. First the user needs to specify the amount in terms of kg of each food cooked in one day for the household:

amt1 = kg of subji cooked per day
amt2 = kg of dal cooked per day
amt3 = kg of water heated for tea per day
amt4 = kg of roti cooked per day
amt5 = kg of water heated for bathing water per day
amt6 = kg of milk simmered per day
amt7 = kg of fodder cooked per day

Once these are specified, the model calculates the total energy demand for each task given as:

yd1 = total energy demand to cook specified amount of subji
yd2 = total energy demand to cook specified amount of dal
yd3 = total energy demand to heat specified amount of water for tea
yd4 = total energy demand to cook specified amount of roti
yd5 = total energy demand to heat specified amount of water for bathing
yd6 = total energy demand to simmer specified amount of milk
yd7 = total energy demand to cook specified amount of fodder

Next the stoves on which the different cooking tasks are carried out needs to be specified. Five possible different stoves may be used:

hara chula - hara_dem
biogas stove - biogas_dem
tmc / ics - tmc_ics_dem
lpg stove - lpg_dem
kerosene stove - kero_dem

The energy task demands for each stove is specified by setting the demand values equal to a desired combination of ydn values. For example, to model a household which uses: a hara chula for simmering milk and cooking fodder, an ics for making roti and heating bathing water, and an lpg stove for making subji, dal, and tea, the demands would be specified as:

hara_dem = yd6 + yd7
tmc_ics_dem = yd4 + yd5
lpg_dem = yd1 + yd2 + yd3
biogas_dem = 0
kero_dem = 0

The final demand which needs to be specified is the amount of manure required for fertiliser. This may be set equal to zero or to a known value, depending on the scenario definition. For example, it may be known that the farmer requires 40 kg per day of dung to be allocated as manure to adequately fertiliser his fields, thus the variable manure_dem would be set equal to 40 (manure_dem = 40).

5. Environmental Resource Costs

The final set of parameters which need to be defined to finish the scenario definition are the unit costs of the Environmental Resource Variables. Sixteen different unit costs need to be specified and in some cases some of the costs will be zero. The following unit costs must be specified:

xe1 - cost of 1 kg of cooked fodder
xe2 - cost of 1 kg of fresh fodder
xe3 - cost of 1 kg of dry fodder
xe4 - cost of 1 m^3 of water
xe5 - cost of 1 kg purchased fuelwood
xe6 - cost of 1 kg fuelwood from own land
xe7 - cost of 1 kg fuelwood from tree plantation
xe8 - cost of 1 kg fuelwood from government forest area
xe9 - cost of 1 kg of fuelwood from panchayat forest area
xe10 - cost of 1 kg of fuelwood from the roadside
xe11 - cost of 1 kg of fuelwood from other private sources
xe12 - cost of 1 kg of crop residue
xe13 - cost of 1 kg of kerosene
xe14 - cost of 1kg of lpg
xeo1 - sale price of 1 kg of milk
xeo2 - sale price of 1 kg of slurry

The remainder of the code in the file is divided into three sections, none of which need to be modified by the user. The first section contains the code for the calculation of the 'y equations', the second section contains the code for the calculation of the 'x equations', and the third contains the code to format and write the model results to the output file. Once the user has specified all of the costs the file must be saved under the same file name and the steps detained in Sections 1 and 2 followed to run the model.

How to Run the Model

The software platform used for the model is Matlab, which stands for Matrix Laboratory. The model code is written in a text file which essentially contains a series of Matlab commands. All Matlab files have the extension .m. The text file is run in Matlab and the results are output to a second file, which may be then examined using a generic word processor. For the agricultural subsystem the model code is contained in the file:

agrisys.m

and the output is written into the file:

agriout.m

1. Starting Matlab

The first step in running the model is to open up the Matlab program. From the Windows Program Manager, select the Student Edition of Matlab icon to open the Matlab folder. To invoke Matlab, double click on the Matlab icon and the Matlab Command Window will open. The prompt in the Command Window is EDU>> and this is similar to the c:> dos prompt.

2. Running the Model

To run the model first change the directory to the model directory: EDU>> cd d:\cynthia\model [enter]. Then to run the model simply type EDU>> agrisys [enter]. When the prompt reappears the model has finished running (only a couple of seconds). The output can then be viewed in the Matlab Command Window by typing: EDU>> type agriout.m.

3. Modifying the Model Parameters

Obviously, before running the model, the user will want to specify the specific parameters for the scenario to be investigated. To do this the agrisys.m file has to be modified. To modify the file use the Notepad text editor available under the Accessories icon from the Program Manager of Windows. Once the Notepad editor is invoked, open the file d:\cynthia\model\agrisys.m. The changes that are to be made to create different scenarios are described step by step below. Once the changes have been made i.e. the new scenario is fully described, save the file. To run the model using these new parameter values follow the steps described in 2. Running the Model.

4. Setting Up an Agricultural Subsystem Scenario

Once you are into the Notebook editor with the agrisys.m file open you are ready to begin creating your scenario. At the beginning of the file their is a brief description of the model. A % sign at the beginning of a line indicates a comment this means that Matlab will skip over this line and not read it. Comments are generally used to provide description to the Matlab code.

Model Parameter Section of Code

1. Identify the Crops which are grown by the household.

The production of three different crops may be modelled: mustard, wheat, and guar. For any given run of the model at least one crop must be selected and to a maximum of all three being selected. To select a crop set the variable equal to 1 to unselect set the variable to 0 e.g.,. if for the scenario the farmer is to grow mustard and guar set mustard = 1, wheat = 0, and guar = 1.

2. Select the Fertiliser Scenario

For each crop there are six possible different fertiliser combinations to be examined. The same fertiliser combination is selected for all crops for any given run of the model. To select the scenario set the variable scenario equal to the scenario number you wish to run: i.e. if you want to run scenario 4 - 50 % slurry + 50 % dung then set scenario = 4.

3. Specify the Horsepower of the Irrigation Pump

As the water is paid for on a per horsepower flat rate, instead of a per m3 used, the hp of the farmer=s irrigation pump needs to be specified for use later in the model to calculate the cost of the water used for irrigation. For example if the farmer has a 5 hp irrigation pump the variable pump_hp should be set = 5 (pump_hp = 5).

4. Specify Parameters for Mustard Crop

If mustard has been selected as a crop, then the parameters for the mustard crop need to be specified. There are two sets of parameter values to be specified, the parameters for the field and crop components and the decision weightings for the decision web. First the field component parameters are specified. Because only one of six fertiliser scenarios can be examined, the actual parameter values do not need to be changed, only the set of parameters which relate to the fertiliser scenario selected need to be uncommented. The parameters are currently set for the agroclimatic growing conditions in Haryana.

The only reason the actual values would change is if the crop production in a different agroclimatic region is to be investigated. If, continuing the example from above, fertiliser scenario 4 is to be run then the comment (%) signs need to be removed (deleted) from the front of the five lines specifying the 'k'values for scenario 4 and comment signs must be added to the front of all of the other five scenario 'k' value lines. Second the crop component parameters need to be specified. Similar to the case with the field parameter values, the crop parameter values are defined by fertiliser scenario and all the user has to do is uncomment the 2 'k' value lines corresponding to the selected fertiliser scenario. Third the decision weightings for dividing the crop and crop residue need to be specified.

5. *Specify Parameters for Wheat and Guar Crops*

The process for specifying the parameters for the wheat and guar crops is identical to that described for the mustard crop. The appropriate parameters need only be uncommented if the crop has been selected.

6. *Select the Case to be Investigated*

As described above, one of three different cases can be investigated, where:

Case 1 = Crop / Crop Residue demand levels are specified.
Case 2 = Environmental Inputs (seed, water, fertiliser) are specified.
Case 3 = Field Size is specified.

Only one case can be investigated for any given run of the model. To select a case set the variable equal to 1 to unselect a case set the variable equal to 0. For example, to investigate case 3 set: caseI = 0; caseII = 0, and caseIII = 1.

Model Equation Section of Code

The model equations are divided into the 'y equations' and the 'x equations'. For each of the three cases, a different set of 'y equations' is solved. Consequently, a different set of demands or driving values must be specified. For each of the three cases the same set of 'x equations', which calculate the cost of producing the outputs given the costs of the environmental inputs, is used. Thus these equations only appear once, after each of the three sets of 'y equations' for the three cases.

7. If Case I is Selected.

If Case I is selected then the demands have to next be specified for each crop to be investigated. The demand values are initialised to zero and not all variables need be given a value, depending on the particular scenario being examined. For example, if a crop such as mustard, which has no fodder component of the crop residue, is grown then the demands yd5 (fresh fodder crop residue for sale) to yd9 (dry fodder for animal feed) will be left as zero. The specified demand values are stored in a 13 x 3 matrix, with the first column corresponding to the values for the mustard crop, the second column corresponding to the wheat crop and the third column corresponding to the guar crop. For this reason, the variable being specified is an element in the matrix represented by the variable spec_dem(m,n). For mustard crop the column (n) is always equal to 1, for wheat the column (n) is always equal to 2 and for guar n=3. Although there are only 9 demands to be specified, the matrix has 13 columns because it is used for solving a system of 13 equations and thus the values: spec_dem(3,n), spec_dem(4,n), spec_dem(7,n), and spec_dem(8,n) are always set automatically to zero. Thus for each crop:

spec_dem(1,n) = yd1 - kg of crop for sale
spec_dem(2,n) = yd2 - kg of crop for household use
spec_dem(5,n) = yd3 - kg of non-fodder crop residue for fuel
spec_dem(6,n) = yd4 - kg of non-fodder crop residue for building material
spec_dem(9,n) = yd5 - kg of fresh fodder crop residue for sale
spec_dem(10,n) = yd6 - kg of fresh fodder for animal feed
spec_dem(11,n) = yd7 - kg of dry fodder for sale
spec_dem(12,n) = yd8 - kg of dry fodder for cooked fodder
spec_dem(13,n) = yd9 - kg of dry fodder for animal feed

Once the demands are specified the next step is to specify the cost parameters for the set of 'x' cost equations. See Section 10.

8. If Case II is Selected.

If Case II is selected as the case to be investigated then the total environmental inputs available for each crop must be entered. For each of the five inputs to be specified, one (3,1) column vector is used to store the values for all three crops. For this reason for the mustard crop the index is = 1, for wheat crop the index = 2, and for guar crop the index = 3. The inputs being specified must correspond to the fertiliser scenario selected, i.e. if fertiliser scenario 4 is selected, comm _fert must equal zero and a value must be given for the amount of dung (dung = n) and slurry (slurry = m) available to the farmer. Once the total inputs available are specified the next step is to specify the cost parameters for the set of 'x' cost equations. See Section 10.

9. If Case III is Selected.

If Case III is selected as the case to be investigated then the field size allocated to each crop needs to be specified. The field size should be entered in acres which the model converts to hectares. In the output the field size in both units is given. For example, if a farmer wants to plant 3 acres of mustard, 4 acres of wheat, and one acre of guar the variables would be specified as: mustard_acres = 3, wheat_acres = 4, guar_acres = 1.

Once the field size is specified the next step is to specify the cost parameters for the set of 'x' cost equations. See Section 10.

10. Specify the Unit Costs for the Environmental Inputs

The final step to complete the specification of the scenario is the specify the unit costs for each of the environmental inputs. The costs are specified in terms of cost in Rs per unit of material:

seed_cost = Rs / kg of seed purchased
water_cost = Rs / m^3 of water used
comm_fert_cost = Rs / kg of commercial fertiliser purchased
dung_cost = Rs / kg of dung purchased
slurry_cost = Rs / kg of slurry purchased

For some of the inputs the cost may be equal to zero, for instance if the farmer uses dung from his own animals as manure then the dung_cost would be zero (etc.). Currently, the water_cost should be set equal to zero, as at this time the water cost is directly calculated from a flat rate per year per horsepower (Rs 50 per hp per year).

The remainder of the code in the file specifies the format for the writing the output to the file agriout.m and does not need to be changed by the user. Once the costs are specified the file should be saved to the same file name (agrisys.m). The scenario can then be run by following the steps described in Sections 1 and 2 above.