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A generic model for analyzing nexus issues of households' bioenergy use

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Abstract

Bioenergy is a major source of energy in developing countries. However, increasing demand for agricultural commodities can lead to a stronger competition for natural resources with the bioenergy production. The nexus among energy, food production and natural resource use may result in trade-offs and synergies. Accordingly, it is important to consider multidimensional aspects of bioenergy, assess the potential for bioenergy options for meeting rural households' demand for energy, while increasing their incomes, enhancing food security and reducing potential negative effects. For addressing these interrelated issues within a single framework, we develop a generic household model that allows analyzing the *ex-ante* potential impacts of bioenergy use on rural households in developing countries. The model relies on dynamic programming approach and is able to evaluate the impacts of bioenergy on livelihoods of households, on environment, and on natural resource use over time. The model explicitly considers decision making among various members of household, including men, women and children. We also trace direct and spillover impacts of policy and technological changes among different socio-economic categories of households.

Keywords: Dynamic programming, equity, gender, technological innovations, environment, trade-offs, spillovers, synergies.

JEL-classification: C61, D63, O13, O33, Q4, Q12

1 Introduction

Bioenergy plays an important role in the energy mix in developing countries. Globally, 2.64 billion people depend on this energy source (as of 2011; IEA, 2013), with the vast majority being in developing countries. Bioenergy is especially important in rural areas with decentralized energy supply and where most of the poor are located. Bioenergy can provide with incomes, employment opportunities, as well as may bring potential environmental benefits through lower greenhouse gas emissions than fossil fuels (Cushion et al., 2010; Popp et al., 2014). Despite the high role of bioenergy in the livelihoods of people, its current domestic uses have also certain disadvantages. For instance, the traditional use of biomass for cooking and heating has detrimental health effects through indoor air pollution (Lim and Seow, 2012), making women and children the most affected group that are already overburdened with the tedious process of collecting biofuels (Barnes and Floor 1996). Poor health leads to lower working productivities and incomes amongst rural households (Duflo et al. 2008), besides these households incur significant health care costs aggravating their poverty. In addition, agricultural production will have to increase by 60-70% in the next 40 years (FAO, 2012) to cope with higher food, energy and feed demand due to population growth. Increasing demand for agricultural commodities and natural resources can lead to an increased competition with the production of bioenergy. Furthermore, several other factors create uncertainties in the production of food and energy, such as climatic and environmental changes, fluctuations in prices, and changes in institutions and policies (Hardaker et al., 2004). It is not clear what will be the state of nature, market and political conditions in the future for meeting food and energy demands of the population. Interconnections among various sectors and uncertainties about their state may lead to trade-offs in health, incomes, food, energy and environmental protection. The Water-Energy-Food Security Nexus approach seeks to utilize the interdependencies of energy, food production, natural resource use for synergies, and provides a framework to minimize negative externalities in order to achieve sustainable development (Bazilian et al., 2011; Hussey and Pittock, 2012; Mirzabaev et al., 2014; Rasul, 2014).

Model-based analysis is an important tool to explore the relationships between bioenergy and in broader context of energy use, livelihoods and food security. Several approaches are often used in modelling energy use and these studies also differ in their scale of analysis (Jebaraj and Iniyan, 2006). For example, simulation models were used to observe the long-term development pathways of the energy systems. Isaac and van Vuuren (2009) used a global model to analyze the residential energy demand in the context of climate change. The study by Daioglou et al. (2011) projected the world-wide residential energy use using a bottom-up energy model that considers the heterogeneity of households. Other studies used a system dynamics model to model the complexity of the socio-technical system of household energy consumption (Motawa and Oladokun, 2015). Among the energy models developed by the International Energy Agency, MARKAL and its extension TIMES are widely applied (Goldstein and Greening, 1999; Howells et al., 2005; Mondal et al., 2012). The MARKAL is a bottom-up, dynamic linear programming model of a country's energy system. Whereas the TIMES is a multi-period cost minimizing linear programing model that supports rich detail on technology cost and represents technologies in a "bottom up" framework. In addition, studies exist on bioenergy use and linkages with other sectors using partial (Bryngelsson and Lindgren 2013) and general equilibrium optimization models (Kretschmer and Peterson, 2010). Although all of these models are important in analyzing nexus issues within bioenergy use, to our knowledge they lack the impact assessment at disaggregated level. In modelling nexus issues it is important to have in-depth understanding of households' complex activities and decisions and various interconnections among them. A micro-level modeling framework allows investigating households' behavioral responses to policy and technological changes considering the nexus linkages. Besides, with such model it is possible to capture households' heterogeneities and interdependencies in detail. Households can differ in their characteristics and thus the effects of changes are different on various households. Heterogeneous households are also interrelated, e.g., through agricultural contracts, kinship, geographic location, and the changes in policies and technologies may have direct effects on households for whom they are designed and indirect effects on other groups of households.

An agricultural household model, which assumes that a household is engaged in production and consumption decisions simultaneously, is proposed here to address the above issues. Agricultural household models have been extensively used for studying household behavior affected by policy and technological changes in developing countries (Singh et al., 1986; Holden et al., 2005). Several studies used such non-separable models to analyze the bioenergy-based simultaneous production and consumption decisions of households (e.g., see Pattanayak et al., 2004; Chen et al., 2006; Djanibekov et al., 2013; Guta, 2014). However, to our knowledge most of these studies either relied on econometric estimations and missed to have ex ante assessment of possible policy and technological changes, or did not take into account the heterogeneity within and among households and multidimensional issues. In this study we address these gaps by developing an agricultural household model to analyze the nexus interconnections in rural households' bioenergy use. The tool captures the key features of rural households in developing countries to provide the detailed information on households' activities, commodities, consumption, and technologies to improve knowledge on food, energy and natural resource nexus. The novelty of the model is its dynamic representation of decisions at the household level that includes into the economic optimization the multidimensional and interrelated aspects such as incomes, food and energy consumption, natural resources, environment, health, equality, trade-offs, synergies, rural linkages and direct and indirect effects. The aim of this study is to develop the Water-Energy-Food Security Nexus concept in the generic agricultural household model that can be used, adapted and extended to developing country settings for ex ante assessment of households' bioenergy use under different policy and technological scenarios.

The remainder of this paper is structured as follows: in section 2, we present the overall structure and the main components of the model; in section 3, we describe in detail the main model equations; section 4 concludes the study.

2 Model structure and components

This paper develops an agricultural household model (hereafter referred to as household model) based on mathematical programming to examine possible outcomes of bioenergy and other energy sources on rural households' livelihoods. In developing the model we rely on the concepts of Water-Energy-Food Security Nexus discussed in Mirzabaev et al. (2014). The model maximizes an objective function at given prices subject to a set of constraints. More specifically, we develop a dynamic programming model to investigate possible effects on the livelihoods of households that mainly rely on bioenergy and the ones that use less bioenergy sources. We also focus through the nexus concept on the multidimensional impacts of bioenergy use. The nexus is included via the relationships of equations in the programming model. The model can be used for forecasting possible outcomes and providing recommendations for policy and decision makers on rural household incomes, gender equality, consumption of food and energy, employment, land and water use, agricultural production, and management of ecosystem, as well as spillover effects, trade-offs and synergies among them. The model is generic and can be adapted and extended to different case study countries in analyzing bioenergy. It is developed using the General Algebraic Modeling System (GAMS), which is a modeling system for mathematical programming and optimization1.

The main specifications of the model are:

- *A normative model*, which is a prescriptive type of model that starts from a decision rule of the household and determines the levels of different variables when aiming to optimize the objective function of households. In the model, parameters of the objective function and constraints are not calibrated to historical data (due to the lack of rich panel data usually observed for developing countries), but relies on information from census and survey data;
- *A dynamic programming model*, which optimizes an objective function over the period of analysis when the decisions of households are taken. Households have foresight over the whole period of analysis and adjust their activities annually to achieve the optimal outcome. To address dynamics in the model we specify length of time and time intervals in years, rate of time preferences of households (i.e., discount rates), initial conditions and transformation functions. The model duration can be changed depending on activities of households;
- *A mixed integer programming*, which allows us to consider that some of the model variables are constrained to be integers, while other variables are fractional values. For example, our variables on number of livestock head, energy and farming

[1] http://www.gams.com/

technologies are whole values, and variables such as land use area and amount of energy consumed can be fractional;

- *A primal based model*, where households' farming activities are explicitly included to simulate the switch between farm production techniques, production systems and off-farm activities. Such model can assist households in deciding which and how much of each activity to select to maximize income;
- *An activity based model*, which means that households maximize their incomes using different options. For example, products from farming can be produced using different activities, and each activity can produce several different products (Louhichi et al., 2013). Such model is suitable to analyze the trade-offs in household decisions where depending on activity the output of some products can be reduced due to increasing output of other products. Similarly, it is possible to capture synergies. In addition, activity based model can make integrated assessment of policies that are linked to activity. For example, bank loans and state subsidies for households depending on specific agricultural practices or energy production techniques;
- *A stochasticity in the model*, which includes variability of parameters that affect the incomes of households. The variability (risks) is included as the exogenous variables. We assume that the variability can occur in input available for farming such as irrigation water, in crop output yield and prices, and energy provision (e.g., blackouts in centralized electricity and gas supplies). Such type of analysis allows observing the model outputs such as variables under different states of nature. Including the multiple activities in our model provides information on how households respond to risky situations while maximizing their incomes, and accordingly can help to develop the risk management strategies for households.

The core aspect of the model is the use of energy by households. Energy sources have different provision of energy amount and differ in final use (Table 1). In the model we define energy sources as bioenergy, centralized (e.g., central gas and electricity stations), conventional (i.e., liquefied petroleum gas (LPG), coal, kerosene) and renewable (e.g., solar panel). We consider bioenergy sources such as fuelwood and charcoal harvested from forest, perennial crops at own farm for fuelwood and charcoal, crop residues (by-products), and livestock residues (manure). Availability of forest stock allows considering that households can have access to freely available energy resources, yet it can be depleted if harvested unsustainably. Bioenergy technologies include cooking stoves, combined heat and power technologies. In the model, households can select whether to have open pit fire while using energy or burn energy source using technologies (e.g., stoves, combined heat and power technologies). Bioenergy can be used also with certain technologies that influence the efficiency of energy. Bioenergy can be used for cooking, lighting and space heating or for farming and income generation through selling in the market. In addition, we consider the renewable energy technologies such as solar panels. We assume that renewable energy technologies can be only used for own household purposes such as cooking, lighting, space heating and farming. We assume that the solar panels have intermittency problems during the winter season, when insufficient sunshine is available to generate energy. For addressing this issue households can purchase batteries that will ensure sufficient supply of energy for solar panels throughout the year. Bioenergy and renewable energy technologies reduce the negative effects on households (i.e., health of household members) and society as a whole (i.e., environmental externalities), yet, may incur high initial costs.

Table 1. Energy sources available for households by destination use.

For residential purpose			As input for farming	For selling in market
Cooking and water boiling	*Space heating*	*Lighting*		
Coal	Coal			
Liquefied petroleum gas				
		Kerosene, Diesel		
Natural gas	Natural gas			
Electricity		Electricity	Electricity	
Renewable energy technologies	Renewable energy technologies	Renewable energy technologies	Renewable energy technologies	
Charcoal	Charcoal			Charcoal
Fuelwood	Fuelwood			Fuelwood
Bioenergy crop by-products	Crop by-products		Crop by-products	Crop by-products
Animal dung	Animal dung		Animal dung	Animal dung

Note: Electricity states for the centralized electricity supply.

Using the dynamic programming we evaluate contribution of energy sources upon lifetime costs and benefits, taking into account constraints imposed on the household decision making. The model analyzes decisions of households that have income maximization objective. While optimizing incomes, households have to make decisions considering multiple issues that impact their livelihoods while focusing on either to use bioenergy or renewable energy technologies or centralized energy sources. For addressing various aspects of using vs not using different energy sources we consider a set of modules and components, which include annual and perennial crops, bioenergy crops and technologies, renewable energy sources, livestock, variability (i.e., risks), health of household, environment, off-farm income opportunities and policies (Figure 1). Each of these components can be switched on/off following the needs of the model simulation.

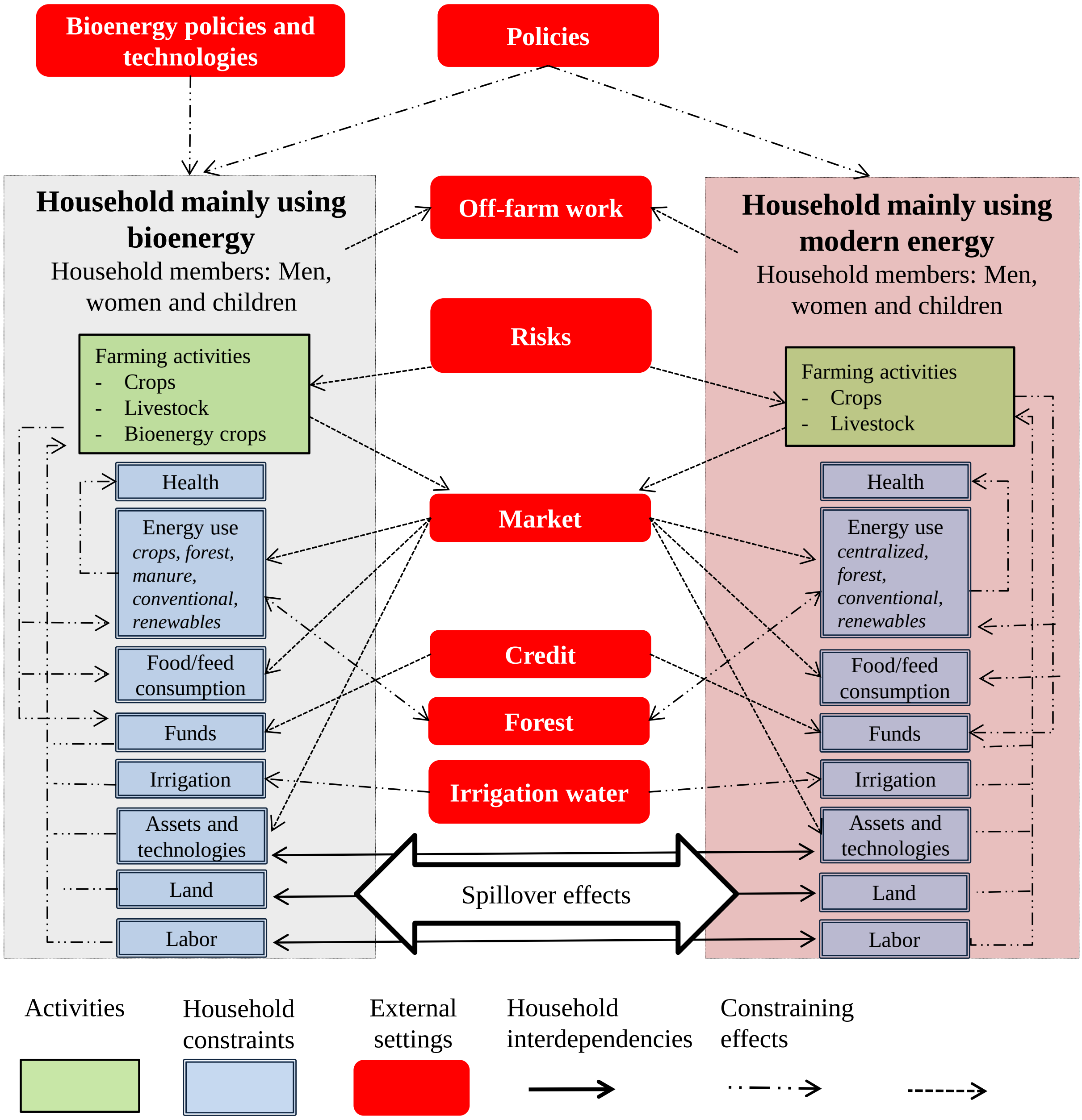

Figure 1. Main components of the model.

In the model, households are heterogeneous. We have the household (household type 1) that has small-scale farm, mainly relies on bioenergy, but also uses conventional energy sources and can obtain renewable energy technologies. Another household (household type 2) that is relatively economically rich, and mainly uses centralized energy sources (i.e., centralized gas and electricity) and sometimes complements it with charcoal, fuelwood, conventional energy sources, and can obtain renewable energy technologies. Usage of energy sources directly affects households' livelihoods, e.g., income, food consumption and health. In addition, households differ in resources available such as initial amount of funds (cash) for expenses, labor hours available, land area, machinery and livestock number. Heterogeneity among households can be removed, and instead the model can be applied to average farm by aggregating the results of individual farms. The purpose of considering various household types is to address the direct and indirect effects (i.e., spillovers) of energy use and related to them policies on different groups of rural population. The spillover effects are important to analyze whether the impacts are positive or negative on the other type of households from policy and technological changes. In rural households the vital spillover effects arise through the rural interdependencies, where rural households can be interlinked, e.g., through agricultural contracts, kinship, geographic location. In our study, households are interdependent through their farming activities and to optimize their farming activities they share resources. We include households' interdependencies through the share of farm production resources (e.g., land, labor and technologies), where their sharing occur through contracts. The spillover effects occur when policy and technological changes targeted to one group of household have impacts through contracts to another group of households.

Furthermore, households differ in their characteristics such as number of household members and role of men, women and children in household. These types of heterogeneity in the model include, for instance, how male, female and children manage crop or livestock, and how much off-farm opportunities they have. Obtaining and using some of the energy sources can be men, women and children specific. For example, collection of wood from forest for fuelwood and charcoal is assumed to be conducted by women and children. The differences within the household allow us to analyze how policies impact each household member. Accordingly, policy implications can be inferred to address the issue of child labor and gender equity in rural areas.

Income of households is maximized annually by selling own farm products, receiving wage from off-farm work and agricultural payments from renting resources and hiring labor from another household. Each household has to satisfy food and energy consumption demand depending on number of men, women and children that increase with time. We assume in the model the population growth, which is an exogenous factor. Increase in household members puts pressure on natural resources such as land and water as well as environment to meet food and energy demand of household members. Consumption of energy sources affects the health of household members. Certain energy sources reduce health and labor productivity. Maintenance/recovery of health leads to additional expenditures for households. In addition to the repercussions on households' health, the usage of energy sources lead to environmental externalities, which are the externality costs of pollution on society. The renewable energy and bioenergy technologies can be options to reduce the negative health and environmental effects.

The main activities of the households are related to own farm (i.e., annual and perennial crops, bioenergy, and livestock), working at farm of another household and off-farm. The annual crop production is based on different inputs but we do not include crop production function due to the lack of data. The agricultural production activities are subject to resources available, as well as satisfying households' demand for food and energy and maintaining health conditions of household members. Some of the agricultural inputs require energy. For example, pumping irrigation water for crops can be performed by the pumps that are run by using centralized electricity, renewable energy technologies, and diesel. Household can select the amount and type of input and resources that can be used for farming, i.e., producing annual and perennial crops and rearing livestock. Hence, there is a trade-off among farming activities. In contrast, some farming activities result in synergies where activities and products can complement each other, e.g., fodder crops can be given to livestock and livestock can have manure that can be used for fodder crops. In addition, the external conditions influence households' decisions. For example, we assume that households have access to the market for selling and buying products. Funds available for household expenses can be from households' both on-farm and off-farm activities, as well as credits received from bank.

In the model, we apply several policy and technological scenarios to assess the options to facilitate bioenergy and renewable energy technology adoption, and improve rural livelihoods. The scenarios are energy source specific and aim to provide benefit sharing within household members and among rural household types. Some of these scenarios can be targeted only to one type of household, whereas some policies are targeted to all types of households. We include the following policy scenarios:

- Business-as-usual scenario;
- Scenario with no government subsidies for fossil fuel based energy sources;
- Innovative bioenergy crop scenario;
- Bioenergy and renewable energy technologies scenario;
- Credit incentives scenario;
- Scenario of no access to forest;
- Scenario for equal share of benefits among household members;
- Scenario to cushion the negative spillover effects.

More description on policy scenarios is given in Section 3.7.

In the following section we describe the model and present its main equations. The complete view of model indices, variables and parameters are presented in the Appendix.

3 Description of model equations

To investigate the impacts of using energy sources we develop the dynamic household programming model that maximizes discounted incomes of households over years under different states of nature. The states of nature are needed to observe the decisions of households under different situations, which can occur due to uncertainty of various factors (e.g., crop yield and price, amount of irrigation availability). We include heterogeneous households that have a foresight over the period of the analysis and adjust their activities to maximize income. The model includes different outputs and inputs that differ depending on involvement of men, women and children. The price of output and input does not change depending on household type and gender.

3.1 Heterogeneity within and among households

In our model households are heterogeneous among their members. We classify household members into men, women and children. Along with men, women and children are crucial labor force in agriculture and contributors to household livelihoods. For instance, in Mozambique strong interrelated effects are observed between bioenergy and food security of households when female laborers reallocate from food production to bioenergy production (Arndt and Benifica, 2011). In our model, each of the households differ in their labor hours available for farm and off-farm work, wage from working in such activities, division of farm management activities, labor productivity in farming, initial and changed health conditions. We omit opportunities for schooling, leaving household and other age and gender specific activities that are not related to farming. Off-farm activities include one aggregated work opportunity. Labor productivity of men, women and children changes with respect to their health status. Number of household members increases annually as a result of population growth. For the simplification of the model, we assume that the share of men, women and children in household remain the same throughout the period of analysis. Accordingly, after certain period of time, in the model there is no shift from one household member to another, i.e., from children to women and men.

The model represents average household types, and can include many different types of households. In this study, for the simplicity of presentation, we assume two types of households, where one household (Household type 1) has small-scale farming opportunities, less economic conditions, mainly rely on bioenergy, but also uses conventional energy sources and can obtain renewable energy technologies, whereas another type of household (Household type 2) has large-scale farming, better economic conditions, mainly uses the centralized energy sources and occasionally uses bioenergy, conventional energy sources, and can obtain renewable energy technologies. We classify households with enough detail to directly address the impacts of using bioenergy on the relevant decision variables of the individual household and accordingly observe potential effects on their livelihoods, consumption of food, energy use and agricultural production. Furthermore, we assume these households to be interrelated to each other through the farming activities. We assume that household type 2 can share (i.e., rent out) its land and machinery with household type 1. Whereas household type 1, we assume, is more abundant in labor and thus surplus of its labor can be hired by household type 2. The number of household types can be extended depending on the model aim and study area settings. For the simplification of model explanation, we present equations of the model that depict the main differences and interdependencies among households. More description on interdependencies of households and spillover effects is described in Section 3.5.

3.2 Livelihoods of households

Income of households. Bioenergy improvement can contribute to rural development and poverty alleviation efforts (Wicke et al., 2011). The model allows assessing the contribution of energy sources to the livelihoods of households. The objective function of the model is the income maximization of households over time, subject to various constraints. We use the income maximization objective to account for the fact that households have several sources of income and expenditures, besides agricultural activities. Households select on- and/or off-farm activities and expenditures to maximize their income. More specifically, the incomes of households are generated from selling agricultural products such as cash, food and energy crops and livestock, wages received from working at another farmer or renting out resources, and from working in non-agricultural activities. Each of these activities can involve costs such as expenditures for agricultural production and transportation. The costs also include purchase of agricultural products for household consumption and meeting energy demand and expenses for maintaining health conditions of household members. We consider that the transaction costs incur when households purchase agricultural commodities from the market. Also, transaction costs occur when households work off-farm and in such case costs are related to transportation from household to off-farm work and cost of time spent for finding the off-farm work. The income function of households is different depending on household type. The main differences among households are that household type 1 does not have access to centralized energy sources, and thus bears no costs for centralized energy (Eq. 2). In addition, this household incurs costs on renting in machinery and land from household type 2, and receiving wage for farming activities from household type 2. In contrast, household type 2 does not purchase bioenergy crops from the market, and generates revenues from renting out land and machinery to household type 1. The households' incomes vary depending on states of nature of certain parameters (e.g., variability of irrigation water availability, crop price and yield fluctuations), which allow analyzing the state of households under different conditions. The following are objective function of households (Eq. 1), and income functions of household type 1 (Eq. 2) and household type 2 (Eq. 3):

$$Max\ Obj = \sum_{f=1}^{F}\sum_{v=1}^{V}\sum_{t=1}^{T} I_{vft} \tag{1}$$

$$\begin{aligned} I_{vft} = \Bigg(& \sum_{a} p_a S_{avft} + \sum_{a}\sum_{b} \bar{p}_{ab}\bar{S}_{abvft} + \sum_{a}\sum_{ln} \bar{\bar{p}}_{aln}\overline{\overline{ln}}_{aln}\bar{\bar{S}}_{avft} + \sum_{a}\sum_{ln} \tilde{p}_{aln}\,\overline{\overline{ln}}_{aln}\tilde{S}_{avft} \\ & + (1-trn)\sum_{g} w_g N_{vfgt} + CR_{vft} + \sum_{i} pw_i L\ddot{W}_{ivft} \\ & - \sum_{i} \ddot{p}_i AI_{ivft} - \sum_{i} \grave{p}_i AT_{ivft} - (1+tra)\sum_{a} p_a B_{avft} - (1 \\ & + tra)\sum_{a}\sum_{b} \bar{p}_{ab}\bar{B}_{abvft} - \sum_{a} \bar{\bar{p}}_{aln}\bar{\bar{B}}_{alnvft} - \acute{p}_o \acute{E}_{ovft} - \ddot{p}_r \ddot{B}\ddot{E}_{rvft} \\ & - \sum_{ec}\sum_{ed} \hat{p}_{ec}\hat{B}_{ecedvft} - \sum_{i} pm_i L\ddot{M}_{ivft} - \sum_{i} pl_i L\ddot{L}_{ivft} - \bar{c}\bar{r}CR_{vft-1} \\ & - pm\sum_{g} ME_{vfgt} \Bigg) \left(\frac{1}{1+dr}\right)^{t} \end{aligned} \tag{2}$$

$$\begin{aligned} I_{vft} = \Bigg(& \sum_{a} p_a S_{avft} + \sum_{a}\sum_{b} \bar{p}_{ab}\bar{S}_{abvft} + \sum_{a}\sum_{ln} \bar{\bar{p}}_{aln}\overline{\overline{ln}}_{aln}\bar{\bar{S}}_{avft} + \sum_{a}\sum_{ln} \tilde{p}_{aln}\,\overline{\overline{ln}}_{aln}\tilde{S}_{avft} \\ & + (1-trn)\sum_{g} w_g N_{vfgt} + CR_{vft} + \sum_{i} pm_i L\ddot{M}_{ivft} + \sum_{i} pl_i L\ddot{L}_{ivft} \\ & - \sum_{i} \ddot{p}_{it} AI_{itvft} - \sum_{i} \grave{p}_i AT_{ivft} - (1+tra)\sum_{a} p_a B_{avft} - (1 \\ & + tra)\sum_{a}\sum_{b} \bar{p}_{ab}\bar{B}_{abvft} - \sum_{a} \bar{\bar{p}}_{aln}\bar{\bar{B}}_{alnvft} - \acute{p}_o \acute{E}_{ovft} - \ddot{p}_r \ddot{B}\ddot{E}_{rvft} \\ & - \sum_{e}\sum_{ed} \tilde{p}_e \tilde{B}_{eedvft} - \sum_{ec}\sum_{ed} \hat{p}_{ec}\hat{B}_{ecedvft} - \sum_{i} pw_i L\ddot{W}_{ivft} - \bar{c}\bar{r}CR_{vft-1} \\ & - pm\sum_{g} ME_{vfgt} \Bigg) \left(\frac{1}{1+dr}\right)^{t} \end{aligned} \tag{3}$$

where Obj is the objective of farmer to maximize the net present value of households' incomes I over the period of analysis t (1, 2, …, T) under different states of nature v, p is the farm gate price of crop main products and livestock head, S is the amount of agricultural products sold including cash, food and energy crops and livestock by different households f where bioenergy can be sold only by household type 1, $\bar{p}$ is the price of crop by-products b, $\bar{S}$ is the amount of crop by-products sold, $\bar{\bar{p}}$ is the price of livestock products ln, $\overline{\overline{ln}}$ is the amount of products that can be obtained from livestock such as milk, meat, eggs and manure, $\bar{\bar{S}}$ is the amount of livestock products sold, $\tilde{S}$ is the amount of livestock slaughtered for meat, trn is the transaction costs for off-farm work, w is the wage from off-farm work that differs depending on members of households g, N is the income from off-farm work of household members, CR is the amount of credit received from bank that needs to be returned in the next year, $\ddot{p}$ is the price of inputs i for agricultural production, AI is the amount of inputs purchased for agricultural production, $\grave{p}_i$ is the price of agricultural production technologies it (e.g., irrigation water pumps), AT is the amount of technologies purchased for agricultural production, pw is the wage amount for household type 1 for working at farm of household type 2, $L\ddot{W}$ is the work time for farming by household type 1 for household type 2, tra is the transaction costs for purchasing agricultural products from the market (higher value than the farm gate price), B is the amount of agricultural products/activities purchased from the market, $\bar{B}$ is the amount of crop by-products purchased, $\bar{\bar{B}}$ is the amount of livestock products purchased, $\acute{p}$ is the price of technology o used for burning crop main products and by-products to generate energy, $\acute{E}$ is the amount of energy technologies purchased that are used for energy crop main products and by-products, $\ddot{p}$ is the price of renewable energy technologies r with batteries and without batteries, $B\ddot{E}$ is the amount of purchased renewable energy technologies with and without batteries, $\tilde{p}$ is the price of centralized energy sources e that can be used only by household type 2, $\tilde{B}$ is the amount of centralized energy sources purchased that can be used for various purposes of household ed (i.e., heating, lighting, cooking, boiling and pumping irrigation water for farming) by household type 2, $\hat{p}$ is the price of conventional energy sources ec (i.e., LPG, coal and kerosene), $\hat{B}$ is the amount of conventional energy sources purchased, pm is the price of renting in machinery for farming by household type 1 from household type 2, $L\ddot{M}$ is the amount of machinery rented out for farming by household type 1 from household type 2, pl is the price of renting in land for farming by household type 1 from household type 2, $L\ddot{L}$ is the area of land rented out for farming by household type 1 from household type 2, $\overline{cr}$ is the interest rate used for returning the credit amount received from bank, pm is the price of purchasing medicine to maintain health of household members, ME is the amount of medicine purchased, and dr is the discount rate. In this equation the values of parameters and variables differ depending on household types. Household type 2 does not generate income from selling bioenergy sources, whereas opposite holds for household type 1. In addition, as can be seen from comparison of Eq. (2) with Eq. (3) household type 1 generates income from wages for working in household type 2, and has expenditures for renting in land and machinery from household type 2. And vise-versa holds for household type 2.

Off-farm income. In the model, households have two sources of income opportunities: from farming and off-farm work. Income from farming involves selling of agricultural commodities in the market. Off-farm income includes employment in the industry, services or other sector that is considered as aggregated off-farm income source outside of household's farm. However, off-farm employment opportunities may result in search costs (as given by trn in Eqs. (2-3)), and is limited according to household members:

$$ow_{gt} \geq N_{vfgt} \tag{4}$$

where ow is the amount of off-farm employment available for men, women and children over time. The involvement at on- and off-farm work can be affected by availability of activities and products for households. For example, in Ethiopia study by Scheurlen (2015) showed that fuelwood shortage reduce off-farm labor time allocation. Furthermore, off-farm opportunities can be different depending on household. We assume that household type 2 has more options for off-farm work than household type 1. Households' off-farm income differs depending on gender and age. For example, men can be more demanded and paid than women when working off-farm. To address such inequality, policy giving equal opportunities for women can be an option and is discussed in Section 3.7.

Expenditure constraint. Households' expenditures, which include agricultural inputs, purchase of food products and energy sources, are limited to household incomes and credit obtained from bank (Eq. 5). The credits received in the previous period will be paid back to bank according to the interest rate in the next period. The optimal value of household incomes becomes the funds available for expenditures for the next period, and such process is cumulative (Eq. 6). To model the dynamics in households' budget, we assume the initial level of households' budget. Hence, depending on the income amount remaining from the previous years and borrowed credit the households have funds available for purchasing agricultural production inputs, food, energy and fodder crops, bioenergy and renewable energy technologies, paying back credit with interest rate, and medicine to maintain health:

$$\begin{aligned} F_{vft-1} \geq \Bigg(& \sum_i pw_i L\ddot{W}_{ivft} + \sum_i \ddot{\bar{p}}_i AI_{ivft} + \sum_i \grave{p}_i AT_{ivft} + (1+tra) \sum_a p_a B_{avft} \\ & + (1+tra) \sum_a \sum_b \bar{p}_{ab} \bar{B}_{abvft} + \sum_a \bar{\bar{p}}_{aln} \bar{\bar{B}}_{alnvft} + \acute{p}_o \acute{E}_{ovft} + \ddot{p}_r \dot{B}\ddot{E}_{rvft} \\ & + \sum_e \sum_{ed} \tilde{p}_e \tilde{B}_{eedvft} + \sum_{ec} \sum_{ed} \hat{p}_{ec} \hat{B}_{ecedvft} + \sum_i pm_i L\ddot{M}_{ivft} + \sum_i pl_i L\ddot{L}_{ivft} \\ & + \bar{cr} CR_{vft-1} + pm \sum_g ME_{vfgt} \Bigg) \left(\frac{1}{1+dr} \right)^t \end{aligned} \tag{5}$$

$$F_{vft} = F_{vft-1} + I_{vft} \tag{6}$$

where F_t is the household fund available for household expenditures, which consist of discounted cumulative incomes from previous years and current income. Hence, our Eq. (4) includes dynamics in the household fund transformation. Depending on household type some of the expenditures are not considered, e.g., centralized energy and labor hire costs for household type 1, and machinery and land rent in costs for household type 2. Accordingly, expenditure constraint equation is specified for each household type.

Food consumption requirement. In developing country settings the food security affects the decision making of households (Singh et al., 1986). In our model, households' income maximization objective is subject to food consumption requirement. Households consume crop and animal products to meet their food consumption requirements. Depending on calorie demand and calorie content of crop and animal products households need to satisfy their nutrient requirement. Consumption of food products is age and gender specific. The consumption can be satisfied from own farm and products purchased from the market:

$$\sum_g c_{alnfgt} \leq DF_{avft} + \overline{DF}_{lnvft} + B_{avft} + \bar{\bar{B}}_{alnvft} \quad (7)$$

where c is the consumption requirement amount of agricultural products of households over years that increases every year depending on growth rate and is met through the consumption of crop DF and livestock $\overline{DF}$ commodities produced in household's own farm, and crop B and livestock $\bar{\bar{B}}$ products purchased from the market. There is no price and income effects on consumption amount of products.

3.3 Use of energy sources

Domestic energy consumption. In the model, depending on household size a certain amount of energy has to be consumed by men, women and children to meet energy requirements. Studies indicate that energy use decision of household is determined by intricate socio-economic factors and is conditioned by type of stoves, energy technologies and energy available, and thus household energy use conforms to multiple fuel use (Heltberge, 2004; Masera et al., 2005; Guta, 2012a). For the simplicity of our model run the energy consumption for domestic purposes depend on annual average energy demand of household members. Hence, we do not consider the daily load curves (energy demand) of households. The model simulates annual consumption of energy sources for cooking, heating and lighting purposes of household from the quantities of energy produced by the centralized, conventional, bioenergy products and renewable energy technologies. Energy sources have different destinations, e.g., crop by-products can be used for heating and cooking, while kerosene only for lighting. Using energy sources for multiple services may reduce the efficiency of energy services supplied. Households can decide whether to use single energy source or diversify and use different energy sources for satisfying energy demand, and thus there is no binding equation on substitution of energy sources. In addition, bioenergy sources can have several destinations in household activities, e.g., some crop main products can be used as energy, food for household consumption, fodder given to livestock and sold in the market, and households can decide the amount of bioenergy use by destination. Multiple destinations of bioenergy sources allows including nexus among various activities and products of households. For example, study by Heltberg (2004) showed that agricultural productivity may improve when households shift away from traditional bioenergy towards modern energy sources, as more resources become available and redirected towards agricultural activities.

Concerning origin of energy sources, we have several options on how households can obtain energy sources. For example, households can produce bioenergy sources in annual basis or wait and receive in longer period of time, use bioenergy sources stored from previous years, purchase from the market, and obtain for free from common natural resource pool (i.e., open access forest). Conventional energy sources can be purchased from the market, while charcoal and fuelwood can be purchased, harvested from households' wood plot and without cost (except labor time spent) harvest from the forest. We consider two possibilities of using wood as energy sources: fuelwood and charcoal. Establishment of tree plantations is assumed to be in the initial year, and household members can decide at which year to harvest entirely trees for fuelwood or charcoal. Hence, we have flexibility in wood harvest decision of household members. Household members can also harvest some amount of wood from broken twigs of plantation without clear-cut of trees. Charcoal can be obtained from harvested wood from forest and tree plantations at farm and purchasing briquettes from the market. Agroforestry is considered as an option to reduce pressure on forest reserves, and generate income and fuelwood for household (Faße et al., 2015). Households can also purchase renewable energy technologies and establish at own household, which necessitate only initial costs.

Consumption of energy sources is different depending on household type. Centralized energy sources are supplied by the state and in return household type 2 pays fees for used energy. Household type 2 satisfies a small share of energy consumption demand through bioenergy. Household type 1 does not use centralized energy sources. The following equation is the constraint on energy consumption requirement of households:

$$\tilde{c}_{fedt} \leq \sum_{a} ec_a D_{aedvft} + \sum_{a} et_a \acute{D}_{aedvft} + \sum_{a}\sum_{b} ecb_{ab} \bar{D}_{abedvft} + \sum_{a}\sum_{b} etb_{ab} \ddot{D}_{abedvft} + \sum_{ln} el_{ln} \widetilde{D}_{lnedvft} + \sum_{r} \ddot{ET}_{redvft} + \sum_{e}\sum_{ed} \widetilde{em}_e \widehat{BD}_{eedvft} + \sum_{ec} \widehat{ec}_{ec} \hat{B}_{ecedvft} + ef \sum_{g} FF_{edvfgt} \quad (8)$$

where the household's energy demand $\tilde{c}$ for cooking, lighting and heating increases every year depending on growth rate of household members, ec is the energy content of crop main products, D is the amount of crop main products used as bioenergy, et is the energy output from crop main products using the bioenergy technologies, $\acute{D}$ is the amount of crop main products used as bioenergy with technologies, ecb is the energy content of crop by-products, $\bar{D}$ is the amount of crop by-products used as bioenergy, etb is the energy produced from crop by-products using the bioenergy technologies, $\ddot{D}$ is the amount of crop by-products used as bioenergy with technologies, el is the energy content of livestock products, $\widetilde{D}$ is the amount of livestock products used as bioenergy, $\ddot{ET}$ is the amount of energy produced from renewable energy technologies, $\widetilde{em}$ is the energy content of centralized energy sources that households purchase for domestic use, $\widehat{BD}$ is the amount of centralized energy sources used for domestic purposes, $\widehat{ec}$ is the energy content of conventional energy sources that households purchase, ef is the energy content of the wood harvested from the forest for fuelwood and charcoal, FF is the amount of wood harvested by women and/or children from forest for fuelwood and charcoal.

Effects of energy use on health. Smoke emissions from burning of solid biomass in open fuelwood stove in developing world is a cause for estimated 2.5 million premature deaths among women and young children (Arnold et al., 2005). In Uganda, for instance, household switch to low quality fuelwood resulted in increase in the incidence of 'children acute respiratory infection' (Jagger and Shively, 2014). In our model, depending on number of household members the indoor pollution resulting from the energy source used for cooking, heating and lighting, and using of stove technologies for energy have effects on health of household members. The negative health effect of energy sources is prevailed on women and children. Bioenergy crops used with relevant technologies can be beneficial to maintain health conditions of households. We assume that renewable technologies and centralized energy sources do not affect health of households. Households' health condition has upper and lower bound values, and hence cannot be lower and higher than certain health level of household members. The following is the equation for modelling the health status of household members over years depending on used energy sources:

$$\begin{aligned} rh_{gt}H_{vfgt-1} &- \sum_{a}\sum_{ed} eh_{aged}D_{aedvft-1} - \sum_{a}\sum_{ed} \acute{eh}_{aged}\acute{D}_{aedvft-1} \\ &- \sum_{a}\sum_{b}\sum_{ed} \overline{eh}_{abged}\overline{D}_{abvft-1} - \sum_{a}\sum_{b}\sum_{ed} \ddot{eh}_{abged}\ddot{D}_{abvft-1} \\ &- \sum_{a}\sum_{ln}\sum_{ed} \widetilde{eh}_{alnged}\widetilde{D}_{alnedvft-1} - \sum_{ed} \widehat{bh}_{geed}\hat{B}_{eedvft-1} \\ &- \sum_{ed}\sum_{g} bf_{ed}FF_{edvfgt-1} + \sum_{g} mu_g\, ME_{vfgt} = \sum_{g} rh_{gt}H_{vfgt} \end{aligned} \tag{9}$$

where rh is the health of household members, H is the health of household members that ranges on scale of 0 and 1, where 1 is the healthiest condition, $\overline{\overline{eh}}$ is the conversion value of using the bioenergy crop main products to health reduction, $\acute{eh}$ is the conversion value of using the bioenergy crop main products that use specific technologies to health reduction value, $\overline{eh}$ is the conversion value of using the bioenergy crop by-products to health reduction value, $\ddot{eh}$ is the conversion value of using the bioenergy crop by-products that use specific technologies to health reduction value, $\widetilde{eh}$ is the conversion value of using the animal manure to health reduction value, $\widehat{bh}$ is the conversion value of using the conventional energy sources to health reduction value, bf is the conversion value of using the fuelwood and charcoal to health reduction value, and mu is the benefit to the health of household members from purchased medicine.

Bioenergy technologies. Energy sources can be used for energy in different ways. For instance, households can have open biomass, coal and kerosene fire, as well as use these products with technologies that have multiple purposes (e.g., combined heat and power technologies), or other technologies can be used with one option (e.g., cooking stove). Households' use of bioenergy sources can be improved by having technologies that increase energy output, e.g., cooking stove, and reduce environmental externalities. Moreover, the use of cook stove improves energy output efficiency and reduces exposure to indoor air pollution (Masera et al., 2005). Such energy transitions can reduce women drudgery and improve childrens' health (Heltberg, 2004). Ezzatia and Kammen (2002) estimated the significant health benefits when households start using improved cook stove instead three-stone fire.

Another main advantage of bioenergy technologies is that they reduce the environmental externalities in the form of pollution incurred on society. Thus, to have less harmful effects on household members and more effective energy use the bioenergy technologies can be an option. Depending on states of nature (variability), the energy capacity level may change. Each of these technologies has the capacity to burn the bioenergy sources, and the capacity can be enhanced by purchasing technologies from the market. Bioenergy technologies have annual depreciation rate, which shows that over time households may need to purchase a new bioenergy technology. At the same time, some bioenergy technologies may reduce the efficiency in supplying energy services to household, due to that these technologies have multiple purposes and thus energy produced is dispersed for different services. Following is the equation of capacity of bioenergy technologies:

$$\acute{E}_{vft}+\acute{E}_{vft-1} \geq \sum_{a} et_{at}\acute{D}_{avft} + \sum_{a}\sum_{b} etb_{abt}\ddot{D}_{abvft} \quad (10)$$

where $\acute{E}$ is the amount of bioenergy technologies available at household.

Renewable energy technologies. Renewable energy technologies, such as solar panels, can be also used by households for energy purposes. The amount of renewable energy produced is restricted to the capacity of technology. Households can increase the capacity of renewable energy technologies by purchasing from the market, and the market availability of such technologies is unrestricted. The energy produced by renewable technologies is suitable for lighting, heating, cooking, boiling and farming purposes of households. Renewable energy technologies such as solar panels may have intermittency during the winter season when insufficient sunshine is available to generate energy (Gowrisankaran et al., 2011). For addressing intermittency households can purchase the batteries which will ensure sufficient supply of energy during the year. Accordingly, we assume two types of solar panels: one with batteries and one without. The solar panels that have batteries are more expensive than the ones that do not have batteries. Similar to the bioenergy technologies the renewable energy technologies have annual depreciation rate. The following is the balance equation on amount of renewable technologies at each household (Eq. 11) and usage of generated energy for domestic and farm purposes (Eq. 12):

$$\ddot{E}_{rvft-1} + \ddot{BE}_{rvft} = \ddot{E}_{rvft} \quad (11)$$

$$er_r\ddot{E}_{rvft} = \ddot{E}T_{rvft} + \ddot{E}I_{redvft} \quad (12)$$

where $\ddot{E}$ is the amount of renewable energy technologies at households, er is the energy produced by renewable energy technologies, $\ddot{E}T$ is the amount of energy from renewable energy technologies used for domestic purposes, and $\ddot{E}I$ is the amount of energy from renewable energy technologies used for farming purposes.

Deforestation for fuelwood harvest. Bioenergy competes for scarce resources and impact ecosystem with consequent effects on welfare of society (Trink et al., 2010; Popp et al. 2014; Ignaciuk and Dellink, 2006; Berndes, 2002; von Braun, 2013). For instance, households' energy use may have repercussions on the state of nature of forests (Bazilian et al., 2011). Households to satisfy energy consumption demand may opt for harvesting wood from the open access forest for fuelwood and charcoal purposes. Wood collected from forest can be from fallen twigs of trees, and from cutting trees. The collection of fallen twigs of trees is sustainable and does not disrupt forest growth, but bring insufficient amount of wood for meeting households' energy demand. Whereas, cutting trees for wood harvest leads to deforestation problem and may eventually entirely deplete forest stock. At the same time, this practice can be attractive for households due to the absence of costs for forest harvest and the only costs that households bear is the time spent for wood collection. Accordingly, in the model we assume that the state of the forest stock in the current year is affected by cutting trees for fuelwood and charcoal in the previous years from the forest. The following are equations on forest stock (Eq.13), amount of wood collected for fuelwood and charcoal from the fallen wood from forest trees (Eq.14), and total amount of fuelwood and charcoal including the harvest of wood by cutting trees and fallen wood of forest (Eq. 15):

$$af_{t-1} - FH_{vfgt-1} = FA_{vt} \quad (13)$$

$$fw\, FA_{vt} - \sum_f \sum_g TC_{vfgt} = TR_{vt} \quad (14)$$

$$FH_{vfgt} + TC_{vfgt} = \sum_{ed} FF_{edvfgt} \quad (15)$$

where af is initial forest stock, FH is the amount of wood harvested from forest trees, FA is the forest stock after the harvest, fw is the fallen twigs from forest stock, TC is amount of harvested wood from fallen twigs, TR is the remained fallen twigs after the harvested wood.

Due to common open access nature of forest, households may compete to collect wood from forest, where each household may choose to cut trees for fuelwood and charcoal while trying to meet own energy demand (Ostrom, 1990). In such case the household that cuts forest first wins, while household that cuts in later periods is losing due to having less available forest stock for fuelwood and charcoal. Such competition for open access forest may lead to the fast and complete depletion of forest. The cutting of wood from forest also affects livelihoods of rural population. Lack of alternative energy sources to fuelwood lead to some household being not be able to satisfy own energy demand and in turn this adversely affects livelihoods of household members. In addition, a study conducted in Malawi suggests that children from severely deforested areas are less likely to attend school (Nankhuni and Findeis, 2004).

Energy for irrigation water supply. Energy resources can be used not only for domestic purposes and sold in the market but also for the agricultural production. We assume that to supply irrigation water for agriculture, households need to have technologies that can pump water from the canal or groundwater. Pumps can be run using the energy types such as electricity from the centralized and solar panel sources, and diesel. The capacity of irrigation use depends on the amount of energy used for pumping irrigation water:

$$\sum_{r} \ddot{ie}_{redvft}\ddot{EI}_{redvft} + \widetilde{ib}_{eedvft}\widetilde{BI}_{eedvft} + it_{ivft}AT_{ivft} \leq l_{ivft}\, ca_{imt} \tag{16}$$

where l stands for irrigation water available for farming, $\ddot{ie}$ is the amount of irrigation water that can be pumped using the energy from renewable energy technologies, $\widetilde{ib}$ is the amount of irrigation water that can be pumped using the energy from the centralized energy source, $\widetilde{BI}$ is the amount of centralized energy source used for pumping irrigation, it is the amount of irrigation water that can be pumped using the agricultural technologies operated on other type of energy source (e.g., pumps running on diesel).

Environmental externalities from energy use. In addition to effects of energy sources on household energy consumption, health and forest stock, such products can also have indirect impacts that go beyond the households' scale. To address effects on society we consider the environmental externality occurring as a result of emissions from burning energy sources. Such environmental externality can be different with farm types, household members and time. Emissions levels depend on type of energy sources burned and using which technologies. We assume that renewable technologies and centralized energy sources do not result in environmental externality. The costs of environmental externality are not perceived by households and hence not included into the expenditure structure of households. We use the emission conversion factors from burning energy sources to convert into greenhouse gases. The externality costs on society from household emissions are associated with the product emission intensity and unit costs of emissions that we assume to be the average value of the existing carbon value in the market:

$$\begin{aligned}\sum_{a}\sum_{ed} ee_{aed}D_{aedvft} + \sum_{a}\sum_{ed} \acute{e}e_{aed}\acute{D}_{aedvft} + \sum_{a}\sum_{b}\sum_{ed} \overline{ee}_{abed}\overline{D}_{abedvft} \\ + \sum_{a}\sum_{b}\sum_{ed} \ddot{e}e_{abed}\ddot{D}_{abedvft} + \sum_{a}\sum_{ln}\sum_{ed} \widetilde{ee}_{alned}\widetilde{D}_{alnedvft} \\ + \sum_{e}\sum_{ed} \widehat{be}_{eed}\hat{B}_{eedvft} + \sum_{ed}\sum_{g} ef_{ed}FF_{edvfgt} = \overline{ep}_{vft}EE_{vft}\end{aligned} \tag{17}$$

where ee is the emission amount from burning crop main products, $\acute{e}e$ is the emission amount from burning crop main products using the bioenergy technologies, $\overline{ee}$ is the emission amount from burning crop by-products, $\ddot{e}e$ is the emission amount from burning crop by-products using technologies, $\widetilde{ee}$ is the emission amount from burning livestock manure, $\widehat{be}$ is the emission amount from burning conventional energy sources, ef is the emission amount from burning fuelwood and charcoal, and $\overline{ep}$ is the price of commonly traded in the market greenhouse gas (e.g., CO2), and EE is the amount of total greenhouse gases emitted from burning energy sources.

Innovative bioenergy technologies such as waste to clean energy conversion; biogas, use of improved cook stove and a transition towards cleaner energy contribute to reduction in environmental pollution (Masera et al. 2005) and greener development (von Braun, 2013; Guta, 2012b). Bioenergy continues to be one of the main sources of energy for climate change mitigation (Bilgen et al., 2015).

3.4 Agricultural production

Crop management. In the model, we define agricultural production of households by considering annual and perennial crops and livestock. Both annual and perennial crops can be grown according to major field operations. Each crop has its seasonal cropping calendar that indicates land occupation period. Rotations allow accounting for temporal interactions between crops. The annual crop production includes operations such as fertilizer and irrigation applications, labor, machinery and oxen activities. We assume that some crops are produced only by men, women and children, and labor hours required for managing crops differ depending on gender and age. The crop selection can be subject to technical, agronomic and policy restrictions. Crop input requirements can be different depending on vegetation period of the crop. The land area can be household's own land or land rented from other household. Resources like irrigation water availability and rented and hired resources from another household are constraining in certain seasons within the year. To address resource constraints for agricultural production, we include monthly calendar for resources availability and requirements in certain months. Accordingly, the sum of resources used for crop production cannot exceed the level of resources:

$$\sum_{a}\sum_{g} r_{aimt} X_{aimvfgt} \leq L_{imvft}\, ca_{imt} \tag{18}$$

where r is the production factor requirement for crops, i index is the production factor, m is the index for months, X is the amount of used households' resources L, ca is the calendar of resource availability. The state of resources L such as labor, land and machinery is variable depending on their hired and rented amount to/from another household.

Among resources for crop production irrigation water availability plays an important role in the model. In the Water-Energy-Food Security Nexus concept the irrigation water is included through its use for agricultural production. Hence, irrigation application determines energy and food production, and use of energy source and crop cultivation determines the state of irrigation. In addition, the energy sources are needed to pump irrigation water for agriculture as is shown in Eq. 16. The low availability of irrigation water, which is addressed via the variability, may affect agricultural output.

Crop product balance. Production of crops depends not only on technical and agronomic requirements but also on output and input prices, food and energy consumption demand of household, and health conditions of household members. In addition, gender and age difference results that some crops have different yield levels, and as shown in Eq. (18) crops also have different labor requirement depending on whether managed by men, women or children. The reduction in health condition consequently reduces farm labor productivity and agricultural production.

Crop output of household can have several destinations. Depending on crop type it can be used for food, cash and energy purposes of households or stored for the next period, as well as inputs for agricultural production such as feed for livestock and produce by-products such as straw. Tree plantations can be planted only for harvesting wood for energy use such as for fuelwood and charcoal. The following model equation is the crop main product balance:

$$r_{ait}X_{aivfgt}H_{vfgt} + B_{avft} + ST_{avft-1} = S_{avft} + DF_{avft} + \sum_{ed} D_{aedvft} + \sum_{ed} \acute{D}_{aedvft} + AF_{avft} + ST_{avft} \quad (19)$$

where AF is the amount of crops used as fodder for livestock, ST is the amount of crops stored for the next year, and ST_{avft-1} is the amount of crops received from storing in the previous year. The storage of crop main products (and by-products) represents the area of house and barn of households. We assume the storage capacity available at each household to be fixed over the period of analysis. Similar to the crop main product balance equation, the crop by-product equation is included into the model.

Livestock number. We consider three types of animals in the model, i.e., cow, bulls, and poultry, which can be also classified depending on the products they produce, i.e., dairy, meat, eggs. The initial level of livestock number differs depending on household type. Households can purchase livestock from the market, sell to the market, and slaughter livestock for receiving meat for household consumption or selling in the market:

$$AN_{avft} = AN_{avft-1} + B_{avft} - S_{avft} - \tilde{S}_{avft} \quad (20)$$

where AN is the amount of livestock available in the current year with index a standing for livestock, AN_{avft-1} is the livestock remaining from the previous year. The amount of sold, consumed and slaughtered livestock is mainly based on livestock and product prices and consumption requirement of household. The important restriction on livestock availability depends on labor available at household, where each livestock type requires certain amount of labor hours every year to take care for it.

Livestock product balance. In addition to generating income from livestock by selling it in market, households can receive annual food products such as milk, eggs or final product such as meat or obtaining manure for crop production or burning for household's energy consumption. Livestock products can be received from own livestock or purchased from the market. These products can be sold in the market, consumed or used for crop products. Some of the livestock products have multiple purposes, e.g., manure can be used as fertilizer for crops or as energy for heating purposes. Accordingly, similar to the crop balance (Eq. 19) we include the balance for livestock products, except that due to their fast perishable nature the animal products cannot be stored for the next year:

$$\overline{ln}_{aln} AN_{avft} + \bar{\bar{B}}_{alnvft} = \overline{\overline{ln}}_{aln} \tilde{S}_{avft} + \overline{\overline{ln}}_{aln} \bar{\bar{S}}_{avft} + \overline{DF}_{lnvft} + \widetilde{D}_{lnedvft} + \sum_{a} \sum_{g} r_{ait} X_{aivfgt} \tag{21}$$

Households have to feed their livestock. The fodder requirement constraint specifies that the feed needed for livestock in terms of calories and protein have to be covered by crop main products such as maize and/or crop by-products produced on households' farms or purchased from the market. Some of the crops can be used as fodder or consumed by households, and can be grown in rotation with other crops. The following is equation on nutrient requirement of livestock:

$$cn_{akvft} AN_{avft} \geq ca_{akvft} AF_{avfgt} + \sum_{b} \overline{ca}_{abkvft} \overline{AF}_{abvfgt} \tag{22}$$

where cn is the nutrient (i.e., calorie and protein) requirement for livestock and index a includes only livestock, ca is the nutrient content of crop main products whose index a includes only crop main products, $\overline{ca}$ is the nutrient content of crop by-products whose index a includes only crop by-products, and $\overline{AF}$ is the amount of crop by-products used as feed for livestock.

3.5 Interdependencies among households and spillover effects

Change in the decision making of one household may affect the decision making of other households. This happens due to that rural households may be interdependent through the agricultural contracts (Roumasset, 1995). Such arrangement exists when one household has advantages in resources over another household and they can better operate their farming activities when exchange these resources. Household might not be able to optimally operate their farming unless they receive resources from another household. Thus, households' complement each other's farming activities, which leads that they are interdependent. For example, Djanibekov et al. (2013) in the case of Uzbekistan analyzed spillover effects from establishing agroforestry at the large-scale farm on semi-subsistence households via the payment (provided by the large-scale farm) and labor (provided by the semi-subsistence households) relationship among these two agricultural producers. They found that households working for the large-scale farm have an improvement in their livelihoods through receiving as payment the fuelwood from agroforestry fields of large-scale farm.

In our model, we consider that households are interdependent through the farming activities. We assume that household type 1 is abundant in labor to manage operations of its small-scale farm. This household can use the surplus of own household labor for working at farm of the household type 2. Households can also engage in land and machinery sharing contracts. Household type 2 that is well endowed with machinery and land can rent out such resources to household type 1 that has much less amount of such resources. Thus, household interdependencies are formed through the agricultural contracts, where one household increases quantity of resources for agricultural production by obtaining them from other household who in return receives payment. In the following equations are given resource in- and outflows for household type 1 (Eq. 23) and household type 2 (Eq. 24):

$$L_{imvft}\, ca_{imt} = (l_{ivft} - L\ddot{W}_{ivft} + L\ddot{M}_{ivft} + L\ddot{L}_{ivft})\, ca_{imt} \tag{23}$$

$$L_{imvft}\, ca_{imt} = (l_{ivft} + L\ddot{W}_{ivft} - L\ddot{M}_{ivft} - L\ddot{L}_{ivft})\, ca_{imt} \tag{24}$$

where l is the initial state of the resources available for farming, where amount of some resources are fixed, although stochastic, (e.g., irrigation water), and amount of other resources such as of labor, land and machinery may change depending on whether household type 1 and 2 engage in exchanging resources.

Farm production interdependencies among households lead to the outcome that the decision of one household may have spillover impacts on decisions and livelihood of another household. For example, a certain policy can improve off-farm working opportunities of household type 2 and consequently this decreases its farming activities that will decrease hiring the labor from household type 1. Reduction of the farm work at household type 2 results in less remuneration to household type 1. In turn, improved off-farm work at household type 2 may increase their incomes but have negative spillover effects on incomes of household type 1. In addition to spillover effects from farming, the spillover effects can also result from other decisions of household members, e.g., change in use of energy sources, adoption of technologies, variability of prices. Although the triggers of spillovers can be different in the model, we assume that its effects are transferred only through the labor, machinery and land arrangements between households.

3.6 Trade-offs and synergies

The principal in optimizing households' objectives using mathematical programming is that their decisions and activities are not independent of each other (Hazell and Norton, 1986). Each decision can be considered of as different interrelated bundle of decisions. Selection of mathematical programming allows us to consider the relationship of each variable. In the model, households' choice for one decision affects the state of other decisions and environment surrounding households. Optimization of households' incomes often may lead to optimal decisions for some single activity while lead to reduction or losses of other activities (simultaneously benefits and losses), and hence they are traded-off. Even though, there is sparse empirical evidence, studies assert that the use of agricultural biomasses for domestic energy purposes can have negative effects on agricultural productivity and food security (Heltberg, 2004). For example, a study by Trink et al. (2010) in the case of Austria found a negative effect of land intensive bioenergy production on the agricultural production due to land competition, lower labor employment benefits, and increase in land price and consumer price index. Accordingly, in the model, the trade-offs can occur among any activities of households. For example, among many others the trade-offs can be following (Lotze-Campen et al., 2010; Acosta-Michlik et al., 2011; Villamor et al., 2014):

- Activities of high income that leads to gender inequality and high reliance on child labor, as well as externality effects;
- Competition in land use between food and bioenergy crop production;
- Trade-offs among energy sources that are cheap and harmful to the environment and health of household members, while other types of energy sources can be more expensive but less harmful;
- Competition between high average and variance of return with the low average and variance of return farming activities.

However, the decisions of households may result not only in competing activities and bring benefits and losses, but also cooperate to generate benefits. In this case, some of the activities complement each other and their combined effect is greater than the sum of single activity. The synergies in the model include activities such as crop production for livestock fodder and manure of livestock for crop production. Another example can be the adoption of bioenergy technologies that do not have harmful effects on health. As a result, good health conditions maintain labor productivity of household members that is needed for agricultural production. Even though some activities of households result in synergies they may also reduce other beneficial activities, and thus still bring trade-offs. But the value of activity leading to synergy may overweigh the trade-offs. In our model, the trade-offs and synergies differ depending on household type. Reducing some of the variables and equations from the model reduces the interactions of model variables and hence observing trade-offs and synergies. For more information on potential trade-offs and synergies in bioenergy use see Mirzabaev et al. (2014).

3.7 Policy scenarios

To achieve the welfare gains from synergies and reducing negative externalities of bioenergy use policy options need to be developed that consider various groups of rural population (Djanibekov et al., 2013; von Braun, 2013; Guta, 2014). We include into the model several policy scenarios relevant for increasing the adoption of bioenergy crops and technologies, and renewable energy technologies, as well as equal share of benefits. The following are model scenarios:

- **Business-as-usual scenario**. In this case the model parameters and constraints are based on survey observations. In that scenario, we assume upper and lower bound on activities of household members and sources of energy use;
- **Scenario with no government subsidies for fossil fuels**. Governments in developing countries provide significant subsidies on fossil fuel supply to the rural population such as subsidies on kerosene, diesel, LPG. Several studies indicate that these subsidies act as barriers to the adoption of renewable energy technologies by rural households (Chakrabarty and Islam, 2010). In this scenario, it is assumed that such subsidies on fossil fuels are removed by the government and its affect will be simulated on the households;
- **Innovative bioenergy crop scenario**. In this scenario it is assumed that innovative bioenergy crops can be cultivated by households. Innovative bioenergy crops can include crops that are rarely planted by households or not yet implemented in the study area and only tested in experimental research site. We assume that such bioenergy crops is produced by household type 1 and these crops are not available in the market, however, this household can sell output of this crop in the market;
- **Bioenergy and renewable energy technologies scenario**. In addition to the previous scenario on innovative bioenergy crops, households use bioenergy and renewable energy technologies. To evaluate the impacts of technological innovations we assume that households start to use such technologies from year one. However, the number of adopted bioenergy and renewable energy technologies is determined by the model. Such technologies are available in the market, and cannot be produced or sold by households and obtained from other households. Moreover, to keep the heterogeneity of households in the model we assume that household type 1 can adopt both bioenergy and renewable energy technologies, while household type 2 can adopt only renewable energy technologies;

- **Credit incentives scenario**. Bioenergy and renewable energy technologies can be expensive for households. For increasing the budget the households can receive credits from financial institutions. Credits can be used for any purposes and need to be returned in the next period with the interest payment. The amount of possible loans that households can receive is restricted but does not differ depending on household type;
- **Scenario of no access to forest**. In addition to providing incentives to households for enhancing the bioenergy use, the increase of bioenergy use can be through the restrictive policies. Banning access to the common pool forest for harvesting wood for fuelwood and charcoal may require households start producing more bioenergy at farm at the expense of other farming activities. Such policy, consequently, can stimulate the use of bioenergy and renewable energy technologies. In addition, this policy may result in the forest being conserved and externality costs of forest harvest to be avoided. However, the disadvantage of such policy is that households cannot also harvest fallen twigs from forest trees, which can be the practice that does not have negative consequences on forest stock;
- **Scenario for equal share of benefits among household members**. The incomes of households stem from different sources and are contributed by different household members. Children can be engaged in farm and off-farm work and bring incomes. Child labor activities can be reduced through enhancing the working opportunities and incomes of adults, and reducing available working hours of children. In addition, among the household members income of men and women differ where men have higher off-farm opportunities with higher wages. Inequality may increase the farming activities of women and reduce their health. Empowering women and reducing child labor by providing better off-farm working opportunities, i.e., through more off-farm employment opportunity with higher wages, for women can be an option to address these issues. In the model, we include this scenario through the change in parameters on wage and off-farm working opportunities for women;
- **Scenario to cushion the negative spillover effects**. Promoting the use of bioenergy and implementing other above policies towards one type of household may benefit only this household, whereas other type of household may lose (i.e., lower incomes than in the business-as-usual scenario). The benefits may be directed only to some rural population, and as a result the rural inequality emerges or widens. Also, the spillover effects can occur as a result of the rural interdependencies (i.e., land, labor, and machinery contracts among household type 1 and 2), where policy directed to one type of household has negative spillovers to another type of household. The options to address the negative spillover impacts are increasing off-farm working opportunities and credit amount for household that is losing from above policies.

4 Conclusions

In this study, we present a generic household model as a tool to be used in the context of developing countries to gain knowledge on Water-Energy-Food Security Nexus issues and assess households' response to policy and technological changes, specifically, through the adoption of bioenergy crops and technologies. From methodological point of view, this model allows to make detailed and finer policy analyses considering the main characteristics of developing countries. The model opens up opportunities to assess rural incomes, gender equity, child labor, food and energy security, employment, agricultural production, natural resource use, variability and externalities in different regions and their spillover effects, trade-offs and synergies. The main specifications of the model are that it is normative, dynamic and mixed integer programming, a primal based, activity based, and has stochastic component. The model captures interactions among variables, which helps us to address the nexus issue. Furthermore, a number of key methodological choices driven by the analysis of bioenergy use can be adjusted to more distinct case study areas in developing countries.

To our knowledge, the model is one of the few household programming models which consider various activities of households, interdependencies and heterogeneity among households and their members. Our model assumes the rational households that are heterogeneous within household members and among households. The difference in characteristics of households allows us to observe diverse effects of policies and technologies on the rural population, and accordingly derive policies addressing income and gender equality and poverty issues. The interaction among households investigates the formation of rural contracts as well as both positive and negative spillover effects from bioenergy crop and technology adoptions, and implementation of new policies. By developing on- and off-farm activities and various destinations of agricultural output and input use in the model, we can address trade-offs and synergies. The energy sources are diverse and include crop main products and by-products, livestock manure, centralized energy, renewable energy, coal, LPG and kerosene. Energy sources can be obtained from different places and can have multiple destinations. As the bioenergy crops and technologies are the main focus of our study, and based on heterogeneity of households, we develop potential policy scenarios in the model that will increase use of bioenergy and improve rural livelihoods while considering the nexus issues.

The model has several limitations. One of the main limitations is that although the model is designed to be generic the question will be to test how the model will respond to the specifics of case study countries, whether it can be easily extended to other developing countries and what precautions and changes will be needed for achieving such aims. Answering these questions is not easy and mainly depends on the context of the study area and the research problem. From the technical part, the model is not calibrated such that the optimality conditions will be satisfied at observed levels of variables. Positive mathematical programming can be used to generate close to reality output, where some parameters are adjusted to be able to reproduce a given reference situation (Howitt, 1995). In addition, expanded use of bioenergy may affect output and eventually input prices. This will result in change in demand and supply of households. For addressing demand changes we need to include the income responsive demand function into the model. However, this requires information on energy and food demand elasticities of each household member, which is not available at the current stage. Furthermore, the effects of changes in energy use can be economy-wide. These issues need to be addressed using the general equilibrium model.

Appendix

Table with indices, parameters and variables used in the model.

Indices	Description
g	Household members
f	Household types
a	Agricultural activities/products including main products of food, cash and energy crops, and livestock type (i.e., crop main products and livestock head)
b	Crop by-products
ln	Livestock products
k	Nutrient requirement for livestock
i	Agricultural production inputs
ed	Energy use destinations
e	Centralized energy sources
ec	Conventional energy sources
o	Bioenergy technologies
r	Renewable energy technologies
t	Years
m	Months
v	States of nature

Parameters	Description
p	Price of agricultural products including cash, food and energy crops, and livestock
$\bar{p}$	Price of crop by-products
$\bar{\bar{p}}$	Price of livestock products
$\dddot{p}$	Price of agricultural production inputs
$\grave{p}$	Price of agricultural production technologies (e.g., irrigation water pumps)
$\ddot{p}$	Price of renewable energy technologies
$\acute{p}$	Price of bioenergy sources
$\hat{p}$	Price of conventional energy sources
$\tilde{p}$	Price of centralized energy sources
pm	Price of renting machinery for farming by household type 1 from household type 2
pl	Price of renting land for farming by household type 1 from household type 2
pw	Wage level for household type 1 for working at farm of household type 2

$\overline{ep}$	Price of traded in the market greenhouse gas
mc	Price of medicine for maintaining health of household members
$\bar{\bar{ln}}$	Amount of livestock products that can be obtained from livestock
w	Wage amount for off-farm work
trn	Transaction costs for off-farm work
tra	Transaction costs for purchasing agricultural products from the market
$\bar{cr}$	Interest rate paid for returning credit taken from bank
dr	Discount rate of households
ow	Off-farm employment available for household members
c	Food consumption requirement of household members
$\tilde{c}$	Energy consumption requirement of household
ec	Energy content of crop main products
et	Energy output from crop main products using the bioenergy technologies
ecb	Energy content of crop by-products
etb	Energy produced from crop by-products using the bioenergy technologies
el	Energy content of livestock manure
er	Energy produced by renewable energy technologies
$\ddot{\imath}\dot{e}$	Amount of irrigation water that can be pumped using the renewable energy technologies
$\widetilde{em}$	Energy content of centralized energy sources
$\widetilde{\imath b}$	Amount of irrigation water that can be pumped using the centralized energy source
it	Amount of irrigation water that can be pumped using the agricultural technologies operated on other type of energy source (e.g., irrigation water pumps running on diesel)
$\widehat{ec}$	Energy content of conventional energy sources
ef	Energy content of wood harvested from forest for fuelwood and charcoal
rh	Health of household members
eh	The health reduction value from using as energy the bioenergy crop main products
$\acute{eh}$	The health reduction value from using as energy the bioenergy crop main products with bioenergy technologies
$\overline{eh}$	The health reduction value from using as energy the bioenergy crop by-products
$\ddot{eh}$	The health reduction value from using as energy the bioenergy crop by-products with bioenergy technologies
$\widetilde{eh}$	The health reduction value from using as energy the livestock manure

$\widehat{bh}$	The health reduction value from using the conventional energy sources
bf	The health reduction value from burning the fuelwood and charcoal
af	Initial forest stock
fw	Fallen twigs from forest stock
ee	Amount of greenhouse gas emissions from burning crop main products
$\acute{e}e$	Amount of greenhouse gas emissions from burning crop main products using the bioenergy technologies
$\overline{ee}$	Amount of greenhouse gas emissions from burning crop by-products
$\ddot{e}e$	Amount of greenhouse gas emissions from burning crop by-products using the bioenergy technologies
$\widetilde{ee}$	Amount of greenhouse gas emissions from burning livestock manure
$\widehat{be}$	Amount of greenhouse gas emissions from using conventional energy sources
ef	Amount of greenhouse gas emissions from burning fuelwood and charcoal
r	Production factor requirement for crops and livestock
l	Household resources available at the initial state (before renting in/out labor, land and machinery) for farming
ca	Calendar of resources available
cn	Nutrient requirement for livestock
ca	Nutrient content of crop main products
$\overline{ca}$	Nutrient content of crop by-products

Variables	Description
I	Households' income
S	Amount of agricultural activities/products sold (i.e., crop main products and livestock head)
$\bar{S}$	Amount of crop by-products sold
$\bar{\bar{S}}$	Amount of livestock products sold
$\tilde{S}$	Sale of meat from slaughtered livestock
N	Working off-farm
AI	Purchase of agricultural production inputs
AT	Amount of technologies purchased for agricultural production (e.g., irrigation water pumps)
B	Purchase of agricultural products/activities (e.g., crop main products, and livestock)
$\bar{B}$	Amount of crop by-products purchased

$\bar{\bar{B}}$	Amount of livestock products purchased
$\acute{E}$	Amount of bioenergy technologies purchased
$\tilde{B}$	Amount of centralized energy sources purchased
$\widetilde{BD}$	Amount of centralized energy sources used for domestic purposes
$\widetilde{BI}$	Amount of centralized energy source used for pumping irrigation water for farming
$\ddot{BE}$	Amount of purchased renewable energy technologies
$\hat{B}$	Amount of conventional energy sources purchased
ME	Amount of medicine purchased
$L\ddot{W}$	Labor activities for farming by household type 1 for household type 2
$L\ddot{M}$	Amount of machinery rented for farming by household type 1 from household type 2
$\ddot{L}L$	Area of land rented in for farming by household type 1 from household type 2
CR	Amount of credit received from bank
F	Budget available for expenditures
DF	Food consumption of crop main products
$\overline{DF}$	Food consumption of livestock products
D	Amount of crop main products consumed as bioenergy
$\acute{D}$	Amount of crop main products consumed as bioenergy with bioenergy technologies
$\overline{D}$	Amount of crop by-products consumed as bioenergy
$\ddot{D}$	Amount of crop by-products consumed as bioenergy with bioenergy technologies
$\widetilde{D}$	Amount of livestock manure consumed as bioenergy
$\ddot{E}$	Amount of renewable energy technologies
$\ddot{E}T$	Amount of energy from renewable energy technologies used for domestic purposes
$\ddot{E}I$	Amount of energy from renewable energy technologies used for pumping irrigation water for farming
FF	Amount of harvested wood from forest for fuelwood and charcoal
H	Health value of household members
$\acute{E}$	Amount of bioenergy technologies available at household
FH	Forest stock harvested
FA	Forest stock after the harvest
TC	Amount of harvested wood from fallen twigs in the forest for fuelwood and charcoal
TR	Remained fallen twigs after their harvest for fuelwood and charcoal
EE	Amount of greenhouse gases emitted by households from using energy sources
X	Area allocated for crops
L	Household resources available for farming
ST	Amount of crops stored for the next period

AN	Amount of livestock available at household
AF	Amount of crops used as feed for livestock
$\overline{AF}$	Amount of crop by-products used as feed for livestock

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