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# Assessing nexus effects of energy use in rural areas: the case of an inter- and intra-household model for Uttar Pradesh, India

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# Abstract

The focus of our analysis is on nexus issues among energy use, incomes, employment, investment decisions, and agricultural production for meeting food and feed demands, as well as health-related effects on rural households. As an example we investigate potential policies, such as public subsidies for solar panels and increase in non-agricultural employment opportunities, for meeting energy demands and improving rural livelihoods, using an agricultural household dynamic programming model. The model includes two types of households that differ in their socio-economic characteristics - poor and rich as measured by their asset and resource endowments, which are linked through the agricultural contracts such as wage-labor and payment for irrigation supply. Moreover, we differentiate the potential impacts of policies at the intra-household level, with special focus of effects on men, women and children. The case study area is the Uttar Pradesh province of India and the main data source is the household survey. The study shows that state subsidies for solar panels improve energy use, agricultural production and incomes of both households in comparison to the business-as-usual case. Also, interactions among two households with agricultural contracts increase. The policy scenario on increasing non-agricultural employment opportunities do not change much energy use pattern of rural households but substantially improves the income levels of poor household, where such household allocates most of labor force for non-agricultural work. In contrast, the household that is better endowed with agricultural production resources looses from such a policy due to less labor available to manage its farm.



Keywords: Nexus, Energy use, Heterogeneity, Rural inequality, Dynamic programming

JEL codes: C61, D63, J41, O13, Q4, Q12

# Contents

# 1 Introduction

Globally, about 2.64 billion people depend on bioenergy (IEA, 2013), especially in rural areas of developing countries where there is a lack of decentralized energy supply and located most of the poor. Bioenergy sources are used not only for domestic purposes of households but also for farming and sold in the market for income generation and food security. At the same time, increasing demand for agricultural commodities by 60-70% in the next 40 years due to population growth (FAO, 2012) will lead to an increased competition with the production of bioenergy. In addition, use of bioenergy for domestic purposes has disadvantages, such as air pollution that has detrimental health impacts, particularly for women and children (Duflo et al., 2008). Accordingly, interdependencies among health, incomes, food, energy and natural resources, while considering population growth, may lead to trade-offs in rural households' livelihoods.

Several studies were conducted for exploring the potential energy sources and policies and their nexus effects (Jebaraj and Iniyan, 2006). For instance, Bryngelsson and Lindgren (2013) showed that large-scale introduction of bioenergy reduces production of food crops and as a result increases food prices. While Gebreegziabher et al. (2013) showed that the bioenergy investment in Ethiopia can improve smallholders' agricultural productivity as well as their livelihoods. Alfaro and Miller (2014) reported that biomass and hydro based local decentralized power system gives more savings to households compared to local diesel based decentralized power system. Hiremath et al. (2010) in the case of a village in India argued that the promoting decentralized energy systems, such as local biomass for producing biogas and electricity, increase incomes and reduce CO2 emissions compared to other renewables.

At the same time, due to heterogeneity of population the change in energy use within the nexus concept might have different effects on livelihoods of different households (Villamor et al., 2014; Mirzabaev et al., 2015). For example, poor households are less likely to adopt modern energy technologies in contrast to richer households (Isaac and van Vuuren, 2009). Thus, some energy technologies may not be afforded by households and state support such as subsidies needs to be provided (Frondel et al., 2010). Also, the possible negative effects from competition in producing food and energy commodities are particularly acute for poor, and thus necessitate policies to cushion them, e.g., increasing non-agricultural employment. Chen et al. (2006) showed that households that have higher working opportunities outside of agriculture have lower dependency on traditional bioenergy sources due to more time allocation for non-agricultural activities. However, implementation of new policies results in indirect effects on population. For instance, Gebreegziabher et al. (2013) found that the investment into bioenergy not only benefits the welfare of rural poor households but also indirectly the urban households who receive benefits from the returns to labor. Djanibekov et al. (2013) showed that adoption of agroforestry by large-scale commercial farms have positive spillover effects on rural households through the remuneration with fuelwood for farm management, although with high waiting costs. Moreover, household is heterogeneous within itself, e.g., difference in gender and age of household members, where activities of household differ among its members. For example, women in rural areas of developing countries are often contributing to energy and food security of households (Arndt and Benifica, 2011), which may lead that the change in bioenergy production may change the labor composition of households. Thus, it is important to identify policies that address nexus issues occurring from households' decisions in meeting energy demand, while taking into account heterogeneity within and among households, and spillover effects.

To our knowledge previous studies missed to include simultaneously the nexus issues in household decisions, as well as heterogeneity within and among households when addressing the energy supply and use by households. Hence, we try to fill these research gaps by addressing the effects of policy changes on intra- and inter-household levels by considering the energy nexus issues. For addressing these research gaps we develop a dynamic programming household model that combines two types of households which are interlinked through the labor-wage and irrigation supply-payment contractual arrangements. We further differentiate household members into men, women and children. This modeling frame allows investigating the energy use, non- and agricultural activities, resource use, direct and indirect effects on households, as well as gaining and losing households from policy changes in the dynamic context. We simulate two scenarios such as state subsidies for renewable energy technology (e.g., solar panel), and improving non-agricultural employment opportunities for poor household. We use the example of Uttar Pradesh province of India, where rural households substantially rely on bioenergy and depend on agricultural production for consumption and income generation. The objectives of this study are to: (2) investigate energy and food commodities supply, and change in environment and livelihoods of heterogeneous households within the nexus concept, and (2) analyze policies that can improve the welfare of heterogeneous households within the nexus concept.

# 2 Methods

## 2.1 Study area

The Indian province of Uttar Pradesh has been selected for this study because of 2 major reasons. Firstly, National Sample Survey 66th round, 2009-2010 indicates that the dependence on traditional bioenergy in Uttar Pradesh is amongst the highest across all regions in India as well as this province has one of the lowest household electrification rates in the country (Census of India, 2011). Secondly, it is an agriculture dominant economy with around 2/3rd of its labor force dependent on agriculture (Singh, 2014). The province has a population of 199.58 million. The main land uses are wheat, rice, sugarcane and mustard, which are used for own household purposes (i.e., food consumption, fodder for livestock) and surplus is traded in the market. Households do not have sufficient provision of energy from state grid for cooking, boiling and lighting purposes. Energy demand of households can be satisfied through bioenergy sources such as dung cake, fuelwood harvested from forests, solar panels, biogas, as well as from other sources such as liquefied petroleum gas (LPG), kerosene and batteries for storing electricity.

## 2.2 The model

To analyze nexus issues and effects on rural livelihoods of introduced policies, we develop an agricultural household dynamic programming model. The model is normative, which is a prescriptive type of model determining the levels of variables when aiming to optimize the objective function. Our dynamic programming model optimizes decisions of households to have a maximum objective value over the period of analysis (i.e., discounted net present value of incomes). Using such model we assume that households have a perfect foresight over the period of analysis and accordingly adjust their activities annually to achieve the optimal outcome over the whole period of analysis. Hence, households' decisions are made in annual basis. For including dynamics we consider transformation functions, state variables, length and intervals of time in years and discount rate. The model maximizes incomes of households over 10 years under the 10% discount rate. The model is deterministic and includes linear relationships.

The model includes two types of households (Figure 1). Households differ in demographic composition and socio-economic characteristics. We assume that household type 1 (hereafter household 1) is less economically endowed in a sense of less farmland area (household 1 has 0.84 acres and household 2 has 4.1 acres), livestock number, initial budget for expenses and non-agricultural income opportunities than household type 2 (hereafter household 2). In addition, households differ by crop cultivation practices (household 2 cultivates crops with higher yields, input and output prices than household 1), livestock available (household 2 has more livestock than household 1), use of energy sources (household 2 receives more central grid electricity and has better opportunities to obtain energy sources than household 1), and labor availability by age and gender (household 1 has more labor available than household 2). Households are interrelated through the agricultural contracts, where members of household 1 can work at the farm of household 2 and receive payments for each working day. Further interdependencies of households appear when household 2 can sell water pumped by diesel generator, tube well and solar panels to household 1 and obtain payments for the energy used during pumping irrigation water.

In addition, each household is heterogeneous among its members. For addressing heterogeneity within households we include three types of household members – men, women and children (both male and female up to 15 years old). In each household, members differ in their labor hours available for farm and non-agricultural work, wage from working in such activities, division of farm management activities, labor productivity in farming, labor time spent for preparing and collecting bioenergy sources. We omit opportunities for schooling, leaving household and other age and gender specific activities that are not related to labor. We assume an annual population growth rate of household members as 1.2%, which is a population growth rate in India. For the simplification of our analysis, we assume that the share of men, women and children in household remain the same throughout the period of analysis.

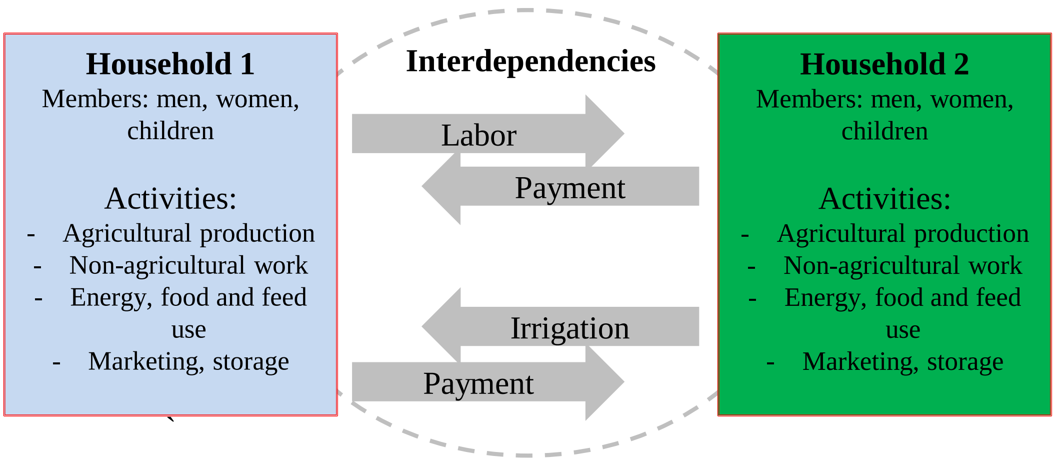


**Figure 1. Overview of interdependencies among households in the model.**

The model is also an activity based where objective value (i.e., income) is maximized using different activities. Households' incomes are generated by selling own farm products such as crops (wheat, rice, sugarcane, mustard and potato), crop by-products (wheat, rice and mustard straw, rice husk, sugarcane top, sugarcane leaves, and mustard cake), animals (buffalo and cow) and their products (milk and manure), employment at the farm of another households, payments for selling irrigation supply services, and receiving wage from non-agricultural work. Wage from non-agricultural work differ depending on household type and members. Households have to meet their food (crop and milk amount) and energy (in megajoule = MJ) consumption demand, as well as feed demand of livestock. The number of livestock can change through sale and purchase. Costs are related to agriculture, purchase of energy sources and technologies, labor and irrigation payments to another household, maintenance of health due to use of domestic energy sources. The costs to health from domestic energy use are based on emissions from carbon monoxide (CO) and particular matter (PM 2.5) of energy sources. The basis of these costs is Litman and Doherty (2009), which uses RWDI Inc. (2006) data to present the health damage costs due to the emission pollution of CO and PM 2.5 from the vehicles in Canada. While calculating the health damage by PM2.5 and CO on human health, RWDI Inc. (2006) considers the quantified health effects (in monetary values, i.e., Canadian dollars) of these emissions on premature mortality, chronic bronchitis, asthma symptom days, acute respiratory symptoms, respiratory hospital admissions, cardiac hospital admissions, emergency room visits, restricted activity days and the cognitive effects. It is to be noted that Litman and Doherty (2009) calculated the health damage costs in the settings of Canada. For converting these values for the Indian settings, the ratio of GDP per capita between India and Canada was calculated. Thereafter this ratio was multiplied by the health damage cost of CO and PM2.5 given in Litman and Doherty (2009). Products that are insufficiently produced for household demand can be purchased from the market. We assume that crops such as barley and sorghum can be purchased only from the market. Prices are assumed to be exogenous and fixed.

The core aspect of the model is the energy use by households. We consider different energy sources such as traditional bioenergy (i.e., crop by-products, fuelwood, and dung cake), centralized electricity grid from the state (i.e., electricity), modern (i.e., LPG, kerosene, diesel), and renewables (i.e., solar photovoltaic panels (hereafter solar panels), biogas) that also differ in their destination (Table 1). The model assumes that initially households do not have energy technologies and can purchase them from the market. We consider bioenergy sources such as fuelwood collected from forest, crop residues, and dung cake. Availability of forest stock allows taking into account that households can have access to freely available energy resources, yet it can be depleted if overharvested. Dung cake can be received from own cows and buffalos or purchased from the market. Except wheat straw, sugarcane top and mustard cake, all other crop by-products can be used for domestic energy purposes. These bioenergy sources can be also used with improved bioenergy based cook stove (hereafter improved cook stove) that increases the efficiency of energy supply in comparison when it is used with traditional approach. Usage destination of bioenergy is for cooking and water boiling, or as crop production input or selling in the market. Electricity supply from the centralized grid differs depending on household type, where household 2 receives more electricity than household 1. Supply of electricity amount and costs for domestic use are fixed. Due to the fact that such electricity is mainly supplied at late night time or in odd hours, which was observed during the surveys in our study area, we include batteries that can be purchased from the market and can store electricity to make electricity available during other time of the day when electricity is not available (i.e., battery power backup). Electricity stored by batteries can be used for lighting and electrical appliances. In addition, we assume that household 2 can receive electricity for operating tube well for pumping groundwater for crop irrigation. The costs of such electricity is also at fixed level, but for pumping irrigation water the household 2 incurs initial costs of establishing tube well. The modern energy sources can be purchased from the market. Among these energy sources, diesel can be used with diesel electricity generator for lighting and electrical appliances, as well as with diesel pump for crop irrigation. We assume that such technology can be obtained by both households. However, we assume that pumped irrigation water can be also sold to household 1 (in case household 1 does not have a pump for farming). Amount of irrigation use for crops are expressed in energy units used during pumping irrigation water. Solar panels can be obtained by households from the market. Domestic use of solar panels includes lighting and operation of electrical appliances and for these purposes the households need to purchase the batteries as well. In addition, solar panels can be used for irrigating crops. Pumped irrigation water with solar panels can be used for own farm or sold to another household (i.e., selling irrigation water from household 2 to household 1).

Households can use manure directly for cooking and boiling water and with biogas. The energy obtained from biogas is higher than the manure used with traditional technologies. Besides the slurry remained from the biogas can be used for farming as manure. For using biogas households need to purchase the necessary equipment from the market. Technologies for generating energy such as solar panels, diesel generator and battery for electricity do not result in health damage costs for households (i.e., it is assumed that these technologies do not cause indoor pollution or installed outside the house), while other energy sources used for domestic purpose result in health costs for households. We assume that the health repercussions of using energy sources for domestic purposes lead to costs. Such effects are in overall household level, due to insufficient data on household member specific health costs from energy use. In addition, in the model we consider greenhouse gas emissions from the energy use.

**Table 1. Use of energy sources by destination.**

| For residential purpose | | | As input for farming | For selling in market |
|---|---|---|---|---|
| Cooking and water boiling | Lighting | Electrical appliances | | |
| Fuelwood | | | | |
| Crop by-products | | | Crop by-products | Crop by-products |
| Animal dung | | | Animal dung | Animal dung |
| | Kerosene | | | |
| | Diesel | Diesel | Diesel | Diesel |
| Liquefied petroleum gas | Liquefied petroleum gas | | | |
| | Electricity | Electricity | Electricity | Electricity |
| | Solar panel | Solar panel | Solar panel | Solar panel |
| Biogas | | | Biogas | |

Households have long-term investment decisions into livestock and energy technologies. These decisions are flexible, i.e., households can decide whether to invest now or in later periods. We assume that energy technologies have only sunk costs and their maintenance costs are not considered. We also assume that energy technologies have a lifespan, where improved cook stove, LPG stove, and batteries for solar panels and to accumulate electricity last for five years. The lifespan of irrigation water pump run on diesel is 7 years. Upon the expiration of these technologies they can be renewed, thus we consider replacement option of these technologies. Due to the fact that electrical tube well and biogas cylinder can last about 20 years and hence longer than the considered model duration, we assume no lifespan for these energy technologies.

In addition, the model relies on mixed inter programming that constraints necessary variables to be integer (e.g., number of livestock) and binary (e.g., having biogas, diesel generator, tube well, improved cook stoves), while other variables can be fractional. As the capacity of batteries for storing electricity and solar panel technologies vary we hence assume them to be continues variables.

Due to insufficient data we did not consider income responsive demand function of each household and thus assume that demand of households for food, energy and other products changes only with respect to households' population growth rate. In addition, our model analyzes the household level effects, and does not consider the market effects from production changes of households, as few households may not be able to influence the market. The main parameters used for the model are given in Table A1 of Appendix A. More details about the model and its mathematical representation can be found at Djanibekov et al. (2016).

## 2.3 Scenarios

To assess the options for addressing nexus issues in energy use among heterogeneous households, we simulate three scenarios:

- Business-as-usual scenario (BAU), where the model settings are based on current observations;
- Subsidies scenario (SUB). More sustainable energy providing technologies such as solar panels can be expensive for households to adopt. We assume that state provides subsidies for establishing solar panels and covering costs of solar panels and batteries for them from 10 to 90% used for domestic and farming purposes. The range of these values allows finding subsidy levels that leads to adoption of solar panels. For simplicity of interpretation, we show results of subsidies for solar panels for farming and domestic use with 50 and 80% respectively (values that lead to substitution of alternative energy sources used for domestic and farming activities). In comparison to the BAU scenario, in this scenario we change income function and expenditure constraint by reducing the costs of solar panel technologies;
- Scenario of equal non-agricultural employment opportunities for household types and members (EQL). As future increases in trade-offs, such as in food, energy, feed and incomes, may have stronger negative impact on poor households than for rich ones, we include the scenario of equal non-agricultural working opportunities for household types and members. In the BAU scenario, men have higher opportunities in non-agricultural work than women. In addition, richer household (i.e., household 2) has better non-agricultural opportunities than poorer households (i.e., household 1). Hence, in this scenario we assume that the non-agricultural work opportunities and salaries by household type and gender are the same. We also assume in this scenario that children can only assist in farming in their own farm, and thus no employment for children at non-agricultural work and at the farm of another household. To include this scenario into the model we modify the BAU scenario by increasing the non-agricultural work availability constraint and wages at the income function to the level that is the same by household types and gender. Also, we indicate that children cannot work outside of own farm by restricting the variable of labor allocation of children to only own farm.

## 2.4 Data sources

Considering confidence interval of 95% for the research outcomes, sample size was calculated to be around 400 households. In order to select these 400 households, following 3 sampling steps were undertaken. First step was to select districts taking into account the variance of socio-economic and energy systems in the province. For this task, a district level dataset was created with their following district attributes: per capita net district product, percentage of primary sector in net district product, population density, percentage of households using firewood for cooking, cattle dung for cooking, crop residue for cooking, LPG for cooking, percentage of households using electricity for lighting, yearly biomass surpluses in the districts, percentage of cultivated area under wheat and rice production and their respective yields.

On this dataset, a statistical clustering technique was applied and homogenous district clusters were identified and then 4 districts were chosen randomly from these different clusters. These districts along with their coordinates are: Mathura (27°14’-27°58’N, 77°17’-78°12’E), Moradabad (28°16’-28°21’N, 7°4’-7°9`E), Rae Bareilly (25°49’-26°36’N, 81°34’-100°41’E), Sant Kabir Nagar (26°47’-26°79’N, 83°3’-83°3.45’E). Second step was to select villages from these districts. For the above selected districts, the list of their respective villages was drawn from Census of India: Uttar Pradesh (2011). With the assumption that all the villages of a district resemble the characteristics of their district, 2 villages were randomly selected from each district. In this way, 8 villages from 4 districts were chosen. Third step was to select households. For this, systematic sampling technique as used by Levy and Lemeshow (2008) was applied. Using this, surveyor went to the center of the selected village, selected a random direction and randomly chose a household. Thereafter, another household after a certain gap in the same direction was selected. Hence, around 40-70 households were surveyed from each village, depending on its size. This way, in each district, about 100-110 households were surveyed. During the interviews the surveyor collected information on household demography, income sources (agriculture, service, enterprise, business, remittance), expenditures (food, energy, medical, education, agriculture), asset endowments, agricultural production techniques, and energy use (fuel types and source, labor required for fuel collection, equipment, investment, market expenses).

# 3 Results

## 3.1 Energy use

Different policy scenarios have different effects on the usage of energy sources (Figure 2). Population growth of households increases energy demand but not the energy use pattern. In the BAU scenario, over years, both households use directly supplied electricity from the central grid for lighting and running electrical appliances for the domestic purposes. During the periods when such energy source is insufficiently provided, households rely on battery power backup for electrical appliances, and for lighting they rely on LPG. Households install the battery power backup already in the first year and gradually augment its capacity to meet the electricity demand (Figure B1 in Appendix B). For cooking and water boiling the household 1 (poor household) uses sugarcane leaves with improved cook stove. Households obtain improved cook stove from the initial year of model simulation and household 1 replaces it with new improved cook stove when its usage is expired in year five. For cooking and water boiling the household 2 (rich household) using the improved cook stove burns in the first two years the fuelwood harvested from the forest and in subsequent years it does not purchase cook stove and instead establishes biogas operating on livestock manure. Household 2 installs biogas starting from the third year even under current establishment and management costs, due to sufficiently accumulated funds to invest into the biogas technologies. On the other hand, supporting policies are required for poorer households to adopt biogas, e.g., state subsidies to purchase biogas technologies. In addition, we did not consider possible transaction costs that can be involved in purchasing and installing of biogas (Brown, 2001), which can be the reason of low usage of biogas by rural population in the study area.

For farming activities, i.e., pumping irrigation water for crops, household 2 purchases diesel pump in the initial year and uses it during the first two years. Due to the high costs of diesel pump, the household 1 does not install this technology and prefers to purchase irrigation water pumped by household 2 during year one and two. In the next year, i.e., year three, household 2 sets up water tube well (water pump) operating on electricity, because of sufficient funds available to set it up and its associated lower operating costs compared to its alternative irrigation pumps. It is to be noted that although electricity based water tube well is not an expensive technology but getting its government electricity connection and its setting up is a costly process. During these periods, household 1 fulfills its irrigation demand by purchasing the irrigation water pumped by household 2 with its electric tube well. Low endowment of farmland is a major reason that it is more financially viable for the household 1 to purchase irrigation water then to set up its irrigation water pump.

State provision of subsidies for solar panel technologies, i.e., SUB scenario, leads to cost reduction of these technologies and households adopt solar panels for domestic use from the first year. Thus, the current costs for installing the solar panels are high for rural households and they prefer to invest into the cheaper but less sustainable energy technologies. To motivate farmers to adopt such technologies the state support is required such as subsidizing the purchase costs of solar panels. Further, it could also be expected that with the declining costs of solar panels, more rural households will make a transition to solar panels for domestic electric use. For cooking and water boiling, households rely on the same energy sources as in the BAU scenario. In case of energy use for farming, in the initial two years households use diesel pump and in subsequent years rely on pump operating on solar panels. It should be noted that even assumed level of subsidies for solar panels for farming, i.e., state covers 50% of establishment costs, may not lead to immediate adoption of solar panels and require time to adopt such technology. Whereas household 1, even with the state subsidies, due to low budget available does not obtain pump for irrigation and hence depends entirely on household 2 for irrigation supply. For poor household, hence, further supporting state policies are needed to have less dependency on resources of another farm in agricultural production.

Improving non-agricultural opportunities for women (i.e., same as for men) and poorer households (i.e., equal level for both types of households) reduces the agricultural activities of households (see section 3.3), and consequently households use less energy for irrigating crops. This in turn leads that the amount of total energy use in the EQL scenario is slightly lower for farming than in the BAU scenario due to reduction in agricultural production. Despite higher budget available for agricultural expenses from off-farm income, the household 1 still prefers to irrigate crops from irrigation water purchased from household 2. For cooking and water boiling as well as for lighting and running electrical appliances households use the same energy sources as in the BAU case. Accordingly, providing better non-agricultural employment opportunities for households do not affect substantially their energy use, as expenses of energy sources can be still high for households while households have to meet their domestic energy use and food consumption demands.

For the model results on the number of energy technologies adopted by households see Figure B1 in Appendix B.

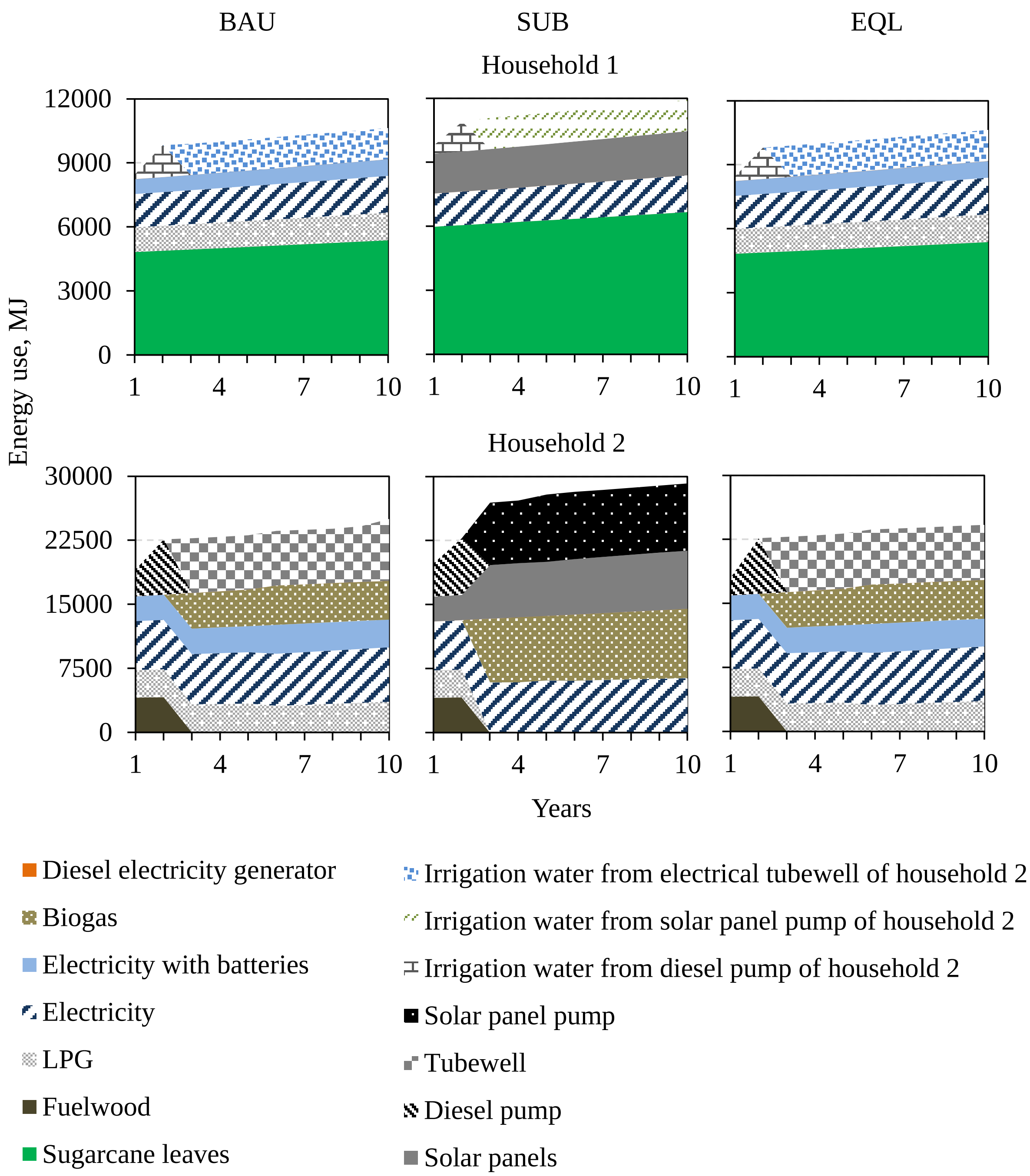


**Figure 2. Energy use of households for domestic and farming purposes over 10 years in the business-as-usual (BAU), subsidies (SUB) and equal (EQL) scenarios, megajouls.**

## 3.2 Agricultural production and use by destination

The change in agricultural production influences among others the incomes and food security of rural households. Depending on household type the land use choices differ (Figure 3). The main land use of both households is potato, which is the most profitable crop and is also used as food for consumption (for crop gross margins see Table A1 in Appendix A). The difference in cropping pattern among household types is due to assumed differences among households in the model, e.g., land size, initial budget for agricultural expenses, labor and livestock available, non-agricultural employment, and gross margins of crops. For example, household 1 in addition to potato cultivates sugarcane, although on a small share of land. Household 2 has more diversified land use pattern, especially in the SUB scenario. Also, the state subsidies for solar panels give an opportunity for households to obtain energy technologies with reduced costs and reduce crop production costs and as a result increase crop area. In contrast, although slightly, the increase in non-agricultural working opportunities lead to shift of rural labor outside agriculture (see section 3.3) and reduce the crop cultivation area of households, particularly of household that is better endowed with farm resources, i.e., household 2. This is mainly because in the EQL scenario returns from non-agricultural work are becoming higher than the returns from agricultural work in other scenarios (i.e., BAU and SUB scenarios). In the simulated scenarios, the crop cultivation pattern of households changes substantially with respect to the initial periods of analysis. This land use trend is because of lower amount of resources available (i.e., budget for agricultural expenses, pump for irrigation water) in year one than in the subsequent years.

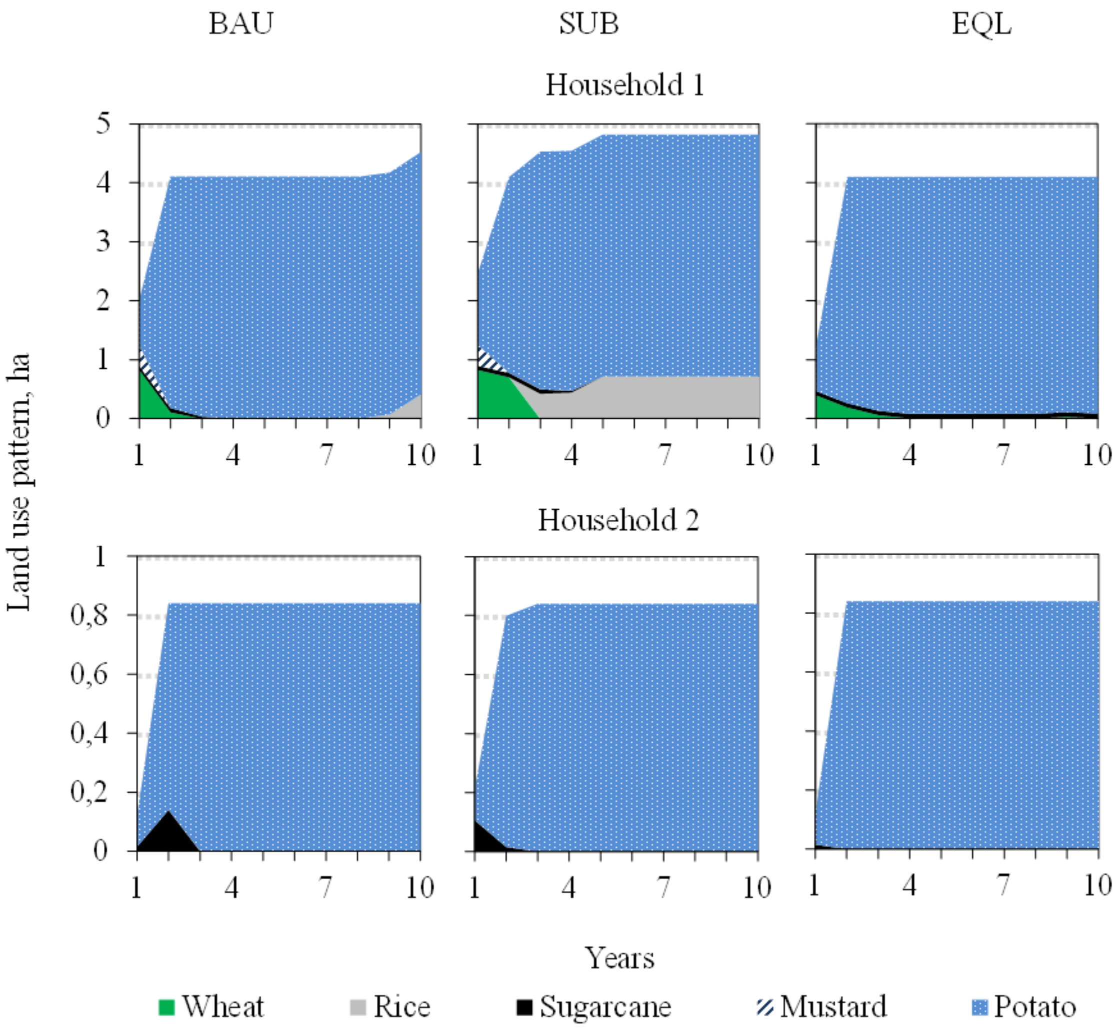


**Figure 3. Land use pattern of households over 10 years in the business-as-usual (BAU), subsidies (SUB) and equal (EQL) scenarios, ha.**

With respect to livestock number ownership, the households keep cows to have milk for consumption and manure for crops (Figure 4). Only household 1 in the SUB scenario sells the entire livestock and with the received money, it invests into the solar panels for domestic use and crop production. Whereas household 2 purchases additional cows, especially in the SUB scenario it has the largest number of cows, which is due to its reduced energy use expenses and having sufficient resources to manage a larger number of livestock.

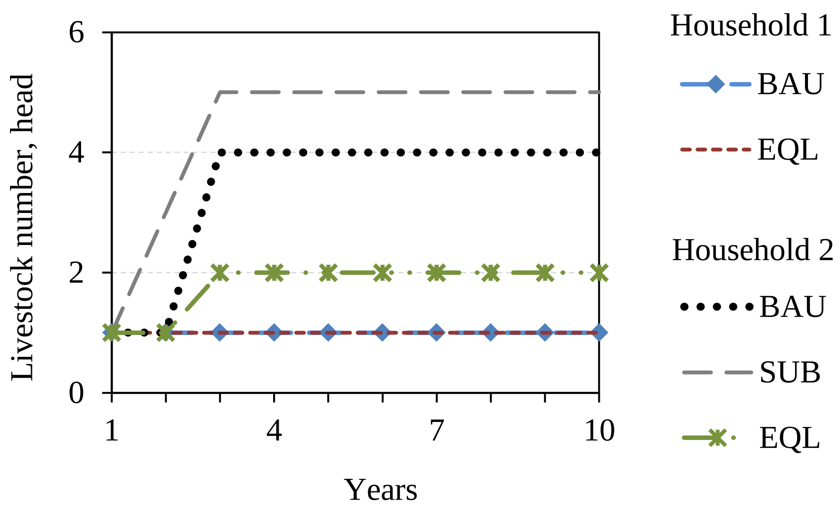


**Figure 4. Livestock number of household 1 and 2 over 10 years in the business-as-usual (BAU), subsidies (SUB) and equal (EQL) scenarios, head.**

The biomass produced from agricultural production contributes to various purposes of households. The livelihoods of households is influenced by biomass use through selling in market for income generation, purchase from market, satisfying food, energy and feed demand, agricultural production, and its storage for using in the next periods. At the same time, the use of biomass for one purpose may reduce the biomass availability for another use. In terms of crop main product use by destination (Table C1 in Appendix C), households mainly sell the surplus of consumed potato, which is the most profitable crop (for crop gross margins see Table A1 in Appendix A). For meeting their livestock feed demand, households buy barley from the market and do not produce this crop on own farm. Households purchase also other crops from the market, except potato, to meet food and livestock's feed demand. When looking at crop by-products and livestock products then the model shows that households have diverse use of products for different purposes (Tables C2 and C3 in Appendix C).

### 3.3 Employment and contracts

Continuation of current settings, i.e., the BAU scenario, lead that the men of poor households allocate most of their time to manage own farm, while women and children mainly manage the farm of rich household (Table 2). This is mainly because the wages of females and children for management of farm of household 2 are lower compared to the males and thus attractive for household 2. In contrast, men of household 2 spend most of the labor time by working outside of agriculture, whereas women and children stay in home and manage farming activities. State subsidies for solar panels improve opportunities to pump irrigation water at lower costs and increases crop cultivation area and livestock number in household 2 (see section 2.2) and subsequently demand for labor. This household type does not have enough labor to manage larger scale of farm operations and hires labor from household 1. This in turn reduces the labor time spend by household 1 in own farm. Provision of equal working opportunities, i.e., in terms of wage and working hours in non-agricultural work for households and by gender, result that the women of poor household are shifting work mainly to non-agricultural activities. Also, men of this household have higher working time in non-agricultural sector than in the BAU and SUB scenarios, and accordingly children spend most of their working time in managing own farm. In household 2, women substantially increase their work time for non-agricultural activities, while men as a result manage own farm. In the EQL case, the men become the main providers of food and energy for households. Such labor allocation for farming and non-agricultural employment can be due to the assumed higher agricultural productivity for men than for women, and increase in wages and working time for women to the same level as for men.

**Table 2. Employment by gender and age of household members over 10 years in business-as-usual (BAU), subsidies (SUB) and equal (EQL) scenarios, days.**

| Employment type | Male (adult) | | | Female (adult) | | | Children | | |
|---|---|---|---|---|---|---|---|---|---|
| | BAU | SUB | EQL | BAU | SUB | EQL | BAU | SUB | EQL |
| *Household 1* | | | | | | | | | |
| Own agricultural production | 2130 | 310 | 1982 | 368 | 0 | 360 | 123 | 0 | 314 |
| Agricultural production in household 2 | 1034 | 2635 | 141 | 1918 | 2086 | 0 | 188 | 284 | n.a. |
| Non-agriculture | 538 | 779 | 1681 | 28 | 23 | 1954 | 2 | 1 | n.a. |
| *Household 2* | | | | | | | | | |
| Own agricultural production | 1347 | 1082 | 3134 | 1438 | 1438 | 379 | 215 | 215 | 215 |
| Non-agriculture | 3034 | 3316 | 1277 | 10 | 10 | 1076 | 0 | 0 | n.a. |

Note: n.a. is not applicable.

In developing country settings agricultural contracts between households, such as labor and irrigation water supply, characterize the linkages of rural economy. In our case, interrelationships come from wages paid by household 2 for labor services provided by household 1 in managing crops and livestock of the former. The contract can be also the other way around, where household 1 pays for irrigation water supply services of household 2 (Figure 5). According to our model result, members of household 1 work in household 2 mostly in the SUB scenario followed by the BAU. In these two policy settings household 1 is mostly dependent on household 2 and receives the largest payments. The EQL scenario reduces indirectly the agricultural production of household 2 and lead to fewer interdependencies among households. This policy can be especially suitable for poor households with small farm area to reduce their income dependency on rich households with larger farm size. Although the difference with other scenarios is negligible, household 2 receives the largest agricultural contract revenues from providing irrigation water with pumps running on solar panels to household 1 in the SUB case when crop cultivation area is largest and farm energy costs are lowest.

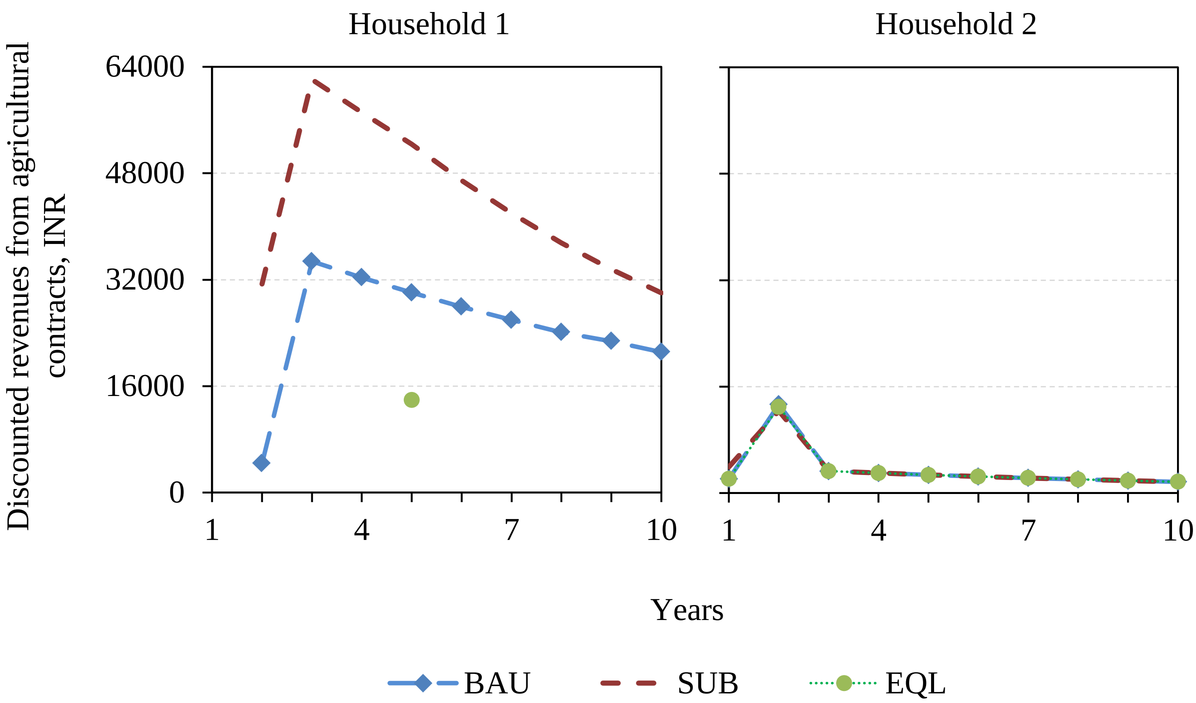


**Figure 5. Discounted revenues from agricultural contracts over 10 years of households in the business-as-usual (BAU), subsidies (SUB) and equal (EQL) scenarios, Indian Rupee.**

Note: discount rate is 10%.

## 3.4 Effects of energy use on health and environment

Burning of energy sources affects environment and health of households. The tCO2 emissions from the energy use are higher for richer household (i.e., household 2) than for poorer household (i.e., household 1) because of higher demand for domestic and crop cultivation purposes (Figure 6a). The pattern of greenhouse gas emissions do not differ substantially among the scenarios as a result of energy sources that are similar in emission levels (e.g., batteries storing electricity, tube well running on electricity, solar panels). The subsidies supporting renewable technologies such as solar panels do not influence the households' emission levels, because in the case of farming in BAU scenario, diesel water pumps are replaced by electric tube well in year 2, whereas in SUB scenario diesel pumps are replaced by solar water pumps in year 2. Both electric tube well and solar water pump are assumed to have no carbon emissions. Besides, energy technologies such as batteries storing electricity are already having low energy emissions (it was assumed that batteries storing electricity do not have emissions). Improved non-agricultural employment opportunities reduce greenhouse gas emissions of households, especially of household 2, due to the reduced agricultural production. Accordingly, diversification of rural employment opportunities and improvement of agricultural production practices can reduce greenhouse gas emissions.

In addition to greenhouse gas emissions from energy use the households also affect the environment through the harvest of wood as fuelwood from the open access forest. In simulated three scenarios the model results show that the harvest of wood from forest is performed in the first year by children of household 2 for cooking and water boiling uses. Harvest of wood for fuel reduces the forest stock and natural resources, and such forest damage is assumed to be irreversible.

The emissions from domestic energy use affect the health of households. We assume that the emissions of carbon monoxide and particular matter from the domestic energy use impact the health of households, which is reflected as monetary costs to households (Litman and Doherty, 2009). Despite higher domestic energy use of household 2 they use lower emitting energy sources and thus have slightly lower health costs from energy use than household 1 (Figure 6b). The main health expenditures of household 1 is from burning sugar leaves for cooking and water boiling activities, followed by the use of LPG. For household 2 the main costs on health come from biogas, followed by fuelwood use with improved cook stove and LPG. Solar panels that are adopted in the SUB scenario are established outside of house and assumed not to have any negative consequences on the health of households. It should be noted that in our study we assume monetary values as metrics for health costs (see section 3.5 for health costs). Hence, consideration of other assumptions on effects of energy use on health (e.g., reduction in labor productivity) can be more realistic and may lead to different health damage effects on households.

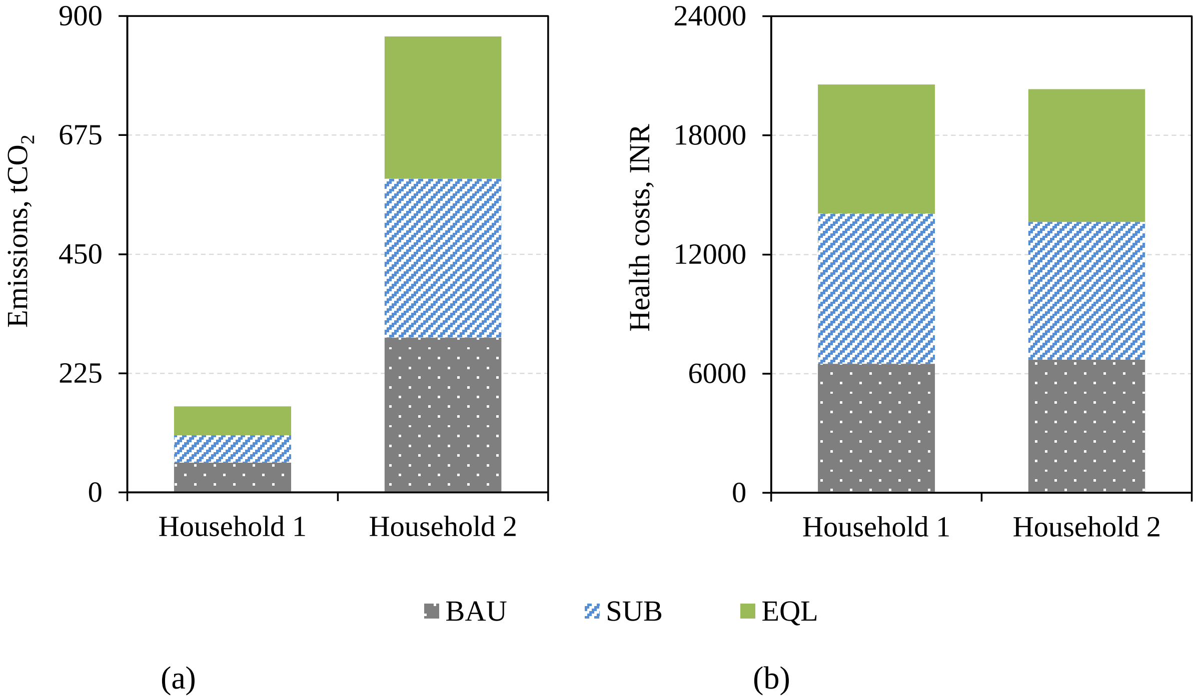


**Figure 6. Greenhouse gas emissions from energy use for both domestic and farm purposes (a) and health costs from domestic energy use (b) over 10 years in the business-as-usual (BAU), subsidies (SUB) and equal (EQL) scenarios.**

### 3.5 Incomes

Policies aimed to improve rural livelihoods necessitate considering changes in income levels of heterogeneous households, which can help to analyze different effects of policies on diverse groups of population. Our model shows that when the subsidies are provided to purchase solar panels the incomes of both households become larger than in the BAU scenario (Table 3). Household types 1 and 2 have increase in net present value of income over 10 years by 20 and 7% respectively. In contrast, giving equal opportunities by gender and household type (i.e., EQL scenario) substantially improve the incomes of household 1 (by 167%), while the incomes of household 2 becomes lower (by 15%) than in the BAU scenario.

**Table 3. Discounted summed incomes over 10 years of households in the business-as-usual (BAU), subsidies (SUB) and equal (EQL) scenarios, Indian Rupee.**

| Household types | Scenarios | | |
|---|---|---|---|
| | BAU | SUB | EQL |
| Household 1 | 324314 | 391115 | 864759 |
| Household 2 | 2239793 | 2399036 | 1912917 |

Note: discount rate is 10%.

To understand better the impacts of policies on rural households we differentiate their revenue and expenditure sources (Figure 7). For poor household, in the BAU scenario, agricultural production is the main income source followed by payment received from working in richer household. Whereas rich household for supplying irrigation water to poor household generates relatively negligible revenues. The expenditure structure mainly relates to the purchase of agricultural inputs as well as food and bioenergy commodities (legend Agriculture in Figure 7).

The state subsidies for solar panels (SUB scenario) improve the incomes of both households, where the main income source increase comes from the larger agricultural production in household 2. Household 2 increases both crop and livestock production (see section 3.2) as a result of obtaining subsidized by state the solar water pump for irrigation. Household 2 hires substantial amount of labor from the household 1 to maintain increased farming activities (see section 3.3). Consequently household 1 receives most of the income from wages paid by household 2 for farm work and hence interaction increases between these two actors, but household 1 becomes more dependent on farming decisions of household 2. Further, subsidies for renewable energy sources can be an option to reduce the energy costs of rural population, particularly of poor households. Among the simulated scenarios, the SUB scenario result in the highest total income levels (summed incomes of both households). In addition, the income gap between household 1 and 2 shrinks by about 8% in comparison to the BAU scenario.

Household 1 has substantial improvement in incomes when equal opportunities are given by gender and household type (i.e., EQL scenario). For this household, the income from non-agricultural work outweighs agricultural production due to small farmland area and low initial capital available for obtaining agricultural production inputs. Thus, such policy shifts poor rural households towards non-agricultural work (see section 3.3). This labor shift result in reduction of revenues from agricultural contracts between households. As agricultural production of household 2 is dependent on labor of household 1, their incomes from agriculture reduce when members of household 1 mainly work in non-agricultural sector. Accordingly, interactions between two households and their revenues for providing services to each other decline. From such changes the incomes of household 2 are reduced (lower by 15% than in the BAU scenario), yet, the total rural livelihood has improved (higher by 8% than in the BAU scenario). Consequently, the EQL scenario increases the incomes of poor households and reduces the income disparity among households but at the expense of income reduction of well-off households. Unless additional policies are provided for supporting agricultural production, the incomes of households that are well-endowed with farm resources and agricultural production in rural areas can reduce due to improved non-agricultural working opportunities.

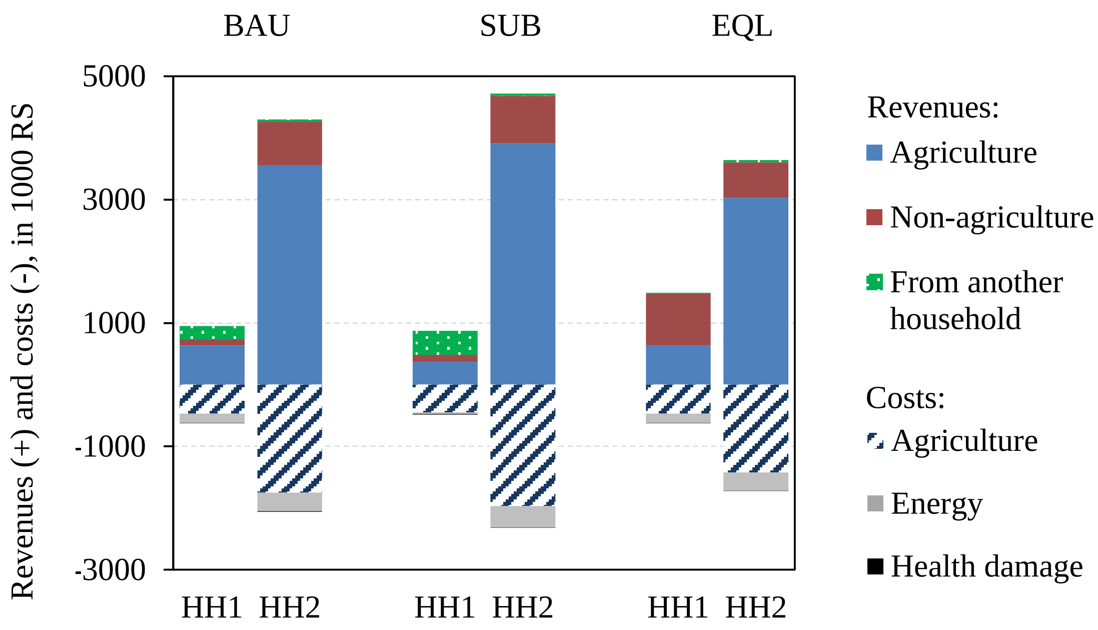


**Figure 7. Summed over 10 years discounted revenues and costs of households in the business-as-usual (BAU), subsidies (SUB) and equal (EQL) scenarios, Indian Rupee.**

Note: HH1 and HH2 are household type 1 and 2 respectively; discount rate is 10%.

## 4 Conclusions and policy implications

This study analyzes nexus issues in energy, food and natural resources for improving rural livelihoods by using the examples of policies such as continuation of current settings, state subsidies for solar panels and increase in non-agricultural employment opportunities s. We argue throughout the paper that it is important to consider the heterogeneity among and within households when analyzing the impacts of policies. Highly disaggregated analysis allows having detailed view on future developments and investigating gainers and losers under different policy settings.

Our study shows that the continuation of current settings while considering the population growth necessitates increase in biomass for satisfying energy demand. In such settings, the wellbeing of poor households do not improve over years, instead the income gap with rich household remain large. Rural households may incur high costs for energy use for agricultural production and may not have sufficient agricultural production to meet their energy and food demand, while considering their resource constraints. State subsidies for solar panels lead that households start to install solar panels for farming and domestic energy use. This improves not only the energy use of households but also the incomes of households and agricultural production, especially the agricultural production of well-endowed with farming rural households. Improved agricultural production also leads to higher labor demand for farming and increases interactions between households through the agricultural contracts. Increased interaction among households can help them to complement each other with resources. In addition, such rural interactions can also serve as an instrument to reduce the negative effects of risks where households pool their individual risks and share risks. Accordingly, state subsidies for renewable energy sources (e.g., solar panels) are needed to improve agricultural production. Adoption of solar panels by households can also bring high value to society by reducing greenhouse gas emissions and repercussions on health. However, it is not clear how the state budget might respond by providing subsidies for such technologies at the large-scale.

Policy that results in equal non-agricultural employment opportunity among gender and households types does not affect the energy use pattern of households. Under such policy scenario households still prefer the same type and amount of domestic energy sources as in the BAU scenario. With such policy, households allocate most of their labor in non-agricultural work. Hence, poor household, which has substantial labor force but usually has unequal non-agricultural opportunities than the rich household, allocates most its labor for non-agricultural work and has improvement in income levels. The household that is better endowed with agricultural production resources, i.e., household 2, incurs losses from such policy due to less hiring of labor from the poor household to manage its farm and hence lower agricultural production. The policy of equal non-agricultural income opportunities can be also considered to reduce the income disparity among households. Yet, this may happen not only due to an increase in incomes of poor households but also due to a decrease in incomes of rich households. In addition, agricultural production of our modeled households decreases and this in turn may affect the availability of food commodities for other households, e.g., urban households. Together with policy improving non-agricultural employment opportunity the policies need to be developed that address possible decrease in agricultural production.

The results of our model show that the policies that are frequently discussed when addressing the energy use of households, e.g., supporting policies for disseminating energy sources (e.g., Frondel et al., 2010), solving the increase in income inequality (e.g., Padilla and Serrano, 2006), may not provide a solution for certain issues when we consider the energy nexus issues by using the disaggregated analysis with different types of households and its members. Certain policies may benefit more for some type of households and may not tackle issues that are covered by other policies. Hence, further policies need to be developed that are comprehensive and include a package of policies for addressing different aspects affecting livelihoods of rural households.

This study is initial step in analyzing the nexus issues of households' energy use while considering heterogeneity within and among households. Changes in agricultural and non-agricultural sectors can influence these sectors by changing their supply, demand and accordingly prices. In addition, there is a high uncertainty of future outcomes, and hence certain variables may vary, e.g., input and output levels and their prices. Moreover, our model considers the joint optimization of households' objectives. Yet, each household can have its own objective function (i.e., individual objective function), where households may bargain in agricultural contracts. The difference between the joint and individual optimization models is transaction costs in managing contracts. Accordingly, further extensions of the model need to increase the scale of analysis towards partial or general equilibrium frame and consider individual optimization and stochasticity.

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# Appendix A

**Table A1. The main parameters distinguishing characteristics of households.**

| Parameters | Household 1 | Household 2 |
|---|---|---|
| Men labor days available | 360 | 418 |
| Women labor days available | 219 | 138 |
| Children labor days available | 30 | 20 |
| Non-agricultural job opportunities for men, days/year | 269 | 333 |
| Non-agricultural job opportunities for women, days/year | 14 | 10 |
| Non-agricultural job opportunities for children, days/year | 1 | 0 |
| Wage for men for non-agricultural work, RS/day | 186 | 381 |
| Wage for women for non-agricultural work, RS/day | 125 | 97 |
| Wage for children for non-agricultural work, RS/day | 75 | n.a. |
| Wage for men for work in agricultural activities of household 2, RS/day | 159 | n.a. |
| Wage for women for work in agricultural activities of household 2, RS/day | 117 | n.a. |
| Wage for children for work in agricultural activities of household 2, RS/day | 100 | n.a. |
| Land area for farming, acres | 0.84 | 4.1 |
| Number of cows, head | 1 | 1 |
| Number of buffalos, head | 0 | 1 |
| Gross margin of wheat, RS/acre | 5243 | 7620 |
| Gross margin of rice, RS/acre | 4444 | 7429 |
| Gross margin of sugarcane, RS/acre | 40225 | 39807 |
| Gross margin of mustard, RS/acre | 1287 | 1900 |
| Gross margin of potato, RS/acre | 49962 | 80589 |
| Energy requirement for cooking, Mjouls/year | 5984 | 7288 |
| Energy requirement for lighting, Mjouls/year | 1823 | 3379 |
| Energy requirement for electrical appliances, Mjouls/year | 1588 | 7489 |
| Energy requirement for wheat production, Mjouls/acre | 1459 | 1825 |
| Energy requirement for rice production, Mjouls/acre | 1806 | 2075 |
| Energy requirement for sugarcane production, Mjouls/acre | 2026 | 2427 |
| Energy requirement for mustard production, Mjouls/acre | 720 | 803 |
| Energy requirement for potato production, Mjouls/acre | 1742 | 1556 |
| Consumption of wheat, kg/year | 700 | 975 |
| Consumption of rice, kg/year | 568 | 805 |
| Consumption of sugarcane, kg/year | 362 | 1663 |
| Consumption of mustard, kg/year | 66 | 138 |
| Consumption of potato, kg/year | 1030 | 2487 |
| Consumption of milk, l/year | 535 | 1251 |

Note: n.a. is not applicable

## Appendix B

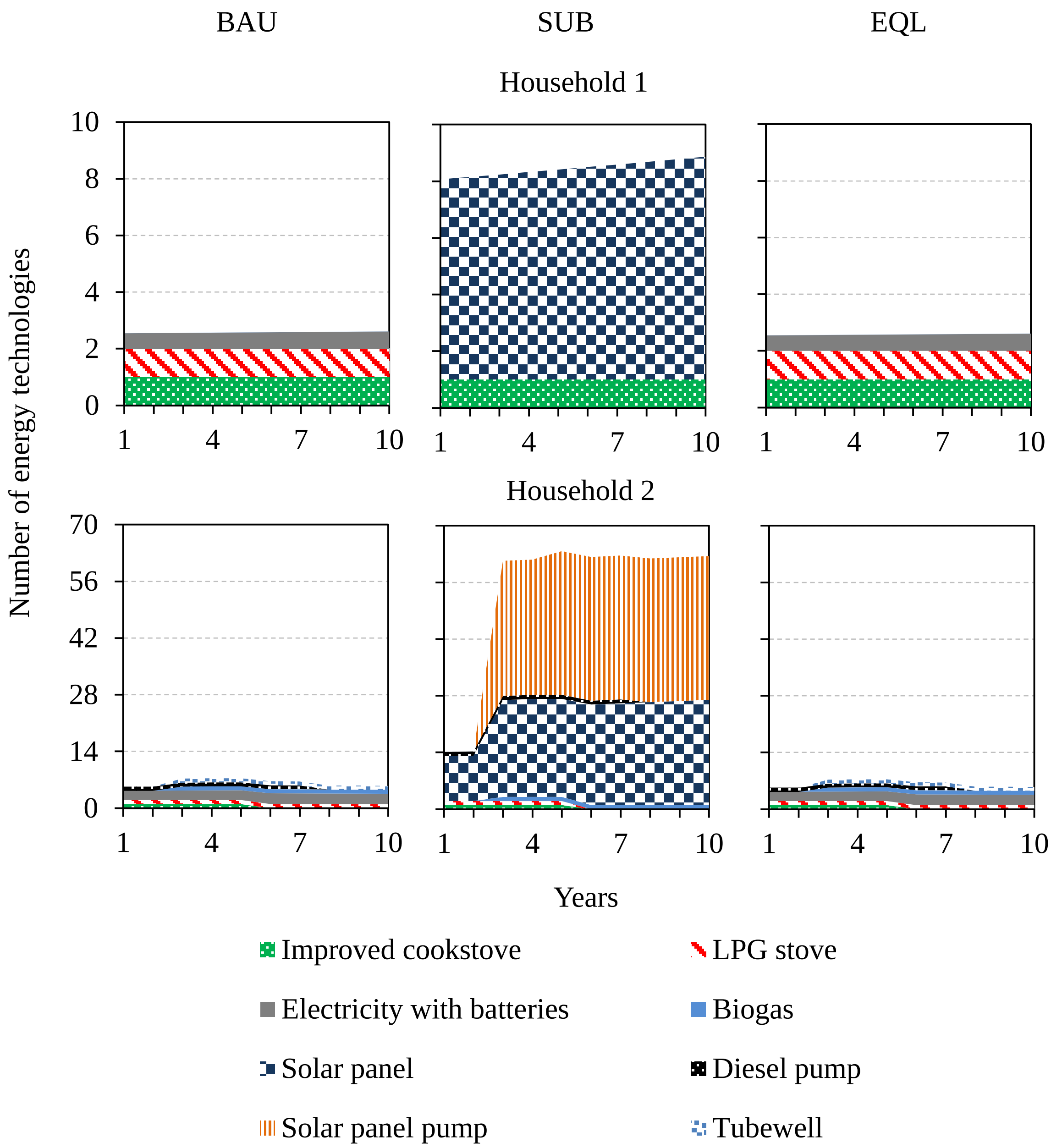


**Figure B1. Number of energy technologies at households for domestic and farming purposes over 10 years in the business-as-usual (BAU), subsidies (SUB) and equal (EQL) scenarios.**

# Appendix C

**Table C1. Use by destination of crop main products in the business-as-usual (BAU), subsidies (SUB) and equal (EQL) scenarios over 10 years, kg.**

| Destination | Crops | | | | | |
|---|---|---|---|---|---|---|
| | Wheat | Rice | Sugarcane | Mustard | Potato | Barley |
| *BAU scenario* | | | | | | |
| Sale | 0 | 0 | 2882 | 0 | 433217 | 0 |
| Purchase | 262270 | 13857 | 16492 | 2008 | 0 | 2258 |
| Storage | 0 | 0 | 0 | 0 | 0 | 0 |
| Consumption | 17688 | 14492 | 21369 | 2145 | 37134 | 0 |
| Feed for livestock | 9964 | 0 | 0 | 0 | 0 | 2258 |
| *SUB scenario* | | | | | | |
| Sale | 0 | 350 | 2112 | 0 | 432001 | 0 |
| Purchase | 26319 | 8148 | 14975 | 2008 | 0 | 2640 |
| Storage | 0 | 0 | 0 | 0 | 0 | 0 |
| Consumption | 17688 | 14492 | 21369 | 2145 | 37134 | 0 |
| Feed for livestock | 10894 | 0 | 0 | 0 | 0 | 2640 |
| *EQL scenario* | | | | | | |
| Sale | 0 | 0 | 0 | 0 | 426142 | 0 |
| Purchase | 22615 | 14492 | 3455 | 2008 | 0 | 1298 |
| Storage | 0 | 0 | 0 | 0 | 0 | 0 |
| Consumption | 17688 | 14492 | 21369 | 2145 | 37134 | 0 |
| Feed for livestock | 6003 | 0 | 0 | 0 | 0 | 1298 |

**Table C2. Use by destination for both households of crop by-products in the business-as-usual (BAU), subsidies (SUB) and equal (EQL) scenarios over 10 years, kg.**

| Destination | Crop by-products | | | | | | |
|---|---|---|---|---|---|---|---|
| | Wheat straw | Rice straw | Rice husk | Sugarcane top | Sugarcane leaves | Mustard straw | Mustard cake |
| *BAU scenario* | | | | | | | |
| Sale | 951 | 0 | 127 | 0 | 243 | 248 | 0 |
| Purchase | 36057 | 26212 | 0 | 14122 | 480 | 0 | 6349 |
| Storage | 0 | 0 | 0 | 0 | 32 | 0 | 0 |
| For energy purposes | n.a. | 0 | 0 | n.a. | 547 | 0 | n.a. |
| Feed for livestock | 37181 | 27165 | 0 | 14898 | 0 | 0 | 6438 |
| *SUB scenario* | | | | | | | |
| Sale | 951 | 0 | 1339 | 284 | 261 | 248 | 0 |
| Purchase | 36444 | 15883 | 0 | 12361 | 599 | 0 | 7351 |
| Storage | 0 | 328 | 334 | 1299 | 254 | 0 | 0 |
| For energy purposes | n.a. | 0 | 0 | n.a. | 678 | 0 | n.a. |
| Feed for livestock | 38887 | 25925 | 0 | 12927 | 0 | 0 | 7440 |
| *EQL scenario* | | | | | | | |
| Sale | 0 | 0 | 0 | 346 | 702 | 0 | 0 |
| Purchase | 21426 | 17738 | 0 | 8406 | 532 | 0 | 3733 |
| Storage | 0 | 0 | 0 | 663 | 1930 | 0 | 0 |
| For energy purposes | n.a. | 0 | 0 | n.a. | 547 | 0 | n.a. |
| Feed for livestock | 23040 | 17738 | 0 | 10197 | 0 | 0 | 3733 |

**Table C3. Use by destination for both households of livestock products in the business-as-usual (BAU), subsidies (SUB) and equal (EQL) scenarios over 10 years.**

| Destination | Livestock products | |
|---|---|---|
| | Milk, l | Manure, kg |
| *BAU scenario* | | |
| Sale | 58655 | 7142 |
| Purchase | 15854 | 40122 |
| Consumption | 18846 | n.a. |
| For energy purposes | n.a. | 1776 |
| For crop production | n.a. | 329857 |
| *SUB scenario* | | |
| Sale | 61363 | 27490 |
| Purchase | 16330 | 67719 |
| Consumption | 18846 | n.a. |
| For energy purposes | n.a. | 3110 |
| For crop production | n.a. | 337758 |
| *EQL scenario* | | |
| Sale | 36692 | 6636 |
| Purchase | 17120 | 14407 |
| Consumption | 18846 | n.a. |
| For energy purposes | n.a. | 1776 |
| For crop production | n.a. | 324995 |

Note: n.a. is not applicable.