Impacts of energy use nexus on inter- and intra-heterogeneous households: the case of Uttar Pradesh, India

U. Djanibekov[1]; V. Gaur[2]

1: Manaaki Whenua - Landcare Research, Governance and Policy, New Zealand, 2: Center for Development Research (ZEF), , Germany

Corresponding author email: djanibekovu@landcareresearch.co.nz

Abstract:

This study analyzes the nexus issues of energy use, agricultural production, income and employment among heterogeneous and interdependent rural households in Uttar Pradesh, India. We use an agricultural household dynamic programming model that includes two types of households differentiated by their socio-economic characteristics and linked through agricultural contracts. Households are also differentiated by their membership in terms of men, women and children. The model simulates the effects of policies such as state subsidies for the purchase of solar panels, improvement in non-agricultural employment opportunities, and combinations of the two. Our main data source is a survey of 400 rural Uttar Pradesh households. The model results indicate that households improve energy use patterns by using solar panels; yet, adoption of such technology is conditional on state subsidy levels of 50% and 80% for the purchase of solar panels for farming and domestic purposes respectively. Subsidies for solar panels together with improvement of off-farm work increases off-farm employment and income of the poorer household and reduces rural income inequality, however, agricultural production is reduced. In addition, the wealthier household incurs losses from improvement in non-agricultural employment opportunities due to reduced labor availability for farming.

Acknowledegment:

JEL Codes: Q12, Q48

#1585

Impacts of energy use nexus on inter- and intra-heterogeneous households: the case of Uttar Pradesh, India

Abstract

This study analyzes the nexus issues of energy use, agricultural production, income and employment among heterogeneous and interdependent rural households in Uttar Pradesh, India. We use an agricultural household dynamic programming model that includes two types of households differentiated by their socio-economic characteristics and linked through agricultural contracts. Households are also differentiated by their membership in terms of men, women and children. The model simulates the effects of policies such as state subsidies for the purchase of solar panels, improvement in non-agricultural employment opportunities, and combinations of the two. Our main data source is a survey of 400 rural Uttar Pradesh households. The model results indicate that households improve energy use patterns by using solar panels; yet, adoption of such technology is conditional on state subsidy levels of 50% and 80% for the purchase of solar panels for farming and domestic purposes respectively. Subsidies for solar panels together with improvement of off-farm work increases off-farm employment and income of the poorer household and reduces rural income inequality, however, agricultural production is reduced. In addition, the wealthier household incurs losses from improvement in non-agricultural employment opportunities due to reduced labor availability for farming.

Keywords

Bioenergy; Heterogeneity; Rural interdependencies; Agricultural household model.

1. Introduction

Worldwide, households' consumption accounts for 30% of all end-use energy and nearly 2.6 billion people rely on bioenergy uses (IEA, 2013). Energy production is linked with other sectors that influence population welfare. Projected increase in the demand for agricultural commodities by 60 to 70% over the next 40 years due to global population growth will lead to increased competition of resources for agricultural and bioenergy production (FAO, 2012). Accordingly, increased use of bioenergy may reduce food crop output and negatively affect food security. Also, increase in bioenergy production is expected to impact the employment composition among household members (Gebreegziabher et al., 2013). Moreover, trade-offs might exist between energy production and income generating activities and environmental pollution (Mirzabaev et al., 2015).

Several policy options intended to improve household energy production are analyzed with consideration of the importance of the nexus among energy production and other dimensions such as food output, employment, income generation and environment (Padilla and Serrano, 2006; Mirzabaev et al., 2015). For example, producing energy using renewable technology might increase household income and reduce greenhouse gas emissions (Hiremath et al., 2010). Yet, rural households in developing countries may not have sufficient financial resources to invest in the purchase of solar panel systems. To incentivize the adoption of alternative energy sources, state support in the form of subsidies that reduces associated costs might be necessary (Frondel et al., 2010). In addition, policy that contributes to improved non-agricultural employment opportunities can mitigate trade-offs between bioenergy and food production, and can help to diversify rural households' income (Chen et al., 2006).

Most of the studies that have considered policy approaches for addressing the nexus of energy production with other dimensions were based on aggregated analysis approaches (Frondel et al., 2010; Gebreegziabher et al., 2013). However, aggregated analyses do not take into account heterogeneity among rural households. Consideration of household heterogeneity allows us to explore the diverse impacts of energy use changes on different types of households and their members. At the household scale, heterogeneity is manifested within membership and the responsibilities and activities of individual household members (Gasson and Winter, 1992). For example, in developing countries women are usually responsible for sustaining household energy and food provision (Arndt and Benifica, 2011), accordingly, changes in energy use are likely to influence labor activities among women and thus affect energy pattern and food security of household. In addition, there is heterogeneity among rural households, e.g., differences in socio-economic status, and scale and types of household farming activities. As a result of such differences, changes in energy production and use can have differential effects at the household scale. Wang et al. (2016) found that the adoption of improved energy sources can increase overall societal welfare, yet socio-economic differences among households need to be considered due to variability in the adoption of such sources among households. In particular, poor households may not be able to afford alternative means of meeting their energy demand. Additionally, poor households tend to be disproportionately affected by energy and food production trade-offs, as well by changes that affect income generating activities (Chen et al., 2006).

More importantly, consideration of heterogeneity among rural actors allows us to capture direct and indirect effects of energy production changes and the nexus among energy production and other sectors. Such effects can occur due to interdependency of households. For example, in developing countries rural households usually interact and may influence each other's agricultural activities through contracts intended to complement households' farming activities through the provision of resources (e.g., Otsuka et al., 1992). Such contractual interactions may lead to changes in energy production for one household type (or changes in policies and technologies targeted for one rural household demographic) and have indirect effects on other household types. For instance, Gebreegziabher et al. (2013) found that investment in bioenergy capacity not only benefits the welfare of poor households, but also indirectly households that benefit through labor relationships with the primary beneficiary households.

To our knowledge, previous studies have not simultaneously considered the nexus of energy use and production with other aspects of household welfare along with heterogeneity within and among households and their interactions. To address this research gap we developed an agricultural household dynamic programming model that combines two types of households that differ in their socio-economic characteristics and that are interlinked through labor-wage and irrigation supply-payment contractual arrangements. We further differentiate household membership in terms of men, women and children. Our modeling frame allows investigating energy use, agricultural production, employment in both agricultural and non-agricultural activities, direct and indirect effects on households, and household gains or losses affiliated with introduced policy changes. We analyze policies such as state subsidies for the purchase of renewable energy equipment (e.g., solar panels), improving off-farm employment opportunities for households, and combinations of the two, because such policies have been suggested for improving energy production and reducing related trade-offs for rural households (e.g., Chen et al., 2006; Padilla and Serrano, 2006; Frondel et al., 2010). The objectives of this study are to: (1) investigate the effects of policy changes with respect to the nexus of energy use and agricultural production, employment and income, while taking into account heterogeneity among household membership and types as well as interactions between households; and (2) identify policies that improve livelihoods of heterogeneous households within the energy use nexus.

2. Methods

2.1 Study area

The study area is in the Uttar Pradesh province of India. We selected this area due to the results of the National Sample Survey 66th round in 2009–2010 indicating that dependence on traditional bioenergy in Uttar Pradesh is among the highest across all regions in India, and also because this province has one of the lowest centralized energy supply to households in the country (Census of India, 2011). The economy of the province depends on agricultural production, which accounts for about 2/3rd of the provincial labor force (Singh, 2014). The province has a population of 199.58 million. Predominant land uses are potato, wheat, rice, sugarcane and mustard, which are primarily cultivated for household subsistence purposes and surplus is traded in local markets. Households are not provided sufficient energy from the state grid for meeting needs related to cooking, heating water, lighting and operating electrical appliances. Households usually satisfy their energy demand through bioenergy sources such as dried cattle dung, crop by-products, fuelwood, as well as with alternative sources such as solar panels, biogas, liquefied petroleum gas (LPG), kerosene, and batteries for storing electricity.

2.2 Data sources

Our main data source is a survey of 400 rural Uttar Pradesh households. We undertook three sampling steps to determine household selection. In the first step we selected districts based on consideration of the variance associated with socio-economic and energy systems. For this task, a district level dataset was created based on the following characteristics: per capita net district product; percentage of primary sector in net district product; population density; percentages of households that use fuelwood, cattle dung, crop residue, and LPG for cooking; electricity from the centralized grid; biomass surpluses at the district level; and the percentage area of wheat and rice production and their respective yields. We applied a statistical clustering technique to the database to identify district clusters and then randomly chose four districts from these clusters. The selected study districts 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), and Sant Kabir Nagar (26°47’–26°79’N, 83°3’–83°3.45’E).

In the second step, we selected villages from within the identified districts. We prepared lists of villages within each district based on Census of India: Uttar Pradesh (2011). We assumed that all villages of the identified districts shared the characteristics used to designate the district clusters. Two villages were randomly selected from each district for a total of eight villages. In the third step, we chose sample households by applying a systematic sampling technique. To employ this technique we began at the center of the village, chose a random direction and then randomly selected a household in that direction. Afterwards, we selected another household located in each direction. Selected rural households were then surveyed for information on demography, income sources, expenditures, asset endowments, agricultural production techniques, and energy use.

Based on the survey information, we classified households into two groups according to their economic characteristics. First, we determined the mean annual household revenues for the entire sample and then divided the sample based on the results. Relatively poorer households with annual revenues below the mean annual household revenue level were classified as type 1 households, and relatively wealthier households with annual revenues above the mean were classified as type 2 households. During the survey effort we observed that households sometimes exchange resources through agricultural contracts. Such interactions occur when type 2 households with abundant farmland but insufficient labor resources to manage that farmland recruit labor from type 1 households. In addition, type 1 households usually have limited amounts of farmland and do not invest in irrigation capacity, but instead obtain irrigation water from type 2 households. A summary of the main characteristics of two household groups is given in Table A in Appendix.

Furthermore, we collected information on carbon monoxide and particulate matter emissions from energy sources as an index of household health and related expenses. These costs are based on the findings of Litman and Doherty (2009) regarding health costs related to carbon monoxide and particulate matter emissions of vehicles in Canada. To convert these values to the context of rural India we calculated the ratio of GDP per capita between India and Canada and multiplied the health costs of carbon monoxide and particulate matter as described in Litman and Doherty (2009). We also collected information from US EPA (2000) and Sovacool (2008) on greenhouse gas emissions from energy sources such as crop by-products, fuelwood, cattle dung, LPG, kerosene, biogas, and diesel.

2.3 Model description

We apply an agricultural household dynamic programming model to investigate energy use change nexus issues and effects on the livelihoods of heterogeneous households. Agricultural household model considers simultaneous production and consumption decisions of household (Singh et al., 1986). The model is normative, which is a prescriptive type of model that determines the levels of variables to optimize the objective function. The dynamic programming model assumes that households make their decisions based on consideration of the entire analysis period and adjust their annual activities accordingly to achieve optimal values over the entire period. Our model maximizes the net present value of household income over ten years at a 10% discount rate. The model also relies on mixed integer programming that considers continuous, integer (e.g., number of livestock) and binary (e.g., adoption of biogas, diesel generator, tube well and improved cook stove) variables. The model is deterministic and uses the mean values of collected information.

The model considers two types of households (Fig. 1) that differ based on demographic and socio-economic characteristics. Type 1 household is relatively less economically endowed in terms of farmland area, initial budget available for expenses, off-farm income generating opportunities and livestock number than type 2 household. Households also differ with respect to labor availability by age and gender. Households are interrelated through agricultural contracts, where members of a type 1 household can be employed by a type 2 household and receive per diem payments for such work. Another interaction among households occurs when a type 2 household sells pumped irrigation water to a type 1 household in return for payments reflecting the energy used to obtain irrigation water.

We assume also that households are heterogeneous with regard to membership. We include three types of household members to treat intra-household heterogeneity—men (males above 15-years old), women (females above 15-years old) and children (males and females 15-years old or younger). Household member categories vary with respect to labor time availability, wages for agricultural and non-agricultural employment, agricultural labor productivity, and time spent collecting and preparing bioenergy sources. We assume that household membership remains constant. We do not consider education and other age or gender-specific activities unrelated to income generation labor activities. We use an annual household membership growth rate in India in 2015 of 1.2% (World Bank, 2016).

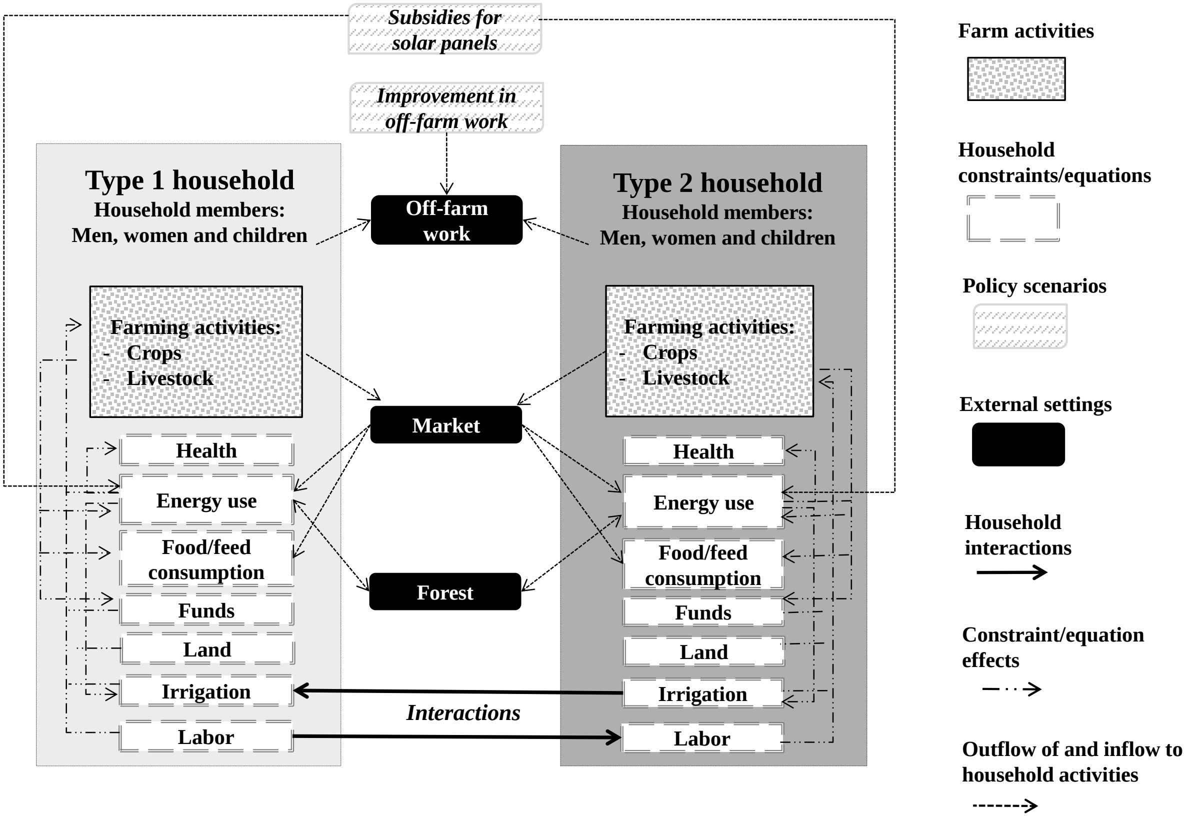


Fig. 1. Household energy use nexus model.

Households can generate income by selling surplus farm products (wheat, rice, sugarcane, mustard and potato), crop by-products (wheat, rice and mustard straw; rice husks; sugarcane debris (includes top and leaves); and mustard cake), livestock (buffalo and cow) and their products (milk and manure), as well as from employment at another farm (for type 1 household), payments for irrigation water (for type 2 household), and non-agricultural employment wages. Household men have greater opportunities to find non-agricultural work than women, and type 2 household members have better non-agricultural working opportunities in terms of salary and work schedules than type 1 household members. Households must satisfy their crop, milk and residential energy consumption needs and feed demand of livestock. Agricultural products have multiple destinations (e.g., crops can be consumed, sold, stored, used as feed for livestock, or used as energy sources). Input and output prices are assumed to be exogenous. Household expenditures include the purchase of agricultural production inputs, agricultural commodities, energy resources and related equipment, payments for labor and irrigation services, and health care costs related to the use of household energy sources. In the latter case of household expenses for health care due to issues arising from energy use, we are considering the negative impacts of carbon monoxide and particulate emissions from burning energy sources for residential purposes.

The core aspect of the model is household energy use. Residential energy demand includes energy used for cooking and heating water, lighting, and the use of electrical appliances (Table 1). Energy resources can be also used for farming or sold in local markets. We focus on energy resources that are currently used by the surveyed households and according to discussions with local experts on preferences and suitability of energy resources in Uttar Pradesh. Different energy resources considered in the model, include: traditional bioenergy use (i.e., crop residues, fuelwood and cattle dung), electricity from the state grid, petroleum based products (i.e., LPG, kerosene, and diesel for electrical generator), and renewables (i.e., solar or photovoltaic panel systems and biogas), which differ in their destination use. Energy sources can be utilized with different hardware for residential purposes. For instance, bioenergy can be burned with either traditional cook stove or improved cook stove that is more efficient and generates less harmful emissions. Batteries for storing electricity can be purchased from local markets and installed at households so that electricity is available when the state grid is not functioning. Several bioenergy sources have other uses; for instance livestock dung can be used as manure for crops and can be sold in local markets. In addition, livestock dung can be used for biogas digester, and the organic by-products from biogas digester can be used as manure for growing crops. Households also use energy to supply water for crop irrigation. Irrigation water can be pumped from tube well using electricity from the central grid or from generators powered by diesel or solar panels. Usage of hydrocarbon-based energy contributes to greenhouse gas emissions, whereas the use of solar panels and batteries for storing electricity does not. In the model, households cannot install more than one unit of improved cook stove, diesel generator, biogas digester, tube well, pumps operating on diesel and on solar panels, and thus these technologies are included as binary variables. On the other hand, households can install batteries for storing electricity and solar panels at different capacities and the energy provision capacity of these systems can be increased and hence these technologies are treated as continuous variables.

Households make long-term investment decisions with respect to livestock and energy choices and can decide whether to invest now or in the future. We also assume that energy equipment has a lifespan and in the model improved cook stove, LPG stove, and batteries are expected to function for five years, whereas the lifespan of a diesel irrigation pump is seven years. Households can renew expired energy hardware. Due to the fact that electrical tube well pump and biogas digester can function for up to 20 years (longer than the model simulation period), there is no lifespan for these technologies.

Table 1. Application of energy sources by end-use.

	Application				
	Residential purposes			Agricultural inputs	For sale in local markets
Source	Cooking and heating water	Lighting	Electrical appliances		
Fuelwood	■				
Crop by-products	■			■	■
Livestock dung	■			■	■
Kerosene		■			
Diesel		■	■	■	■
Liquefied petroleum gas	■	■			
Grid electricity		■	■	■	■
Solar panels		■	■	■	■
Biogas	■			■	

Due to insufficient data we do not consider income responsive demand function of households and thus assume that demand for food, energy, and other products only changes with respect to the growth rate of households' members. In addition, our model considers household level effects but does not consider market effects from household production changes as few households may not influence market forces. The model was programmed in GAMS.

2.4 Scenarios

The model simulates four scenarios to explore the effects of changes in the nexus of energy with other factors and activities on the two household types, and on interactions among households. The model analyses four scenarios based on current observations and policies that can incentivize adoption of renewable energy sources and reduce trade-offs between energy choices and food production and income:

- Business-as-usual scenario (BAU)—The model settings are based on observations from household surveys and secondary data;
- Subsidies scenario (SUB)—Increased use of solar panels can help meet energy demand and increase income, but such technologies are expensive. In this scenario the model considers a range of subsidies that cover up to 90% of the costs of solar panels and their batteries. The use of a range of values allows us to explore the effect of changes in subsidy levels relative to the adoption of solar panels. For simplicity, we present model outputs with a 50% subsidy for solar irrigation pump and an 80% subsidy for residential solar panels, which are the values that lead to the adoption of these technologies according to the model;
- Improved off-farm employment scenario (EQL)—Providing rural households with better non-agricultural working opportunities may reduce dependency on traditional bioenergy use and improve the economic situation of poor households. In this scenario, we assume households have equal off-farm employment opportunities (i.e., equal number of working days and wages for adult members). We further assume that children can only assist in household farming efforts and not in non-agricultural activities or on farmland of type 2 household, and thus restrict the labor allocation of children variable to household farming only;
- Combination (COMB) scenario—In this scenario both solar panel subsidies (SUB) and improved off-farm employment opportunities (EQL) are considered.

3 Results and discussion

3.1 Energy use

In developing countries, household livelihoods often depend on different energy sources, which are decentralized in nature and used for residential and farming purposes. In the BAU scenario, the model shows that households increase the use of biomass energy such as sugarcane leaves over time for cooking and heating water (Fig. 2). For lighting and operating electrical appliances households rely on electricity from the state grid. When grid based electricity is unavailable households rely on battery and LPG powered lights. Households install battery backup systems in the first year and gradually augment capacity to satisfy the electricity requirement (Fig. B). Also, disparity in the adoption of alternative energy technologies exists among households. Households with relatively greater economic resources are more likely to adopt energy alternatives, and to adopt them earlier, than households with less economic resources (Diaz-Rainey and Ashton, 2015). For example, among households of both types that began with improved cook stove in year one, type 1 household (which burns crop by-products such as sugarcane leaves) replaces it with another improved cook stove upon expiration in year five, whereas type 2 household (which burns fuelwood) substitutes it with biogas digester, even under current biogas establishment and management costs, once sufficient funds are accumulated to invest in biogas system. This suggests that supporting policies are necessary for improving the adoption of biogas among poor households. We did not consider transaction costs that affect the adoption of biogas digester, which might be the reason for low adoption rates of such technologies in rural areas (Brown, 2001).

Differences in energy use among households can also be observed in relation to farming. Type 1 household meets irrigation needs by purchasing water from type 2 household. Ownership of relatively smaller area of farmland is a major reason that purchasing irrigation water is more financially viable for type 1 household than investment in an irrigation pump. The model shows that type 2 household that initially uses diesel operated pump switches to electric tube well irrigation system (which has lower operating costs relative to alternative irrigation pumps) in year three after sufficient funds are available to do so. Changes in energy sources for both residential and farming purposes are mainly attributable to increases in household income, which differ among households.

Currently the costs of solar panels are prohibitive for rural households and households prefer to invest in cheaper energy sources. Even with the state subsidies, i.e., SUB scenario, type 1 household is not adopting solar irrigation pump because of small availability of farmland and finances, but rather continues to depend on irrigation water purchases from type 2 household. Subsidies may not lead to immediate adoption of solar irrigation pump and type 2 household still needs time to accumulate sufficient funds to be able to invest in this technology. In contrast, state subsidies for residential solar panel systems improved solar adoption rates for both household types beginning the first year of the simulation. The results suggest that 50% subsidy for solar irrigation pump and an 80% subsidy for residential solar panels can reduce costs sufficiently to incentivize adoption among rural households, and such policies might be particularly effective for incentivizing adoption among better-off households.

Poor households are less likely than wealthy households to switch from traditional bioenergy use to the improved and modern renewable energy sources. Chen et al. (2006)

reported that improving non-agricultural working opportunities can change energy use composition and reduce dependency on traditional bioenergy use. The model results show that improving off-farm work opportunities, i.e., EQL scenario, lead to similar residential energy use pattern for both household types as in the BAU case. Also, despite greater financial resources available for agricultural expenses from off-farm income, type 1 household continues to irrigate crops with water purchase from type 2 household. Accordingly, improved off-farm employment opportunities do not substantially affect household energy use patterns, as the costs of alternative energy sources are high. Improved off-farm employment is expected to reduce household agricultural activities, and consequently households irrigate crops less. In turn, the energy use in the EQL scenario is slightly lower for farming than in the BAU scenario.

The COMB scenario leads to the adoption of residential solar panel systems by both household types. In this scenario the energy use pattern of type 1 household is the same as in the SUB scenario, whereas type 2 household installs biogas digester in the first year of the simulation in response to the greater availability of subsidies and income from non-agricultural work. In the COMB and SUB scenarios, households need more energy for residential needs, in terms of megajoules, relative to the BAU and EQL scenarios, because in the latter scenarios households use LPG for both lighting and cooking. In addition, having subsidies for solar irrigation pump only lead to adoption by type 2 household, this is similar to the results of the SUB scenario, and contributes to similar agricultural energy needs as in the EQL scenario due to increased household labor allocation to non-agricultural employment.

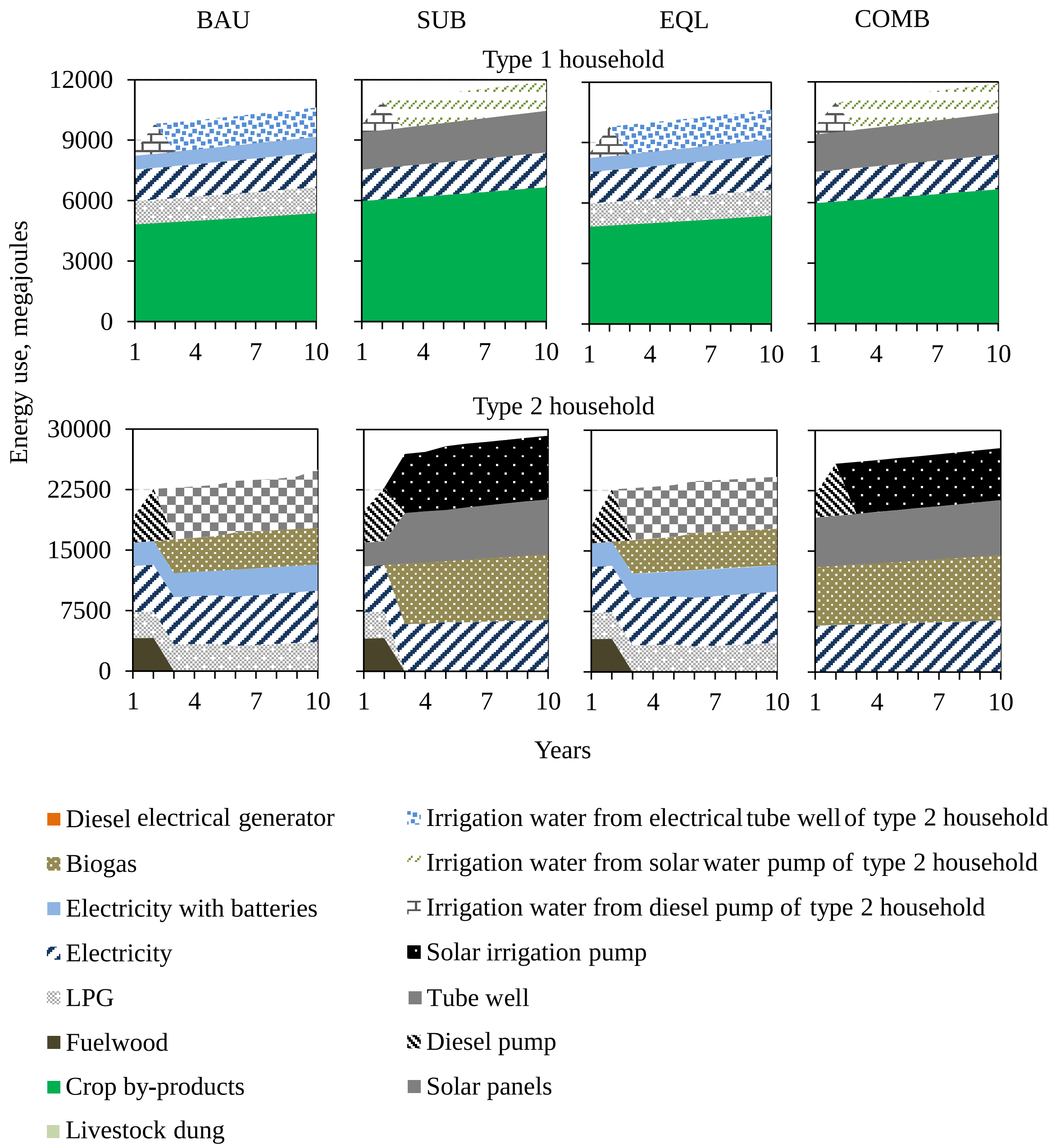


Fig. 2. Energy use patterns for residential and agricultural purposes by household type over 10 years under the business-as-usual (BAU), subsidies (SUB), equal (EQL) and combined (COMB) scenarios.

3.2 Agricultural production

Demand for energy and food will increase with future population growth (FAO, 2012), and may lead to production trade-offs between the two, as these sectors are interrelated and compete for resources (Mirzabaev et al., 2015). The model results do not suggest any trade-offs between energy sources and food security, as study area households have perfect access to various energy sources and food commodities, and can obtain commodities from local markets if they are not produced on household farmland. According to the model result, the main crop of both household types is potato (Fig. 3), which is also the most profitable crop (crop gross margins are given in Table A in Appendix). Household crop cultivation patterns change with respect to the initial part of the simulation period because of less resource availability (i.e., agricultural expense budgets and irrigation pump) in year one than in subsequent years. Crop production is also heterogeneous among households, and type 2 household has more diversified land use pattern than type 1 household due to assumed differences between household types.

The results reveal that state subsidies for solar panel systems increase crop cultivation area, because households that adopt solar energy reduce crop production costs. This suggests that solar irrigation pumps can enhance rural food security. In contrast, improvement in off-farm work opportunities leads to a shift of labor resources from agriculture (see section 3.3) and subsequently slightly reduces household crop cultivation area, particularly of type 2 household. The COMB scenario leads to a similar reduction of crop cultivation area for type 1 household and slightly more reduction for type 2 household relative to the EQL scenario. Thus, despite high subsidies for solar irrigation pump, households prefer non-agricultural employment activities over agricultural work due to higher earning capacity.

Although improved non-agricultural work may lead to investments in agriculture (Zhong and Ji, 2009), in our study area markets function well and we assume that households can meet their consumption and livestock feed demands by purchasing commodities from local markets, therefore households allocate most of their labor to off-farm work. However, households in many developing countries produce agricultural commodities for subsistence purposes as local markets do not function well and there are high transaction costs related to these markets. Therefore, households might need to augment output of agricultural commodities to meet food demand of increasing household members, which will lead to trade-offs between food and bioenergy production. In such situations households are likely to invest in agriculture and alternative energy sources.

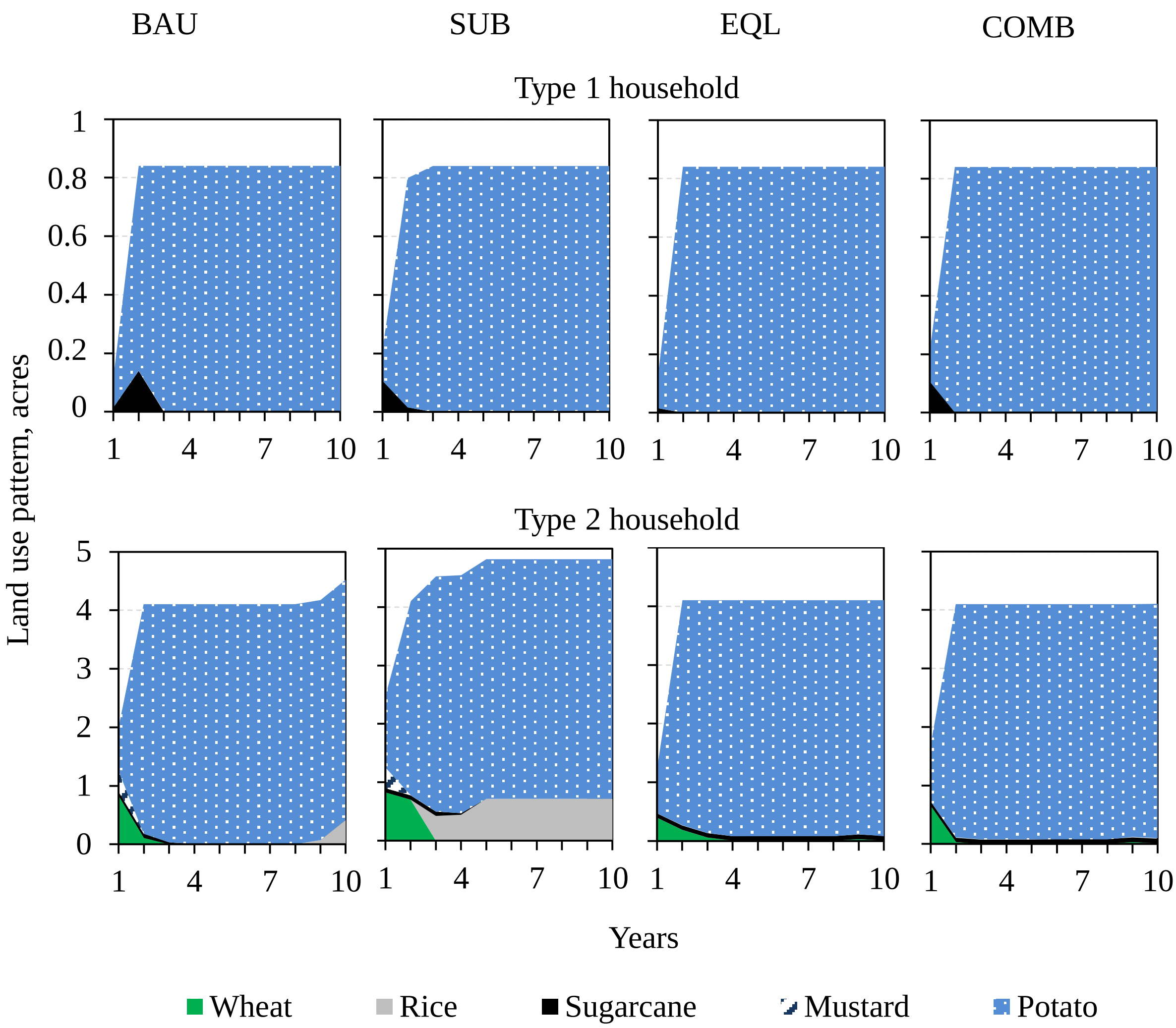


Fig. 3. Land use patterns by household type over 10 years under the business-as-usual (BAU), subsidies (SUB), equal (EQL) and combined (COMB) scenarios.

3.3 Employment

Changes in energy use and agricultural production subsequently impact household employment. There are important employment differences among rural household members (e.g., gender and age specific division of labor) and therefore policy changes can have differential effects on household members (Gasson and Winter, 1992). For instance, BAU scenario results indicate that at type 1 household, men allocate most of their time to their own agricultural activities, while women and children mainly perform agricultural work for type 2 household (Table 2). In contrast, men of type 2 household primarily seek off-farm employment, and women and children perform agricultural work for the household. Household division of labor among working activities often falls along traditional gender roles with women being mainly responsible for household needs and men seeking income generating employment (Whatmore, 1991). The EQL scenario that modeled equal off-farm work opportunities among household types and increased off-farm employment for females is a form of labor diversification and offers new opportunities for rural poor, especially women. In this scenario, women from type 1 household primarily shift employment to non-agricultural activities. Women from type 2 household also increase off-farm employment substantially, while men mostly engage in household agricultural work. These changes in labor allocation for farming and non-agricultural work are due to the increase in wages and working opportunities for women for both households and based on the assumption that men typically have greater agricultural productivity than women. Another result of the EQL scenario is that due to improved off-farm work opportunities members of type 1 household reduce their employment for type 2 household and become less dependent on type 2 household than in the BAU scenario.

Household employment structure can also be influenced by policies that promote energy alternatives. Agricultural production increases in the SUB scenario due to subsequent reduction of agricultural energy costs. Consequently, household members allocate more of their time to agricultural work. Household with more farmland do not have sufficient labor resources to meet their needs and must hire laborers, who in this case come from household with insufficient farmland but abundant in labor availability. The agricultural contract interactions among households are greatest in the SUB scenario, where type 1 household members allocate most of their labor time to agricultural work for type 2 household. The solar panel subsidy policy can also reduce household dependency on child labor, because of increased participation by both men and women in agricultural work, which makes child labor less necessary and could potentially improve school attendance.

In the COMB scenario, households allocate a substantial amount of their labor time to off-farm work, for which they earn greater income than from agriculture employment, even considering the subsidies for solar irrigation pump. Type 2 household continues to hire a considerable amount of labor from type 1 household (although lower than in the BAU case), because of reduced energy expenses for agricultural production.

Table 2. Cumulative labor allocation distribution by household type and membership over 10 years under the business-as-usual (BAU), subsidies (SUB), equal (EQL) and combined (COMB) scenarios, in days.

Labor type	Type 1 household			Type 2 household		
	Men	Women	Children	Men	Women	Children
			BAU scenario			
Household agricultural production	2130	368	123	1347	1438	215
Agricultural work for type 2 household	1034	1918	188	n.a.	n.a.	n.a.
Non-agricultural work	538	28	2	3034	10	0
			SUB scenario			
Household agricultural production	310	0	0	1082	1438	215
Agricultural work for type 2 household	2635	2086	284	n.a.	n.a.	n.a.
Non-agricultural work	779	23	1	3316	10	0
			EQL scenario			
Household agricultural production	1982	360	314	3134	379	215
Agricultural work for type 2 household	141	0	n.a	n.a.	n.a.	n.a.
Non-agricultural work	1681	1954	n.a	1277	1076	n.a
			COMB scenario			
Household agricultural production	153	0	313	2467	208	215
Agricultural work for type 2 household	1042	91	n.a	n.a.	n.a.	n.a.
Non-agricultural work	2610	2224	n.a	1944	1247	n.a

Note: n.a. is not applicable.

3.4 Household livelihoods

To better understand the impacts of energy policies on household wellbeing we differentiate household revenue and expenditure structure (Table 3). For type 1 household, own farm production is the main income source in the BAU scenario, followed by agricultural work for type 2 household. Household expenditure structure is related to the purchase of agricultural inputs, food and bioenergy sources. The income difference among household types is considerable; over the 10-year period type 2 household earns seven times the income level of type 1 household.

State subsidies for purchasing solar panels, i.e., SUB scenario, can improve income of households and income increase comes from the improved agricultural production of type 2 household. The purchase of solar irrigation pump with the state subsidies by type 2 household increases crop production and indirectly affects type 1 household. This is due to that the type 2 household hires substantial amounts of labor from type 1 household for agricultural work (see section 3.3). Consequently, type 1 household receives most of its income from work performed for type 2 household, thus increasing interaction between the two household types. Subsidies for the purchase of solar panels can also be an energy cost reduction strategy, particularly among poor households. In addition, in the SUB scenario the income gap between household types closes by about 8% in comparison to the BAU scenario.

The model results exhibited the least income inequality among households under the COMB scenario with both state subsidies for solar panels and improved off-farm employment opportunities. Type 1 household experiences substantial improvement in income under this scenario due to increased non-agricultural employment. Income from non-agricultural work exceeds income from agricultural production for this household, because of relatively less farmland area and less capital available initially for obtaining agricultural inputs. This labor shift results in reduced agricultural contract revenues and interactions between the two household classes. Accordingly, less labor from type 1 household is available to type 2 household than in the BAU scenario, requiring the latter household to allocate more of own labor to farming. To compensate for reduced labor availability and to meet demand for agricultural commodities, the type 2 household reduces labor allocated to non-agricultural activities, which are more lucrative than agricultural work. As a result, the incomes of this household are reduced (10% lower than under the BAU scenario), even though the overall rural income is improved under this scenario (23% greater than under the BAU scenario). The most substantial income reduction among households occurs for type 2 household under the EQL scenario (15% lower than under the BAU scenario), which also exhibited the lowest returns from agricultural contracts.

With respect to energy use effects on health and the environment, the use of diesel irrigation pump by type 2 household is the main source of greenhouse gas emissions (Fig. C in Appendix). Greenhouse gas emissions and household health costs do not differ substantially among scenarios, although the type 1 household has increased health costs from burning biomass energy under the SUB and COMB scenarios.

Table 3. Cumulative revenues and costs by household type over 10 years under the business-as-usual (BAU), subsidies (SUB), equal (EQL) and combined (COMB) scenarios.

Scenarios	Revenues			Costs			Net incomes
	Agriculture	Non-agriculture	From another household	Agriculture	Energy	Health care	(cumulative revenues less cumulative costs)
Type 1 household							
BAU in 1000s of Indian Rupees	635	90	223	468	150	6	324
Percentage change from BAU							
SUB	-41	21	76	-4	-81	33	21
EQL	1	832	-94	1	0	0	167
COMB	-41	1196	-60	-4	-81	33	253
Type 2 household							
BAU in 1000s of Indian Rupees	3559	706	35	1751	302	7	2240
Percentage change from BAU							
SUB	10	10	3	12	15	0	7
EQL	-15	-18	-3	-19	-2	0	-15
COMB	-12	1	3	-13	9	-57	-10

4. Conclusions and policy implications

We analyze issues associated with the nexus of household energy use, agricultural production, employment and income of heterogeneous and interdependent rural households. Using an agricultural household dynamic programming model, we investigate possible policy options such as state subsidies for the purchase of solar panel systems, improved off-farm employment opportunities and their combination. Under current conditions, population growth will increase demand for biomass energy. Alternative energy options can help meet increasing energy demand, however, the adoption of energy alternatives is affected by household characteristics. For example, relatively wealthier household is able to adopt biogas digester for residential use, whereas relatively poorer household lacks sufficient economic means to do so. Although improving non-agricultural employment opportunities can reduce dependency on bioenergy and increase the adoption of alternative energy options among rural households, according to the results of our study such policy efforts may fail to achieve these objectives (Chen et al., 2006). State subsidies for alternative energy options are needed to improve adoption rates. For instance, subsidies for the purchase of solar panel systems can incentivize adoption among households for both residential and agricultural energy needs. Greater adoption of such energy source not only improves household energy use, but also household agricultural production and income, and changes household employment structure. Model results indicate that solar energy subsidies are more likely to benefit agricultural production among relatively wealthier rural household that own more farmland than their poorer counterparts. Subsidies may allow household with more arable land to invest in solar irrigation pump, which reduces energy costs of pumping irrigation water and increases crop production. Such subsidies can have an important role in meeting food demand and ensuring food security in developing countries.

Improved agricultural production is accompanied by higher demand for agricultural labor. Household that does not have sufficient labor and irrigation resources to manage own farm might be more likely to hire local laborers and obtain irrigation from another household. This situation can lead to increased interactions among households through agricultural contracts that provide mutual benefits through wage-labor and payment-for-irrigation-services relationships. The model results also suggest that state subsidies for the purchase of solar panel systems can reduce the need for child labor to sustain rural household livelihoods by changing rural employment structure. This occurs through a substantial labor shift among adult household members to agricultural production. Reduction of the need for child labor provides greater opportunity for children to pursue educational and other personal development opportunities. Eventually such outcomes will improve human capital and may increase public welfare in rural areas. However, the results of our study do not reveal how government budgets and economies could best approach the provision of alternative energy subsidies at large scales. If the provision of subsidies for the purchase of solar panel systems decreases the government's ability to allocate funds to other sectors of economy such a policy approach might actually reduce public welfare.

The model scenario that yields the highest overall rural incomes involves a combination of policies, including both subsidies for solar panels and improved off-farm employment opportunities, by reducing energy use and agricultural production costs, as well as increasing off-farm income. This policy scenario is the most effective at reducing income disparity among households and may be especially suitable for poorer households that have limited arable land and help to reduce their income dependency on wealthier households. Narrowing the income gap in this way occurs as a result of both the increase in income of poorer household as well as the decrease in income of wealthier household. Relatively wealthier households with greater agricultural production resources may incur losses from such a policy scenario due to reduced rural labor availability for farming. In this scenario, agricultural contracts between wealthier and poorer households are less prevalent than under the BAU and SUB scenarios. The policy for improved off-farm employment opportunities, EQL scenario, results in the lowest income from agricultural contract interactions among households. The improved off-farm employment opportunities shifts labor allocation of members of poorer household, especially women, to off-farm work. Accordingly, agricultural production decreases, which can affect the availability of food commodities for other (urban) households if such a policy is enacted at larger geographic scales. In the event that such a policy for improving the off-farm employment opportunity is considered, it would be worthwhile to evaluate the potential for unintended negative impacts on agricultural production and to consider measures that could be taken to mitigate such outcomes. In addition, implementation of this policy depends on the respective labor increase in service and industrial sectors, which requires substantial funding, effort, and time in developing countries. Implementation of this type of policy in India would also necessitate improvement of employee rights with respect to gender and socio-economic groups.

Overall, our study results show that it is important to consider heterogeneity among and within households and interdependencies among households when investigating the impacts of policy changes that affect the energy use nexus with agricultural production, employment and incomes. A disaggregated analysis approach allows a detailed perspective on future developments and analysis of the potential beneficiaries, unintended consequences, and spillover effects under different policy scenarios. Furthermore, our model results indicate that policy options that are frequently discussed when addressing change in household energy use (e.g., supportive policies for promoting energy alternatives) (e.g., Frondel et al., 2010) and reducing trade-offs between food and energy production (e.g., Padilla and Serrano, 2006), may not provide comprehensive solutions when energy nexus issues are considered using a disaggregated analysis approach that considers different types of households and household members. Policies may benefit some types of households more than others; therefore it is advisable to consider heterogeneous households. Also, individual policies may not solve issues that are covered by other policies. Even combinations of simulated policies may not address issues such as decreased agricultural production or high energy costs when considering different households and their members. Hence, policy development needs to be comprehensive and address multidimensional aspects affecting welfare of various types of households and their members.

Furthermore, within the energy use nexus the policy and technological changes might affect the supply of and demand for commodities and employment structure of many households. Hence, the economy-wide analysis might provide different results than the household level analysis. Future research in energy use nexus of heterogeneous households needs to consider an increase in the scale of analysis.

Appendices

Table A. Descriptive statistics of two household types.

Parameters	Type 1 household				Type 2 household			
	Mean	Std. Dev.	Min.	Max.	Mean	Std. Dev.	Min.	Max.
Farm size, acres	1	1	0	7	4	6	0	57
Non-agricultural work opportunities for men, days/year	275	194	0	1120	358	327	0	1240
Non-agricultural work opportunities for women, days/year	22	47	0	320	14	567	0	393
Non-agricultural work	6	27	0	300	2	10	0	70

opportunities for children, days/year								
Non-agricultural wage for men, INR/day	201	87	73	545	363	225	118	1125
Non-agricultural wage for women, INR/day	120	83	34	339	120	32	83	153
Non-agricultural wage for children, INR/day	65	12	50	80	60	10	50	70
Agricultural employment wage for men, INR/day	170	45	0	250	n.a.	n.a.	n.a.	n.a.
Agricultural employment wage for women , INR/day	122	36	50	180	n.a.	n.a.	n.a.	n.a.
Agricultural employment wage for children, INR/day	117	40	20	200	n.a.	n.a.	n.a.	n.a.
Number of cattle, head	1	1	0	3	1	1	0	6
Number of buffalo, head	1	1	0	6	2	2	0	6
Milk yield of cow, liters/head	1236	246	720	1800	1448	551	540	4800
Milk yield of buffalo, liters/head	1331	267	720	2640	1574	266	720	2160
Wheat yield, kg/acre	1305	411	333	2667	1514	364	667	2254
Rice yield, kg/acre	1175	507	83	3200	1308	508	366	2500
Sugarcane yield, kg/acre	22545	5830	10333	40000	24226	5599	14583	35000
Mustard yield, kg/acre	351	135	50	700	380	123	175	750
Potato yield, kg/acre	7595	2296	2500	10625	10525	2218	6667	15000
Wheat input costs,	11857	3275	4472	24200	12795	3026	6711	22890

INR/acre								
Rice input costs, INR/acre	10360	10295	2610	130980	10496	2524	5544	15901
Sugarcane input costs, INR/acre	17857	4202	11293	25277	18669	4778	11468	31130
Mustard input costs, INR/acre	6864	2977	3020	17824	7113	3247	3978	18769
Potato input costs, INR/acre	36889	131000	15400	63402	40158	10179	23070	67984
Wheat gross margins, INR/acre	17487	5507	4462	35738	20893	5023	9205	31105
Rice gross margins, INR/acre	14453	6236	1021	39360	17527	6807	4904	33500
Sugarcane gross margins, INR/acre	58617	15158	26866	104000	62988	14557	37916	91000
Mustard gross margins, INR/acre	6072	2336	865	12110	8398	2718	3868	16575
Potato gross margins, INR/acre	72912	22042	24000	102000	119985	25285	76004	17100 0
Energy requirement for cooking, MJ/year	6798	5689	213	31159	8270	6373	638	32216
Energy requirement for lighting, MJ/year	1708	1824	0	9072	3229	2128	0	9072
Energy requirement for electrical appliances, MJ/year	1409	2336	0	12204	6504	6751	0	37248
Energy requirement for wheat production, MJ/acre	1245	413	221	3288	1581	492	552	2435
Energy requirement for rice production, MJ/acre	1659	650	221	5326	1933	731	835	3690
Energy requirement for sugarcane production, MJ/acre	1943	599	138	3985	2383	830	1058	4133
Energy requirement	665	183	443	1255	732	235	344	1351

for mustard production, MJ/acre								
Energy requirement for potato production, MJ/acre	1402	546	663	2470	1565	428	933	2458
Consumption of milk, l/year	617	763	0	10440	1313	837	120	4920
Consumption of rice, kg/year	518	354	0	1740	458	507	0	2280
Consumption of sugarcane, kg/year	51	349	0	4000	297	1941	0	20000
Consumption of mustard, kg/year	156	67	0	580	192	96	0	640
Consumption of potato, kg/year	41	219	0	2000	762	2266	0	20000

Note: n.a. is not applicable.

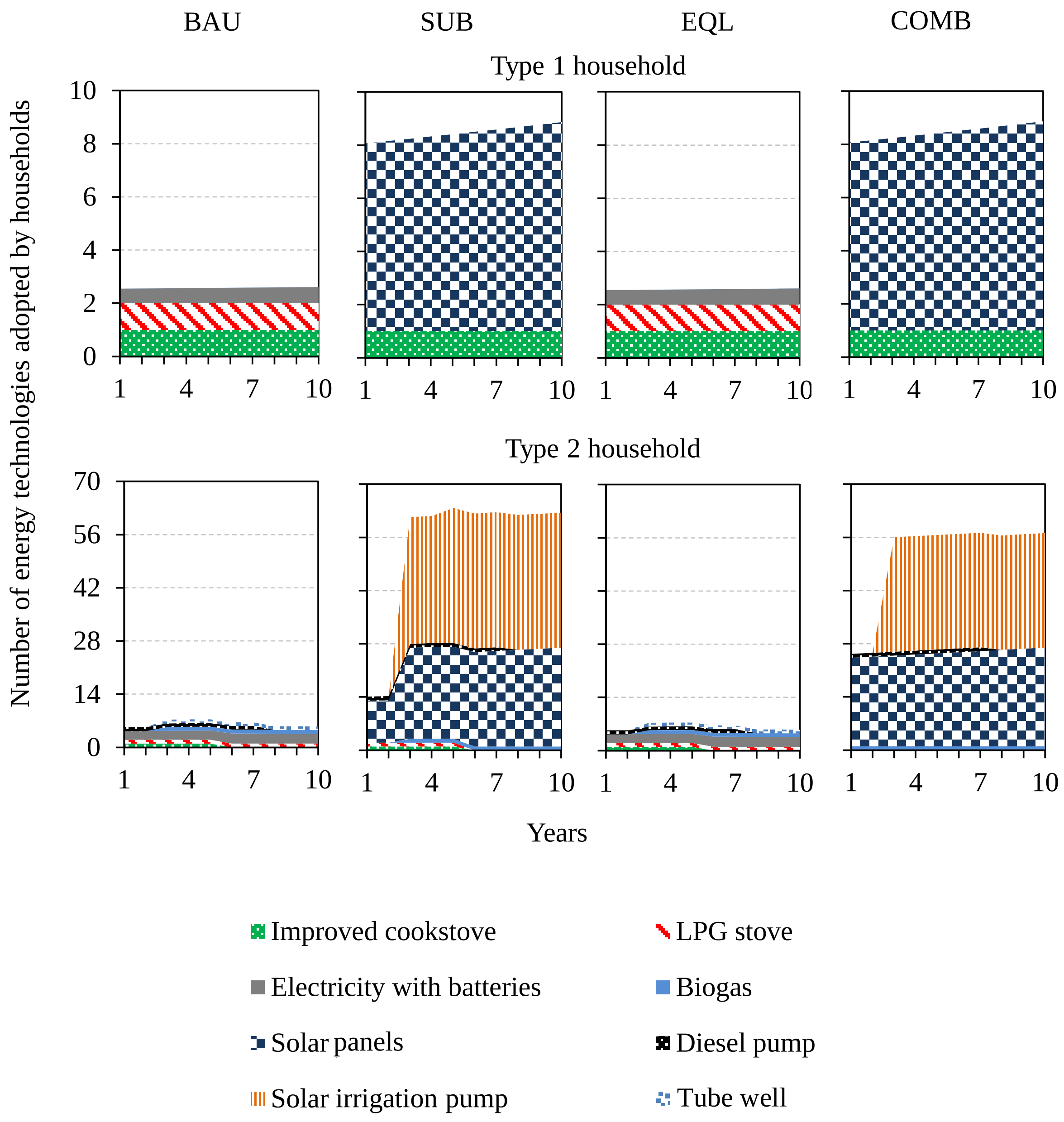
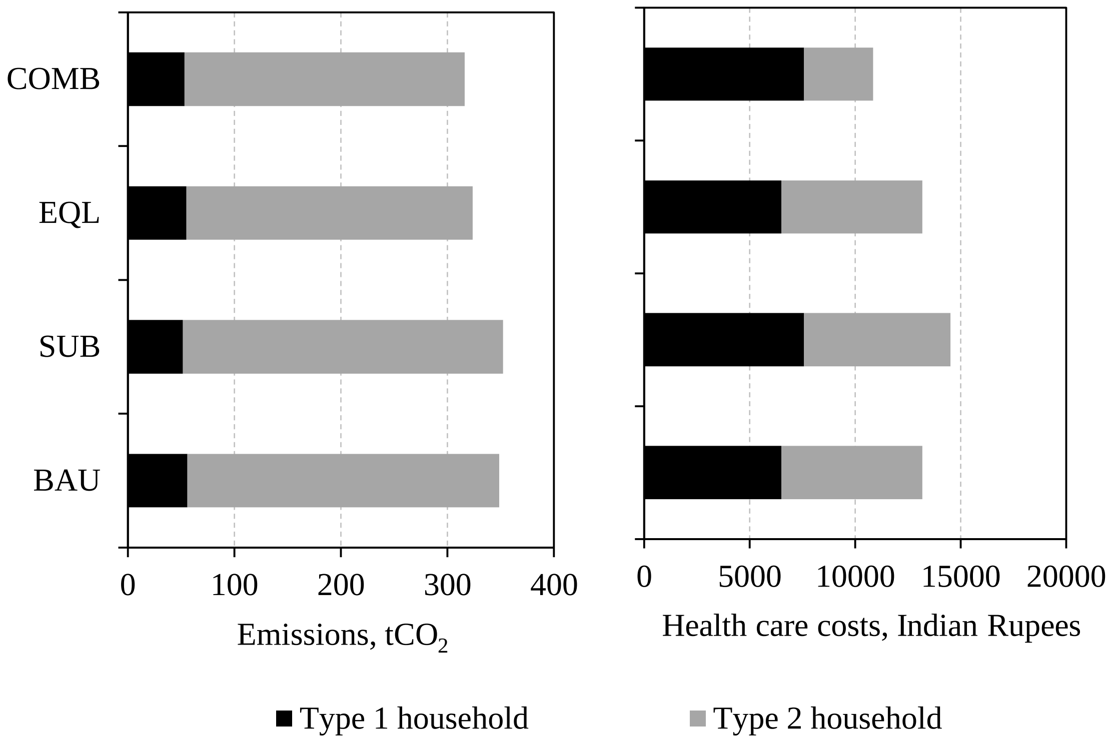


Fig. B. Household energy technology use patterns for domestic and farming purposes over 10 years under the business-as-usual (BAU), subsidies (SUB), equal (EQL) and combined (COMB) scenarios.

Note: Due to the fact that the capacity of batteries for storing electricity and of solar panels for generating electricity vary and can be improved through modular increases we treat them as continuous variables.



(a) (b)

Fig. C. Cumulative greenhouse gas emissions from energy use for both residential and farm purposes (a) and health care costs from residential energy use (b) by household type over 10 years under the business-as-usual (BAU), subsidies (SUB), equal (EQL) and combined (COMB) scenarios.

References

Arndt, C., Benifica, R., 2011. Gender Implications of Biofuels Expansion in Africa: The Case of Mozambique. World Development 39 (9), 1649–1662.

Brown, M.A., 2001. Market failures and barriers as a basis for clean energy policies. Energy Policy 29 (14), 1197–1207.

Census of India, 2011. Houselisting and Housing Census Data Highlights—2011. http://censusindia.gov.in/2011census/hlo/hlo_highlights.html.

Census of India: Uttar Pradesh, 2011. Households by availability of separate kitchen and type of fuel used for cooking. http://www.censusindia.gov.in/2011census/Hloseries/HH10.html.

Chen, L., Heerink, N., van den Berg, M., 2006. Energy consumption in rural China: a household model for three villages in Jiangxi Province. Ecological Economics 58 (2), 407–420.

Diaz-Rainey, I., Ashton, J., 2015. Investment inefficiency and the adoption of eco-innovations: The case of household energy efficiency technologies. Energy Policy 82, 105–117.

FAO, 2012. World agriculture towards 2030/2050: The 2012 Revision. ESAE Working Paper No. 12–03. Food and Agriculture Organization of the United Nations, Rome.

Frondel, M., Ritter, N., Schmidt, C.M., Vance, C., 2010. Economic impacts from the promotion of renewable energy technologies: The German experience. Energy Policy 38 (8), 4048–4056.

Gasson, R., Winter, M., 1992. Gender relations and farm household pluriactivity. Journal of Rural Studies 8 (4), 387–397.

Gebreegziabher, Z., Mekonnen, A., Ferede, T., Guta, F., Levin, J., Kohlin, G., Alemu, T., Bohlin, L., 2013. The distributive effect and food security implications of biofuels investment in Ethiopia. Environment for Development Discussion paper series. EfD DP 13–02.

Hiremath, R.B., Kumar, B., Balachandra, P., 2010. Bottom-up approach for decentralized energy planning: Case study of Tumkur District in India. Energy Policy 38 (2), 862–874.

IEA, 2013. People relying on traditional use of biomass for cooking in 2011 IEA, World Energy Outlook 2013. International Energy Agency, Paris. http://www.worldenergyoutlook.org/resources.

Litman, T.A., Doherty, E., 2009. Transportation cost and benefit analysis techniques, estimates and implications. Victoria Transport Policy Institute, Victoria. http://www.vtpi.org/tca/.

Mirzabaev, A., Guta, D.D., Goedecke, J., Gaur, V., Börner, J., Virchow, D., Denich, M., von Braun, J., 2015. Bioenergy, food security and poverty reduction: trade-offs and synergies along the water-energy-food security nexus. Water International 40 (5–6), 772–790.

Otsuka, K., Chuma, H., Hayami, Y., 1992. Land and labor contracts in agrarian economies: theories and facts. Journal of Economic Literature 30, 1965–2018.

Padilla, E., Serrano A., 2006. Inequality in CO_2 emissions across countries and its relationship with income inequality: a distributive approach. Energy Policy 34 (14), 1762–1772.

Sovacool, B.K., 2008. Valuing the greenhouse gas emissions from nuclear power. A critical survey. Energy Policy 36 (8), 2950–2963.

Singh, I., Squire, L., Strauss, J., 1986. Agricultural household models: extension, application and policy. Johns Hopkins University Press, Baltimore, MD, 335 pp.

Singh, G., 2014. Two decades of globalization in Uttar Pradesh and increasing problems and challenges before agricultural workers. Middle-East Journal of Scientific Research 20 (2), 260–268.
US EPA, 2000. Greenhouse gas emissions from small scale combustion devices in developing countries: Phase IIA, Household stoves in India. United States Environmental Protection Agency, Washington DC.
Wang, C., Zhang, Y., Zhang, L., Pang, M., 2016. Alternative policies to subsidize rural household biogas digesters. Energy Policy 93, 187–195.
Whatmore, S., 1991. Life cycle of patriarchy? Gender divisions in family farming. Journal of Rural Studies 7, 71–76.
World Bank, 2016. Population growth (annual %). Washington DC. Last accessed on 20 February 2016. http://data.worldbank.org/indicator/SP.POP.GROW
Zhong, F. N., Ji, Y. Q., 2009. Land rights, non-agricultural employment opportunities and farmers' agricultural investment. Economic Research Journal 12, 43–51.