Household energy systems based on biomass: Tracing material flows from source to service in rural Ethiopia

Keywords: stock-flow-service nexus; material and energy flow analysis; energy services; biomass energy; Ethiopia

1. Introduction

Biomass provides most of the energy available to approximately three billion rural people in low and middle income countries (LMIC) (Daioglou et al. 2012; GEA 2012). Fuel wood and charcoal remain the most important energy carriers, besides crop residues and animal dung (Kaygusuz 2011). About 10% (60 EJ/yr) of global energy supply stem from solid biomass. Biomass use in rural households in developing countries of Africa and Asia is estimated at approximately 25 EJ/yr (IEA 2022). For those households, biomass energy has several crucial advantages: it is often readily available at limited or no monetary expenses (Reddy 2015; Gill-Wiehl et al. 2021) and allows to generate a range of vital domestic energy services, such as cooking as well as space or water heating (Haas et al. 2008; Gould et al. 2022). But indoor combustion of biomass is linked to serious health impediments (Chandyo et al. 2022; Pratiti et al. 2020; Ravindra et al. 2021; WHO 2018), which among others cause 3.6 million premature deaths annually (IEA 2022). At national and global levels, biomass extraction is associated with negative effects on natural resources and the climate system (Hurni et al. 2015; Liu et al. 2008; Mondal et al. 2018; Tanner and Johnston 2017), although simplistic cause-effect narratives may be misleading (Hansfort and Mertz 2011; Simon and Peterson 2019). Rural energy systems based on biomass have global importance (Erb and Gingrich 2022), yet our current scientific comprehension is limited.

In spite of abundant research, key dynamics of the provision of energy services from bioenergy in rural development contexts remain poorly understood. Complex relationships link rural societies dependent on bioenergy to their natural environment. Appropriation and use of energy carriers, appliances[1] used for biomass combustion, and the energy services generated in the process are important features of rural energy systems. Understanding their interdependencies is vital to address sustainability challenges (Grabher et al. 2023; Yalew 2022; Wassie and Adaramola 2019). This study aims to uncover systemic interlinkages between bioenergy extraction, consumption and the generation of energy service. By adopting a source-to-service perspective on rural biomass energy flows (Figure 1), we trace energy carriers from their source through appliances to different end uses (and beyond to wastes and emissions). Our analysis builds on the stock-flow-service nexus as a

[1] In the context of households of our case study, we use the term 'appliance' to refer to the fireplaces and stoves used by households to generate energy services derived from the release of energy by the combustion of biomass.

conceptual framework (Haberl et al. 2021; Whiting et al. 2021) to disentangle system interactions, reveal potential environmental or social impacts, and highlight opportunities for the integration of case studies.

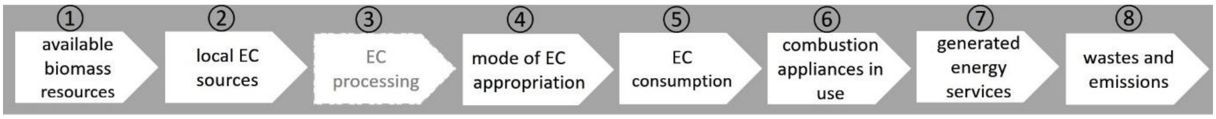

Figure 1: The sequence of processes needed for energy services provisioning for rural biomass-dependent households on which this study is based. Shaded process ③ is a sub-process to the main energy provisioning sequence. Source: authors. (EC = energy carriers)

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The approach depicted in Figure 1 is motivated by our aim to provide a comprehensive view of all stages of domestic energy service provision in biomass-dependent energy systems. Methods from the toolkit of socio-metabolic research allow us to explore interlinkages between material and energy flows and material stocks from source to sink (Eurostat 2018; Fischer-Kowalski et al. 2011b; Haberl et al. 2016). Material and energy flow analyses (MEFA) are regularly conducted at global and national scales (Fishman et al. 2014; Krausmann et al. 2017; Yalew 2022), but only few studies have zoomed in on local or household levels (Singh et al. 2001; Grünbühel et al. 2003; Ringhofer 2009; Fischer-Kowalski et al. 2011a). MEFA has been used to analyse the accumulation of appliances (Wang et al. 2020), lifestyles and food consumption (Sahakian and Erkman 2016; Kissinger and Damari 2021), and socio-economic household attributes (Karcagi-Kováts et al. 2018). We here combine the MEFA approach with the human appropriation of net primary production (HANPP) indicator. We apply both methods to explore how local perceptions of environmental pressures related to bioenergy extraction may be reflected in the actual use-intensity of local land and biomass resource uses (Haberl et al. 2014). To the best of our knowledge, a combined MEFA and HANPP analysis on the different stages of energy service provisioning in rural cases in the Global South has so far never been conducted. Such research may provide crucial insights to advance scholarship on rural energy systems as well as contribute to more sustainable innovations and policies.

Relating domestic bioenergy consumption to appliances and energy services remains challenging, especially in rural settings in LMIC. Different protocols are currently used to account for bioenergy consumption (Capeau and Dercon 1998; FAO 1983, 2017; Han and Wei 2021; World Bank 2017). Hence, considerable data inconsistencies persist (Pachauri and Cherp 2011), despite efforts at standardisation (Bittermann and Suvorov 2012; Eurostat 2013). Energy services feature prominently in recent research (Kalt et al. 2019; Haberl et al. 2021; Tanikawa et al. 2021), but energy service provisioning for rural, biomass-dependent households remains a grossly underrepresented research topic (Kowsari and Zerriffi 2011; Sovacool 2011; Bouzarovski and Petrova 2015). Energy conversion technologies such as stoves play an important role in energy service delivery (Carmona et al. 2021; Haberl et al. 2021; Pauliuk and Müller 2014; Whiting et al. 2020), but the cogeneration of energy services in an appliance makes the attribution of energy flows to services difficult (Grabher et al. 2023). These challenges are compounded by subjective standards and values at play in the provision of energy services (Bouzarovski and Petrova 2015; Kalt et al. 2019).

Bioenergy flows of rural households in the Global South are investigated mostly through case studies (Hoffmann et al. 2015; Jeuland et al. 2021; Johnson and Bryden 2012; Kituyi et al. 2001; Niu et al. 2019). However, findings on rural energy systems are fragmented and often not comparable. Differences between system boundaries may render results incommensurate across locations or scales (Pricope et al. 2020). Hence, energy scholarship forfeits opportunities to integrate case study results to advance interdisciplinary research (Bechtel 1986; Goertz 2017). We compare relevant field studies with our research findings to extract commonalities and differences between case studies (see Discussion, Table 7), and extract key dimensions that need to be considered when aiming to better integrate case study results.

Scientific studies often cover only few of the various stages of rural bioenergy provision (Fig. 1). The availability of biomass for sustainable human use has been investigated at larger geographical scales (Berhanu et al. 2017; Haberl et al. 2011; Hoogwijk et al. 2003; Nansaior et al. 2013; Torres-Rojas et al. 2011). Research has examined the costs of biomass appropriation in terms of time and money (Bhattarai 1998; Mekonnen et al. 2017; Win et al. 2018; Zulu and Richardson 2013). In search of innovations for efficiency gains, technological options for improved biomass combustion have been widely explored (Aggarwal and Chandel 2022; Kumar et al. 2013; Kshirsagar and Kalamkar 2014; Mekonnen et al. 2020; Loo et al. 2016). Lately, research on energy services has received renewed attention (Barnes and Floor 1996; Fuchs et al. 2021; Jonsson et al. 2011), but only few studies succeeded in allocating physical energy flows to energy services (Bose et al. 1991; Liu et al. 2013; Niu et al. 2014; Song et al. 2018; Strydom et al. 2019; Zheng et al. 2014). Notably, (Xue et al. 2020) linked energy flows to appliances and a small number of energy services of households in China. Finally, wastes and emissions of biomass energy use have received considerable attention (Conway et al. 2015; Creutzig et al. 2015; Delina 2017; IPCC 2015). However, we found no study that has consistently tracked biomass flows in rural households through the entire energy system, from extraction to service.

Based on a case study from rural Ethiopia, the objective of this article is to present a physical energy system of biomass-dependent rural communities. The study traces bioenergy flows from source through conversion appliances to energy services and emissions, building on empirical data from a household survey and qualitative research. We investigate whether local environmental challenges can be linked to bioenergy extraction, and propose pathways to more sustainable local energy service provisioning. We seek to answer the following research questions: First, what is the scale and composition of the material and energy flows of households in the case study area to cover their energy service needs? Second, what patterns of domestic energy service provisioning can be discerned? Third, how do biomass resource flows and natural resource stocks relate to environmental challenges identified in the communities?

2. Study area, methods and data

2.1. Characteristics of the case study area

The case study was conducted in three communities (*kebeles*), *Biliti Bawelweld, Denaba* and *Oda Dawata* in the three rural districts of *Dugda, Ziway-Dugda* and *Tiyo,* respectively. All communities are located in the rift valley of Oromia regional state in Ethiopia. An area map is provided in the Supplementary Information (SI, 1). The three villages are located in subtropical climate between 1,500 to > 2,300 meters above sea level. Precipitation ranges from dry to wet, with < 600 mm to > 1,400 mm rainfall per year (Hurni 1998), depending mainly on altitude. With a total area of 32 km^2, the village of *Denaba* has a dry subtropical climate, receives approximately 500-700 mm of annual rainfall and is situated in the dry *weyna dega* agro-ecological zone (Hurni 1998), and located at around 1,600 m of altitude. *Biliti Baleweld* is situated in the dry to moist *weyna dega zone*, with annual rainfall around 700-900 mm, at an altitude of 1,800 to 2,000 m. Its total land area is 20 km^2. With a moist to wet climate, precipitation > 900 mm, and a land area of 41 km^2, *Oda Dawata* falls into *weyna dega* and *dega* agroecological zones, and extends from about 2,100 to 3,600 meters above sea level. The landscape in the study area is dominated by cropland (Picture 1), which primarily produces maize, wheat, barley and the local staple cereal teff (*eragrostis tef*). Livestock plays a paramount role in farm labour as it provides the vast majority of draught power (Grabher 2021). Agricultural fields are sparsely dotted with trees, predominantly acacia species. Farm homesteads are normally fenced with cacti and brushwood or, at the higher elevations of *Oda Dawata*, eucalyptus.

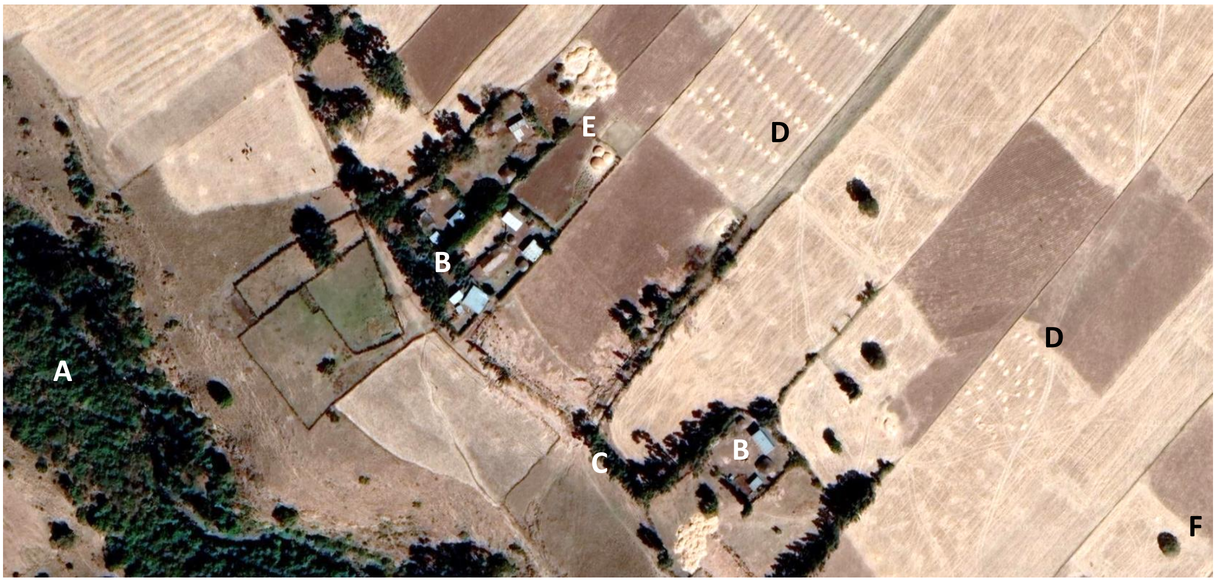
Biomass energy plays a pivotal role in delivering energy services to households in these villages. Most energy services are generated by combustion of fuelwood, charcoal, dung or crop residues. Kerosene may supplement open fires for lighting, and very few households have solar lamps or electricity connection (Mondal et al. 2017; Mondal et al. 2018). This also means that for the vast majority of households, accessible energy services remain largely limited to what can be generated with biomass combustion in simple fireplaces or stoves (Grabher et al. 2023). We present descriptive information on surveyed household variables in

Table 1. For more details on the investigated energy services and appliances, please refer to the SI (8.1 – 8.2).

Variable description	Unit	Mean	SEM
Total household members	persons	6.18	0.19
Number of children in the household	persons	2.97	0.15
Household land holding	ha	1.73	0.10
Number of large livestock (cattle, etc.)	heads	5.06	0.36
Number of small livestock (ruminants, etc.)	heads	2.25	0.27
Number of stoves in household	stoves	2.26	0.06
Fuelwood consumption	kg/dm/year	2,528.17	139.52
Crop residue consumption	kg/dm/year	995.32	81.10
Dung consumption	kg/dm/year	949.52	59.06
Charcoal consumption (as weighed)	kg/year	186.47	15.82
ES frequency food prep. (household)	freq./year	672.87	29.70
ES frequency (drinking water gen.)	freq./year	544.38	31.81
ES frequency room heating	freq./year	367.95	20.74
ES frequency water (hygiene, other)	freq./year	116.71	10.32
ES frequency illumination	freq./year	71.27	11.45
ES frequency insect repulsion	freq./year	32.08	4.36
ES frequency income generation	freq./year	26.41	9.34
ES frequency food prep. (event)	freq./year	16.26	0.83
Total ES frequency	freq./year	1,856.87	66.58

Table 1: Per-household view of selected variables from the field survey. Values for each variable reflect the mean and the standard error of the mean (SEM) per household (N=224). The presented energy service (ES) frequencies reflect the intentions to produce an energy service in a given timeframe. In the local context, the generation of energy services may be combined (for example, heating water with warming the room) and an intention does often not correspond to a discrete combustion event. (dm = dry matter)

Forest cover in Ethiopia has dramatically shrunk in the past decades, and wood fuel has become a scarce resource for many rural communities (Haile et al. 2009; Guta 2014). Unsustainable wood fuel extraction damages remaining forested areas and causes soil erosion (Dresen et al. 2014; Hurni et al. 2015). The energetic use of crop residues and dung reduces the amount of biomass available for ecosystem functions, especially replenishing soil organic matter (Arneth et al. 2021; Mekonnen et al. 2017; Zika and Erb 2009). This negatively affects soil fertility as well as its water holding capacity and causes soil loss (Kassa et al. 2017). Erosion has taken vast tracts of land out of agricultural production (Grabher 2017).



Picture 1: Satellite imagery from Oda Dawata kebele. The satellite image shows the major landscape features relevant for the case study. A remaining forest stand can be seen on the lower left along a seasonal river bed (A). In the middle, separate homesteads can be discerned, each consisting of several buildings, some with grey metal sheet roofs (B). Homesteads or fields are fenced with trees or shrubs (C). The cropland (brown to beige colours) has been harvested and crop residues are stacked in the fields (D) and close to the homesteads (E). Individual trees are sparsely scattered around fields (F). Image: Google maps, ©2023, CNES/Airbus, Maxar Technologies

Figure colour: full colours

2.2. Methods and data

We calculate biomass flows through households and community systems based on methods of material and energy flow analysis (MEFA) (Haberl 2001; Brunner and Rechberger 2016; Haberl et al. 2017) and assess the related impacts on ecosystems using the human appropriation of net primary production (HANPP) indicator. Energy consumption, appliance use and energy services data are derived from a household survey, focus groups and expert interviews. All employed methods are connected to systematically account for local energy provisioning.

2.2.1. Household survey data

To quantify the types and amounts of biomass extracted and energy consumed by households, the field research team gathered data in a household survey in January and February 2022. A sample of 224 households was randomly selected from 2,401 households registered in the three kebeles. Trained field research assistants administered a structured questionnaire to the selected households and took the required measurements. For more information on the household survey, please see the SI (1-6). Assembled variables included the energy-related materials collected or bought, collection or purchase location, energy carriers consumed and the frequency of appliance use to generate all identified energy services. A list of all 129 survey variables is available in the SI (C). Here we report continuous variables with the mean and the standard error of the mean (SEM), and report absolute and relative frequencies for categorical variables. Our data allow for analysis with a margin of error of 6% at a confidence interval of 95%. After assessing the homogeneity of variances with the Levene test, we compare group means posthoc with Bonferroni-corrected tests or independent samples t-tests. There was no need to assume normal distribution of the data due to the central limit theorem. For calculations we used Microsoft Excel and IBM SPSS (version 27).

We first used exploratory qualitative methods to identify common environmental challenges in the communities. Relevant data were collected from 13 households, 7 experts and in six focus group discussions. Based on the identified common environmental challenges, we subsequently asked respondents of the household survey (N=224) to assess to what extend bioenergy extraction influences their environment. Responses were collected on a five-point Likert scale (0-4 representing no, low, moderate, high and extreme influence) and are presented in percentages of the total evaluations. To reduce potential response bias we used pictorial diagrams to assist respondents in their decision on the appropriate evaluation level.

2.2.2. Material and energy flow analysis

We adapt the MEFA methodology (Eurostat 2013, 2018) to the local case context following existing literature on local socio-ecological research (Noll et al. 2022; Ringhofer 2009; Singh 2010; Singh et al. 2020). We investigate flows of biomass-derived energy for domestic consumption because less than 1% of the studied households use other energy sources. Two system boundaries are established to quantify flows of material and energy (Figure 2): the average household as the primary unit of analysis, and the administrative boundaries of the three targeted communities. Locally these administrative units are called *kebeles.* Our study considers material stocks (appliances) relevant for energy service generation, i.e., the fireplaces and stoves used in households.

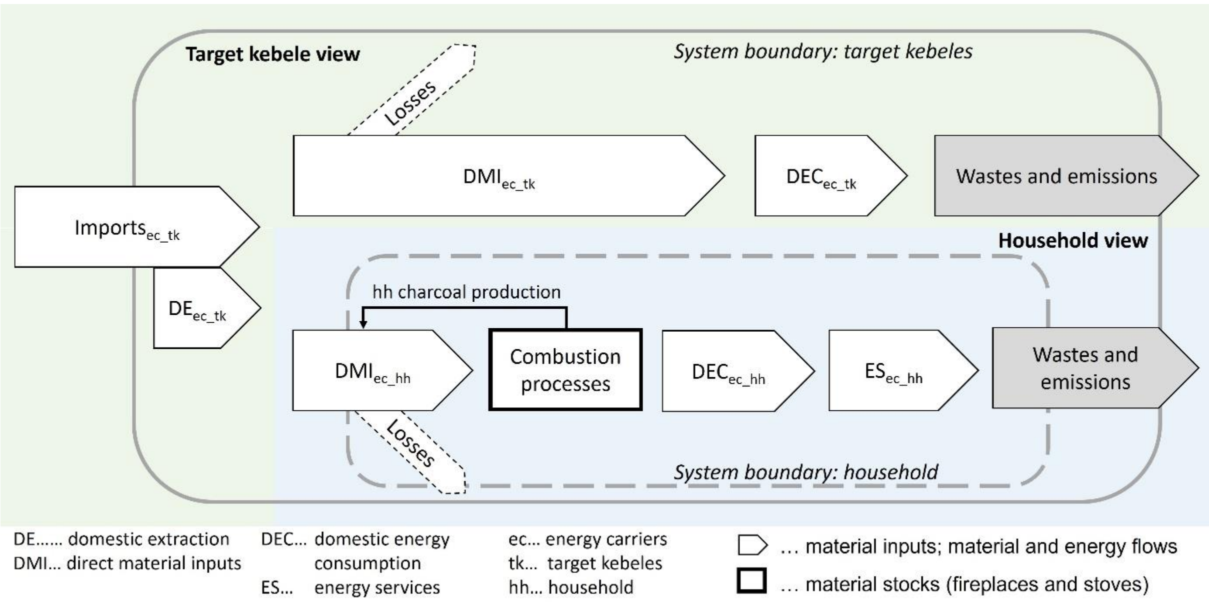


Figure 2: System boundaries for the MEFA and HANPP investigations. The individual household represents the unit of analysis and first system boundary layer, the target kebele (community) the second layer. Energy carriers may cross village boundaries (Imports) or are appropriated locally (domestic extraction, abbreviated DE) through collection or purchase. DMI represents the sum of DE and Imports. DEC denotes the energy derived from the combustion process to generate energy services (ES), leaving wastes and emissions. At household level, fuelwood may partly be converted to charcoal for home consumption.

Figure colour: full colours

2.2.2.1. Measurement of energy consumption

To measure the consumption of all biomass energy carriers (domestic energy consumption, DEC), we addressed the person in charge of tending the fire in the household, who are almost exclusively women. Respondents prepared a 'household standard measures' of wood, crop residues, dung and charcoal with the support of the field research assistants. The household standard measures were weighed with scales and measurements recorded in kg. Respondents then estimated their household's collected and purchased energy carriers as well as the household consumption in reference to the specified standard measures. Estimates were recorded as a weekly or monthly totals (i.e. for all available fireplaces and stoves, and for all energy services.) Because it is illegal to the fell trees in Ethiopia (Crewett et al. 2008), households may underreport fuelwood consumption. We therefore introduced "twigs, branches and leaves" (TBL) as an alternative category. For data analysis, we combined the fuelwood and TBL categories. We converted all measurements in mass units into dry matter and gross calorific value, i.e., the entire energy content of biomass released during combustion in a bomb calorimeter in *Joules* (J) (see SI, 7.), and annualised weekly and monthly data. Factors used to convert dry-matter biomass to gross calorific value were taken from (Motghare et al. 2016; Pahla et al. 2017; Eurostat 2013; Zanuncio et al. 2014). We report charcoal in fuelwood equivalents (fw eq) to facilitate comparison and illustration of energy carrier flows (for details see SI, 7).

2.2.2.2. Imports, Domestic Extraction and Direct Material Inputs

We separately collected data on purchased bioenergy carriers from inside or outside the kebele. Domestic extraction (DE) refers to the sum of energy carriers bought or collected inside the kebele. Imports only apply to materials crossing kebele boundaries, and may stem from purchases or collection. At household level, direct material input (DMI_{hh}) equals average household DE inside the target kebeles plus Imports (for details see SI, 8.3).

2.2.2.3. Linking materials and energy to stocks, energy services and emissions

We link the consumption of energy carriers to material stocks (appliances) with allocation factors derived from focus groups. We conducted two focus group discussions per target kebele, one with mixed gender and one female-only participation. Participants were asked to quantitatively assess the use of energy carriers in relation to the four locally available appliances, using a data collection method described in the SI (5) and in a prior companion paper (Grabher et al. 2023). We use average scores of six focus groups to attribute flows of consumed energy carriers to the four appliances (Table 2).

Energy carrier	3-stone fireplace	Mirt stove	Tikikil stove	Charcoal stove
Wood	49.7%	14.3%	16.3%	19.8%
Crop residues	41.8%	15.0%	17.3%	26.0%
Dung	64.8%	20.1%	13.6%	1.5%
Charcoal	0.0%	0.0%	0.0%	100.0%

Table 2: Factors derived from focus group workshops to allocate energy carriers to stoves. Factors are calculated as % of total points allocated by energy carrier to the four stoves for the six focus groups conducted.

We allocate energy services to the appliances based on the frequency of their use to generate different energy services. To this end, we asked survey respondents how often they use a stove to generate a specific energy service within a set timeframe (weekly, monthly or yearly). Here it is important to note that in bioenergy-dependent households, the generation of energy services is often combined (Grabher et al. 2023). For example, using the charcoal stove to warm up food in the evening may also serve to heat the room and repel insects. Hence, in our survey, households would report three separate events of service generation. We then allocate energy flows from appliances to energy services by computing factors that relate stove-service pairings to the sum of all generation events (Table 3).

Energy service	3-stone fireplace	Mirt	Tikikil	Charcoal stove	Total
Food prep. (household)	15.9%	3.6%	2.7%	14.3%	36.5%
Drinking water prep.	9.7%	0.4%	1.5%	17.9%	29.5%
Room heating	7.9%	0.0%	0.8%	11.1%	19.8%
Hygiene (body, other)	2.8%	0.0%	0.7%	2.8%	6.3%
Illumination	1.7%	0.0%	0.1%	2.1%	3.9%
Insect repulsion	0.7%	0.0%	0.0%	1.0%	1.7%
Income generation	0.9%	0.0%	0.3%	0.3%	1.4%
Food prep. (event)	0.4%	0.1%	0.0%	0.3%	0.9%
Total	**40.0%**	**4.1%**	**6.1%**	**49.8%**	**100.0%**

Table 3: The frequency of the use of the four investigates stoves for the generation of the different energy services. These factors are derived from household survey data and computed into percentages of total use frequencies.

Emissions of CO_2 are calculated by multiplying fuelwood, crop residue, dung and charcoal consumption per energy service with the respective CO_2 emission factors (see SI 8.4).

2.2.3. The human appropriation of net primary production

We use the HANPP methodology to quantify the impact of biomass extraction on the local environment. HANPP is an environmental pressure indicator that allows to compare the annual removal of biomass with the NPP of potential vegetation, i.e. the vegetation assumed to exist in each location under current climate conditions, here denoted as potential net primary production (NPP_{pot}) (Haberl et al. 2014; Krausmann et al. 2013).

In this study, we compute only the HANPP related to biomass-based energy carriers (abbreviated $HANPP_{ec}$, see Figure 3). $HANPP_{ec}$ relates the domestic extraction per average household within the *kebele* to the NPP_{pot} of the average total land area potentially available in the *kebele* per household for biomass production (i.e., not to actual land ownership). For our purpose, DE_{ec_hh} equals $HANPP_{harv\_ec}$, assuming that all biomass extracted for energy is either burned or lost during storage. NPP_{pot} is allocated to the three relevant land cover categories, i.e., forest land, cropland and grazing land per *kebele*. $HANPP_{luc}$ represents the reduction of NPP_{pot} attributable to land use change. NPP_{eco} denotes biomass remaining in the ecosystem after extraction for human purposes.

$HANPP_{ec}$ accounts for domestic biomass energy and does not include HANPP associated with food, feed or fibre provisioning in general. It is important to point out that a detailed assessment of the environmental impacts of bioenergy removal on different land cover classes at local level would require spatially explicit data (Barton et al. 2020). The extensive effort to generate such data was outside the purview of our research. In their absence, we allocate the extraction of wood fuel and grazed biomass to land covered by forest and grazing land, respectively (see 2.2.3.2.). Crop residue as well as flows of fuelwood and grazed biomass exceeding the NPP_{pot} of the respective land cover class are allocated to cropland. However, this attribution is based narrow definitions of land cover classes, and may not properly represent local land use realities, as we point out in the Discussion (4.3).

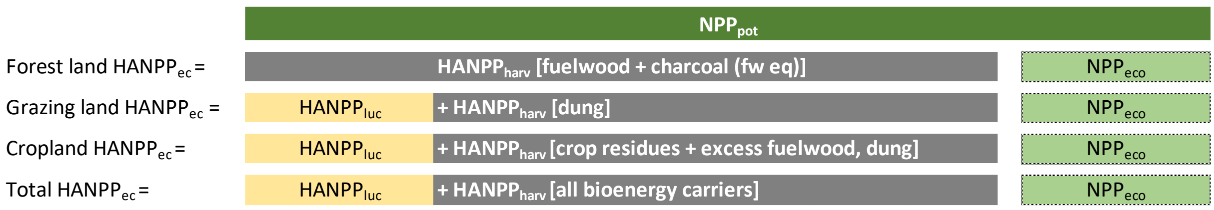


Figure 3: Schematic display of the definitions used to assess the human appropriation of NPP related to biomass energy ($HANPP_{ec}$). $HANPP_{ec}$ is calculated as the sum of $HANPP_{luc}$ and $HANPP_{harv}$. $HANPP_{luc}$ of grazing land was assumed at 20% of NPP_{pot}. $HANPP_{luc}$ of cropland is estimated based on a factor derived from a prior study for Ethiopia (Grabher 2021). The dashed lines for NPP_{eco} symbolise that in our study there may be no biomass remaining in the ecosystem after harvest. See below for details. Graph adapted from (Grabher 2021) based on (Haberl et al. 2014).

Figure colour: full colours

2.2.3.1. Land cover data

Land cover data with a 20x20m resolution from 2016 derived from Sentinel 2A remote sensing prototype data (ESA CCI 2017) adapted for Ethiopia (WLRC Ethiopia 2018; Kassawmar et al. 2018) were used to extract three relevant land cover classes (forests & shrubland, cropland, grazing land). See an example of land cover data used and relevant HANPP data extracted in the SI (8.5 – 8.7). Based on this dataset, the total area covered by each land cover class was calculated for the targeted kebeles using ArcGIS Pro (Version 2.8.0).

2.2.3.2. Net Primary Production and land cover classes

We used NPP_{pot} data from simulations with the LPJmL dynamic global vegetation model (Schaphoff et al. 2018; Roux et al. 2022), thereby using the CRU_TS4.03 historical climatology data (Harris et al. 2020) and extract a time series from 2010 to 2018 for our $HANPP_{ec}$ calculations. In the absence of robust data, actual NPP of forest land is assumed to equal NPP_{pot}, i.e., $HANPP_{luc}$ is set to 0; this is likely a conservative approach, as forest degradation is neglected. $HANPP_{luc}$ on grazing land represents degradation effects from animal trampling and feeding; based on literature, we assume that $HANPP_{luc}$ is 20% of NPP_{pot} (Jackson and Prince 2016; Krausmann et al. 2013). For $HANPP_{luc}$ of cropland we derived a factor of $HANPP_{luc}$:$HANPP_{harv}$ of 1.63 from national HANPP data (Grabher 2021), see SI 8.5. Calculations were based on the land use and NPP_{pot} data in Table 4:

	Biliti Baleweld	**Denaba**	**Oda Dawata**	**3 *kebeles***
Land area in km^2	20.0	31.8	40.8	92.6
# of households (hh)	735	740	926	2401
Avg. land potentially available per hh	2.7	4.3	4.4	3.9
NPP_{pot} forest land [t dm/ha/yr]	16.6	17.3	17.8	17.6
NPP_{pot} cropland [t dm/ha/yr]	18.6	19.4	20.0	19.5
NPP_{pot} grazing land [t dm/ha/yr]	13.6	14.2	14.6	14.5

Table 4: Land use and NPPpot data used for the $HANPP_{ec}$ calculations. NPP_{pot} data is calculated based on the average NPPpot values from 2010-2018 for the locations derived from (Schaphoff et al. 2018), based on historical climatology data (Harris et al. 2020).

3. Results

3.1. Energy service provisioning in households

3.1.1. Household material and energy flows

On average, the biomass collected of surveyed households amounts to about 90 GJ/hh/yr (SEM 4.4, N: 224). They gain the lions share (ca. 86 GJ/hh/yr) through extraction from the local environment, with only the small rest imported from nearby markets (Figure 4). The average household energy consumption is estimated at 84 GJ/hh/yr (SEM 3.6). On a per capita basis, 15 GJ/cap/yr (SEM 0.7) are consumed on average. Fuelwood and charcoal cover 67% of household energy needs, and crop residues and dung make up the remainder. Traditional three-stone fireplaces and charcoal stoves persist as the most frequently used conversion appliances. Food and drinking water preparation (41% and 27%, respectively) and as well as room heating (18%) require the largest material and energy flows. All other energy services combined use up about 14% of energy.

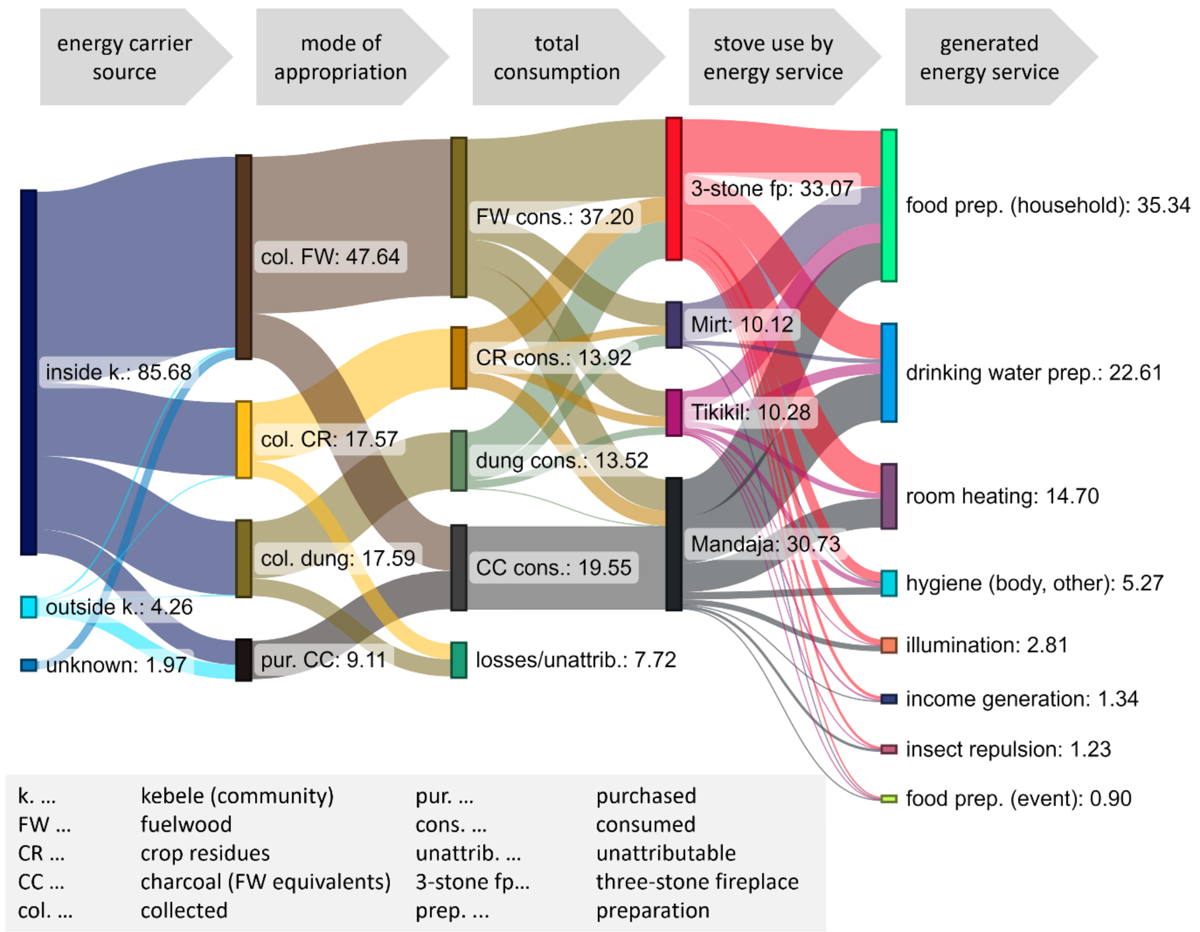


Figure 4: Material and energy flows through an average household. Here we present an average household based on data of all three kebeles (N=224). All biomass flows are converted into gross calorific energy values in GJ/yr. Losses represent the difference in data between energy carriers collected and consumed; 'unknown' presents energy carriers collected for which no data was available to allocate the biomass flow inside or outside the kebele; the flows of consumed energy carriers to appliances are based on allocation factors gained from focus group discussions; the energy flows between appliance and generated energy service are allocated based on data of the frequency of stove use for energy service generation.

Figure colour: full colours

3.1.2. Energy efficiency and CO_2 emissions

On average, households using improved cookstoves (ICS) can be associated with a lower fuelwood and dung consumption by about 20% (fuelwood -8 GJ/yr, dung -3 GJ/yr), compared to households with no ICS. For all energy carriers combined, the use of ICS is associated with energy savings of 12%, concomitant with lower CO_2 emissions. On a per capita basis, a reduced energy consumption of 28% can be linked to ICS use and benefits of scale related to household size (see 3.2). ICS adoption can be related to lower energy flows through three-stone fireplaces, particularly for food preparation (-40%), drinking water preparation (-78%) and room heating (-55%). In contrast, ICS-adopting households display an almost tenfold energy consumption for income generation, and can be linked to a 24% higher energy consumption of water for hygiene (Figure 5 ab), compared to non-adopters.

a) Households without improved cookstove b) Households with 1 or 2 improved cookstoves

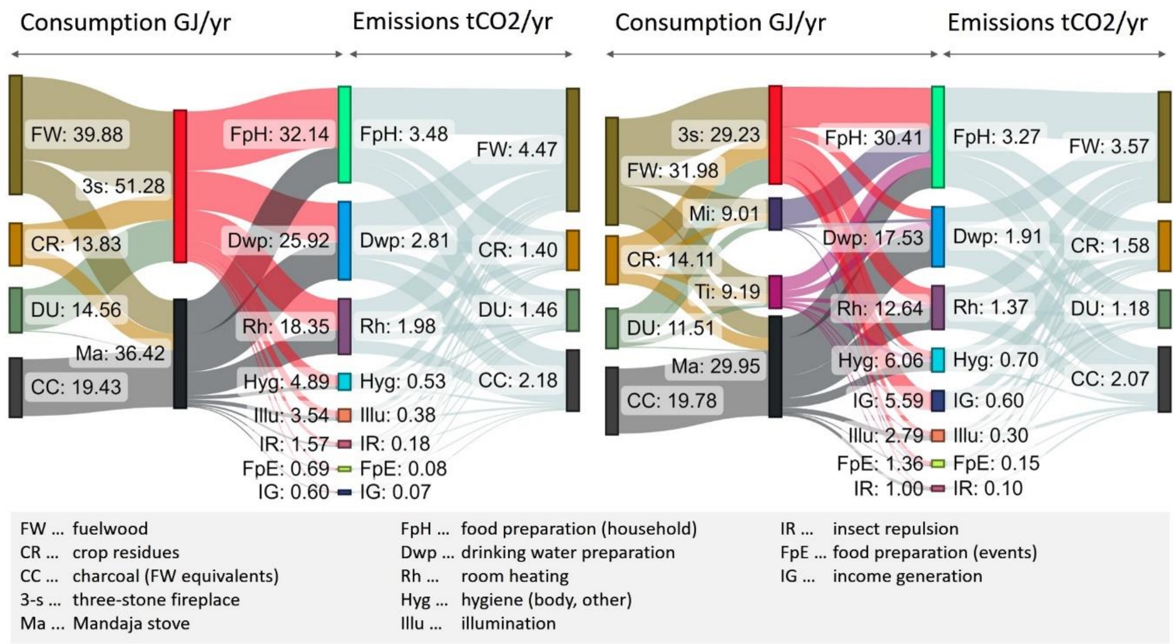


Figure 5: Differences in energy flows and CO_2 emissions based on used appliances. Compared to households without improved cookstove (a), the adoption of improved cookstoves (b) is associated with a significantly lower consumption of fuelwood and dung, with concurrent effects on CO_2 emissions. Note that these numbers refer to the CO_2 released during combustion; carbon uptake of growing plants is not considered.

Figure colour: full colours

3.2. Household characteristics and energy consumption

Household size constitutes a significant factor affecting domestic energy consumption (Table 5). Households with seven to nine members can be associated with more than double (95 GJ/hh/yr) the energy consumption of one- or two-person-households (45 GJ/hh/yr), households with ten and more members display a three times higher (123 GJ/hh/yr) energy consumption. On a per capita basis, however, increasing family size can be related to significantly lower levels of energy consumption, i.e. from 23 GJ/cap/yr (one- or two-person-households) to 10 GJ/cap/yr (10-and-more member households).

Household members	1 to 2	3 to 4	5 to 6	7 to 9	10 and more
Group	A	B	C	D	E
Energy consumption (GJ/hh/yr)	45	68	81	95[1]	123[2]
Energy consumption (GJ/cap/yr)	23[3]	18[4]	15	12	10

Table 5: Energy consumption patterns by household size. On average, larger households are related to significantly higher amounts of bioenergy consumption. Per capita consumption by household size is associated with significantly lower consumption levels. Annotations refer to results of a statistical comparison of group means, based on two-sided tests adjusted for all pairwise comparisons using the Bonferroni test at the 0.05 significance level (N = 224):
[1] … significant difference of mean to A (0.048), B ($p = 0.029$)
[2] … significant difference of mean to A ($p = 0.002$), B ($p = 0.001$), C ($p = 0.025$)
[3] … significant difference of mean to D ($p = 0.018$), E ($p = 0.012$)
[4] … significant difference of mean to D ($p = 0.004$), E ($p = 0.014$)

Household landholding and livestock assets have smaller effects on domestic energy consumption (Table 6). Households with landholdings of 2 ha and more can be linked to a significantly higher energy consumption per year (98 GJ/hh/yr) than those with less than 2 ha (80 GJ/hh/yr; $p = 0.033$). However, per capita consumption does not show statistically significant differences. Ownership of large livestock (cattle, horses, donkeys) is associated with significantly higher mean energy consumption between households with 10 and more animals (114 GJ/hh/yr) than in households without livestock (69 GJ/hh/yr; $p = 0.034$) or with one to three livestock (80 GJ/hh/yr; $p = 0.048$). Again, per capita energy consumption remains on a similar level for all livestock-holder groups and shows no statistically significant difference of means.

Household characteristic	Landholdings		Large livestock assets			
Group	< 2 ha	>= 2 ha	0	1 to 3	4 to 9	>= 10
Energy consumption (GJ/hh/yr)	80	98[a]	69	80	84	114[b]
Energy consumption (GJ/cap/yr)	15	14	16	15	15	14

Table 6: Energy consumption by household landholdings and livestock assets.
Landholdings: On average, households owning 2 ha of land or more are associated with significantly higher levels of bioenergy consumption than those with less land, based on the difference of group means. There is no statistically significant difference in per capita consumption for household groups and landholding.
[a] … ($p = 0.033$, $N = 224$)

Livestock assets: Households possessing 10 livestock or more use significantly more energy than those with none or 1 to 3 large livestock. Differences between other groups are not statistically significant.
[b] … significant difference of mean between households with 10+ livestock compared to households without livestock ($p = 0.034$) and households with 1-3 livestock ($p = 0.048$, $N = 224$)

3.3. From natural resources to energy services

3.3.1. Perceptions of environmental challenges from biomass extraction for energy

Deforestation, soil fertility loss and soil erosion feature as the most severe environmental challenges associated with local bioenergy extraction. More than half of all households attribute an extreme influence of biomass removal on the loss of woodland, and two-fifth see a moderate to high influence (Figure 6). Almost half of all households (45%) perceive an extreme, and a further half a moderate or high negative effect on agricultural productivity due to the loss of soil fertility and soil erosion on cropland. Sheet and rill erosion as well as gully formation (especially on communal lands) are also a major concern, for which three-fifth of respondents attribute a moderate to high, and a further third an extreme influence from bioenergy extraction. Biodiversity loss, increased flood risks and negative effects on the access to water are additional challenges which households link to energy provision.

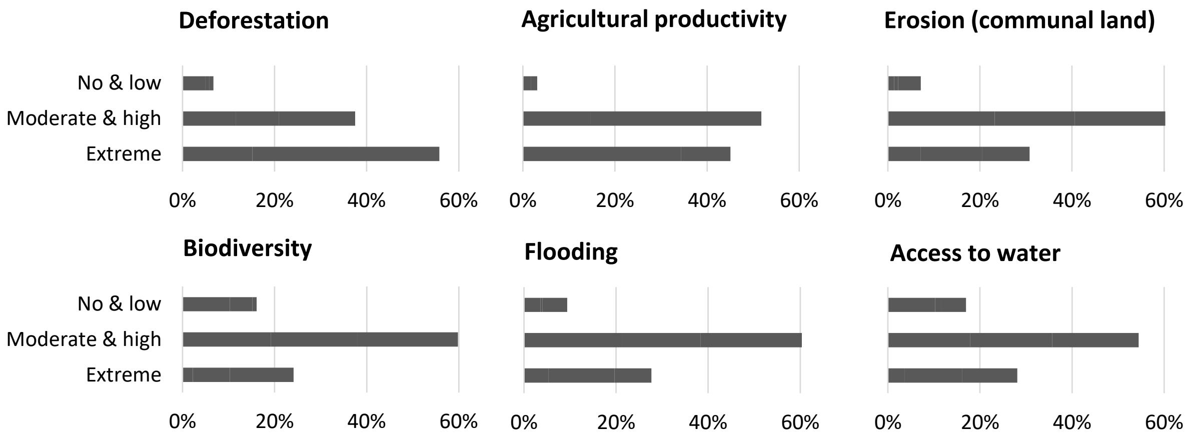


Figure 6: Perceptions of environmental challenges associated with the local energy system. Respondents gave their opinion of the impact of local energy provisioning on the environment (Likert scale, no - extreme impact). Evaluations are depicted as the % of total evaluation points per impact.

Figure colour: BW

3.3.2. A source to service view of village energy systems

To quantify potential environmental impacts of bioenergy extraction perceived by the communities mentioned above (Figure 6), we calculate the HANPP attributable to energy carriers ($HANPP_{ec}$). $HANPP_{ec}$ across all land cover classes is found to be 7 % of NPP_{pot} in *Oda Dawata*, 8 % in Denaba and 10 % in *Biliti Baleweld* (see SI, 9 for detailed results). Here we present the combined HANPP and MEFA for the average household from *Denaba kebele* (Figure 7) from source to service:

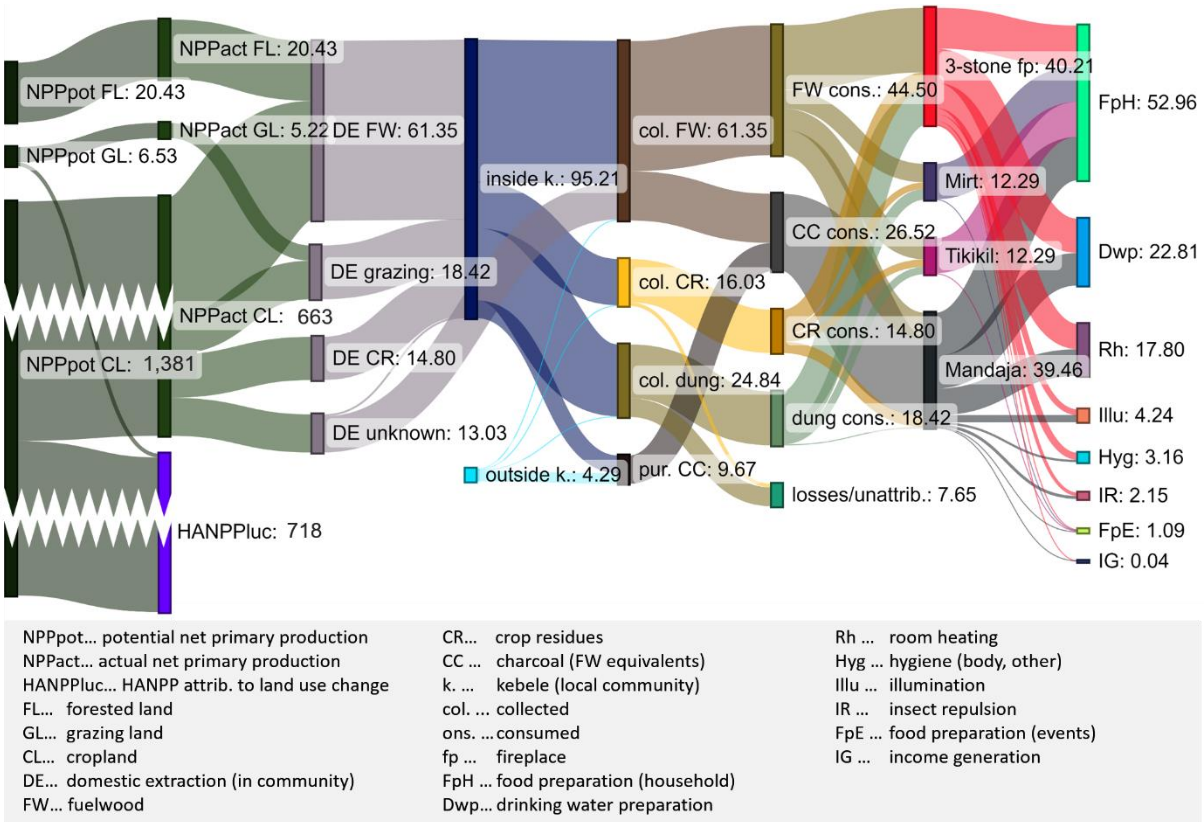


Figure 7: Complete view of the biomass energy system from source to service for an average household in Denaba village. The human appropriation of net primary production (HANPP) methodology is applied to relate biomass extracted for energy to potential and actual net primary production (NPP_{pot}, NPP_{act}) of three land cover classes. Because of the limited extend of forests and grassland, most wood fuel and dung is derived from cropland areas. A relatively large flow of fuelwood of unknown origin in Denaba is also attributed to cropland extraction, where NPP is sufficient to account for the flow.

Figure colour: full colours

For *Denaba* village, an average household procures biomass energy amounting to 100 GJ/hh/yr (SEM 7 GJ, N=71). As explained in Methods (2.2.2.), we were not able to collect data on the exact location of biomass removal within the *kebele*. Hence, we allocate extraction to the most pertinent land cover class, i.e., wood fuel to forests and dung to grazing land. Crop residues, as well as any excess removal from forests and grazing land, are allocated to cropland. Based on this approach, wood fuel removed from the environment would exceed the NPP_{pot} of land covered by forests by a factor of two. The amount of dung collected for combustion would surpass the NPP_{pot} of grazing land three times. By far the biggest amount of bioenergy is extracted from land which is mainly used for agriculture. Here, NPP_{act} is sufficient to support extensive removal of biomass, despite the substantial reduction of NPP due to land use change (high $HANPP_{luc}$). Note that these results are uncertain due to difficulties in allocating bioenergy carriers to land cover categories, see Discussion (4.3.) The large unaccounted flow of fuelwood (labelled DE unknown) may be related to in-home charcoal production.

4. Discussion

4.1. Key factors influencing biomass flows

To put our research findings into the context of prior scientific endeavours on this biomass extraction in LMIC, Table 7 presents case studies on energy consumption of rural biomass-dependent households which we use to discuss our case findings from Ethiopia. Comparisons of case study results on domestic energy consumption from biomass are often challenging. Climatic conditions, household size and wealth, availability of and access to energy carriers, subjective energy service needs and qualities, culture, traditions and diets, housing types and appliance efficiencies are only some factors that may influence energy consumption (Bouzarovski and Petrova 2015; Malla and Timilsina 2014; Warde 2019). Nevertheless, the stock-flow-service nexus and the entailed provisioning processes (Figure 1) offer a general framework, along which different case studies can be described and compared.

Study	Country	Year of field research	Climate	Energy carriers studied	Energy services	Appliances	hh size	Per cap consumption/ year (GJ GCV)	Provisioning processes addressed
(Bose et al. 1991)	India	1986-1987	subtropical	❋◒	✓	✖	7.52[a]	8–14	①②⑤⑦
(Brouwer et al. 1997)	Malawi	1990	subtropical	❋	✖	✖	5.84[a]	7 – 9* (collected biomass)	②④
(Chen et al. 2022)	China	2015	Various	❋◒	✖	✖	3.82 (+- 1.51)	15* (biomass) 18* (all ECs)	②⑤⑥
(Ding et al. 2014)	China (Tibet)	2011 - 2012	temperate	❋◒	✖	✖	5	35 - 53* (biomass) 43* (mean, all ECs)	⑤⑧
(Hoffmann et al. 2015)	Tanzania	2010	subtropical	❋	✖	✓	5.7-7.7	7	⑤⑥⑧
(Imran et al. 2022)	Pakistan	2021 (?)	Various	❋◒	✖	✖	7.57[a]	21* (biomass)	⑤⑧
(Jin et al. 2019)	China	2017	subtropical, humid	❋◒ϟ	✖	✖	3.69 (+- 1.72)	13* (biomass) 17* (all ECs)	⑤⑥
(Johnson and Bryden 2012)	Mali	2009-2010	subtropical	❋◒ϟ✸	✓	✖	12.8	6-8* (all ECs, 98% wood fuel)	②④⑤⑥⑦
(Kituyi et al. 2001)	Kenya	1997	Various	❋	✖	✖	6.09[a]	18* (rural hhs)	②③④⑤⑥⑦
(Liu et al. 2008)	China (Tibet)	2006	temperate	❋◒ϟ✸	✖	✖	4.71[a]	15-28* (biomass)	①②⑤
(Lung and Espira 2019)	Kenya	2018	subtropical	❋	✖	✓	5.3 (+-2.21)	14* (3-stone) 8* (ICS)	②④⑤⑥
(Marufu et al. 1999)	Zimbabwe	1996-1997	subtropical	❋◒ϟ	✖	✖	ca 6	27* (biomass, rural)	②④⑤⑧
(Nansaior et al. 2013)	Thailand	2012	Tropical	❋◒ϟ	✖	✖	3.38[a]	12* (biomass, rural)	①②⑤
(Tabuti et al. 2003)	Uganda	2000, 2001	Tropical	❋	✖	✖	8	4-6* (fuelwood only)	②③④⑤⑥
(Top 2004)	Cambodia	2002	Tropical	❋	✖	✖	6.56	2* (fuelwood only)	②⑤⑥
(Torres-Rojas et al. 2011)	Kenya	2004-2006 (?)	Tropical	❋	✖	✓	5.82[a]	11*	①②⑤⑥
(Win et al. 2018)	Myanmar	2014	Tropical	❋	✖	✓	4.09	13* (fuelwood, only) 8* (charcoal, only)	①②③④⑤
This study	Ethiopia	2022	subtropical	❋	✓	✓	6.18	15	①②③[b]④⑤⑥⑦⑧[c]

Table 7: Overview of selected empirical studies on energy consumption of rural households dependent on biomass. We selected studies that base their results on field research, rather than statistical data available from various international databases. These studies usually address a limited number of processes ① to ⑧ within the rural biomass energy provisioning system presented in Figure 1.

hh… household
GCV… gross calorific value
❁ biomass
☻ fossil ECs
ϟ electricity [source undefined]
✸ renewables

✓disaggregated data presented for energy services, appliances

* … own calculations based on respective study data
[a] … hh size not stated in study; secondary source in supplementary information (SI)
[b] … included in this study by taking conversion from fuelwood to charcoal into account
[c] … this study includes CO_2 emissions, but excludes other wastes and emissions

Research design and employed methods may affect results for energy consumption. Compared to prior field studies with similar designs and climatic contexts (Table 7), our study's scale of per capita energy consumption of biomass is within a range of 8 – 18 GJ/cap/yr (Bose et al. 1991; Kituyi et al. 2001). These two investigations report on the major energy services as well as the most important energy carriers in their research communities. Adopting a different research scope, (Brouwer et al. 1997) estimate lower per capita energy use for Malawi; however, their study includes major energy services only implicitly and focuses on fuelwood. Research on households in Tanzania, Kenya and Uganda also reports lower levels of energy use (Hoffmann et al. 2015; Lung and Espira 2019; Tabuti et al. 2003). These investigations differ from the study at hand in the way they account for energy carriers, energy services and ICS use. Different data collection methods for biomass consumption may also affect research results. For example, (Marufu et al. 1999) describe high levels of biomass energy consumption for households in Zimbabwe. In their study, however, biomass was not measured physically, and their consumption data was derived from self-reported estimates by a small sub-sample.

Reasonable comparisons of domestic energy consumption may depend on the predominant climatic conditions. For example, (Ding et al. 2014) report biomass energy consumption of 35 to 53 GJ/cap/yr and (Liu et al. 2008) 15 to 28 GJ/cap/yr for households in alpine climates of Tibet. For a subtropical setting of China, (Jin et al. 2019) estimated biomass consumption of households at 13 GJ/cap/yr. And (Chen et al. 2022) report average biomass energy consumption of 15 GJ/cap/yr for China across a variety of climatic conditions. The latter findings match the results of our study astonishingly well. For tropical contexts of Thailand and Myanmar, two studies report per-capita biomass energy flows between 12 and 13 GJ (Nansaior et al. 2013; Win et al. 2018). (Top 2004) describes extremely low levels of biomass energy consumption for Cambodia. Their research design, however, is based on self-reported consumption estimates of wood fuel used for a single energy service (cooking), in large families operating a variety of appliances.

The appliances used for combustion have a considerable effect on domestic energy consumption and, concomitantly, CO_2 emissions. Our study results support prior research that links ICS use to reduced biomass consumption for energy (Gebreegziabher et al. 2017) and gains towards other social benefits (Malla and Timilsina 2014). Decreasing energy consumption for cooking may allow households to generate more beneficial services that contribute to household economy (income generation) and wellbeing (water heating for hygiene). These findings are in line with studies highlighting socio-economic benefits of ICS adoption (Beyene and Koch 2013; Malla and Timilsina 2014). However, the attribution of such gains to improved energy efficiency is not straightforward. The socio-economic status of households may influence ICS adoption and energy service levels. Development activities linked to ICS distribution and use (such as rural microfinance or health awareness campaigns) may also partly explain higher energy service generation. As a consequence of reduced bioenergy consumption in ICS-adopting households, CO_2 emissions decrease. Here, it is important to point out that we present biomass emissions as CO_2 released during combustion. The quantification of net Carbon emissions is beyond the scope of this analysis, see (Haberl 2013; Haberl et al. 2012).

Our results echo prior research that points to household size as a major influence on per capita energy consumption. Field research in Mali conveys lower per capita energy uses compared to a several studies compiled in Table 7, including ours. This may be due to the larger families (Johnson and Bryden 2012). In contrast, (Imran et al. 2022) describe rather high biomass consumption rates in relatively large families in Pakistan. Moreover, the statistical analysis of land and livestock ownership (Table 6) reveal significant differences in total energy consumption for households that are not reflected on a per capita basis. In the Ethiopian case study context, this may imply that larger households, on average, have a higher socio-economic status and own more livestock or land.

Adopting a socio-ecological metabolism perspective offers three major benefits to case study research on domestic energy consumption: it can facilitate the comparability and relevance of research by clarifying system boundaries, it supports the standardization of research scope and design, and it helps in aligning (physical) measurement methods. A general framework allowing for comparison or aggregation of case study results across locations and scales would enable research to present more comprehensive accounts of energy system dynamics, discern common impacts and amplify policy relevance. Such efforts to integrate case study findings remain a vital interest of interdisciplinary science (Bechtel 1986; Singh and Haas 2016; Goertz 2017).

4.2. Energy services and wellbeing

Our study highlights the importance of integrating energy services and quantifying associated energy flows. Providing essential energy services is necessary for human wellbeing (Baltruszewicz et al. 2021; Brand-Correa et al. 2018; Modi et al. 2005). Because unsustainable wood harvest and indoor combustion of biomass in open fireplaces can have massive adverse effects on human health (Fullerton et al. 2008) and the environment (Ding et al. 2014; Erb and Gingrich 2022; Jetter and Kariher 2009; Yalew 2022), reductions in biomass energy consumption can have considerable social end ecological benefits, if service levels can be maintained at the same time.

Understanding how material flows are linked to energy services is essential to leverage efficiency potentials or explore innovative alternatives for their supply. In line with prior research, our study demonstrates that households generate multiple energy services. Some of these services prompt considerable material flows (Bazilian et al. 2012; Bose et al. 1991; Grabher et al. 2023). Quantifying the material requirements by service may be essential to spark innovations for energy service provisioning. Nevertheless, alternative technologies or practices to substitute or reduce these biomass flows already exist. Safe drinking water can be supplied with water schemes, chlorination or solar disinfection (Cotruvo and Trevant 2000). Water for hygiene purposes can be warmed with basic solar collectors in many climatic conditions (Langniss and Ince 2004). The need for space heating can be reduced with better building structures (Sovacool and Martiskainen 2020). Adhesive fly traps and insect nets are non-toxic measures against insects, as could be changes in behaviour and practices (Matthews 2011) or housing. And solar lamps and lanterns have significant benefits to household wellbeing in LMIC (Lemaire 2018).

Numerous challenges to an "energy service transition" exist, however: The generation of energy services is often combined in biomass-dependent households (Grabher et al. 2023), hence the provision of domestic energy services must be addressed holistically. Many alternatives described above are beyond reach for most rural households in LMIC contexts. Besides market access and lack of capital (Accenture 2012), few households may possess the awareness and capacity needed to adopt and maintain new technologies or practices (Alemayehu et al. 2020). Creating a suitable environment for uptake is a prerequisite to providing domestic energy services more sustainably.

4.3. Biomass extraction and the environment

Our study shows that communities associate serious environmental concerns with bioenergy extraction (Figure 6). Using the HANPP methodology, we examine how these perceptions may be reflected in the local biomass resource base. This study's $HANPP_{ec}$ results (8 - 10 %) appear relatively low. Our data align with a national study for Ethiopia which reports similar rates of bioenergy extraction (Grabher 2021). At the scale detected, biomass removal might not pose a serious risk to local environmental sustainability (Fetzel et al. 2016; Zhang et al. 2021). However, as pointed out in the Methods section (2.2.2), it is important to keep in mind that our $HANPP_{ec}$ results are calculated on the total land area available for biomass production, and HANPP associated with food, feed or fibre provisioning are not considered.

This study suggests that by far the most biomass energy is appropriated from land that is also used for agriculture. This finding is based on our approach for allocating bioenergy extraction to land cover. Correspondingly, (Berhanu et al. 2017) find considerable potential for bioenergy production in Ethiopia. In the case study area, cropland NPP_{act} is sufficient to sustain large flows of different bioenergy materials, such as crop residues, wood fuel and biomass grazed by livestock. Woody biomass is available from scattered trees or woody vegetation as well as small woodlots surrounding homesteads (see Picture 1), and substantial amounts of wood fuel are extracted for immediate combustion or converted to charcoal in households (Grabher et al. 2023). Our calculations suggest that wood fuel from land not defined as "forest" can be a crucial resource in the local energy system, as has also been shown by previous research (Brandt et al. 2020; Liu et al. 2023; Mugabowindekwe et al. 2023). Similarly, cropland provides a sizable amount of livestock feed. In the local context, cropland is intensively grazed for about six months per year, between harvesting and seeding. Conversely, NPP of the remaining forested areas and dedicated grazing land would not cover the current rates of wood fuel and dung extraction for energy under study assumptions. In such a scenario, remaining stocks of biomass would be at risk of exploitation because harvests exceeding yearly NPP_{act} would rapidly deplete the biomass stocks of forested areas. The entailed potential ecological effects (Hurni et al. 2015; Yalew 2022) would reaffirm the environmental concerns raised by survey respondents.

Our study exposes difficulties in using the HANPP indicator to relate bioenergy removal and consumption to local environmental impacts. While local environmental challenges exist (Figure 6), the data we could establish through our fieldwork do not allow to establish robust links between bioenergy extraction and conceivable impacts such as deforestation, erosion or soil fertility loss. Future research on domestic bioenergy consumption will need to find practicable methods to identify the location of biomass extraction (Barton et al. 2020). Additionally, the coarse distinctions between land cover classes used in HANPP-related research do not adequately reflect local land use realities and definitions need to be refined (Balaj et al. 2022; Gao et al. 2020; Allen et al. 2011). A complete HANPP study related to all human uses (food, construction, livestock metabolism, etc.) might reveal different levels of environmental pressure (Haberl et al. 2014), and time series data would allow to better gauge the effects weather extremes (Khalifa et al. 2018; Peng et al. 2017). The integration of these factors might be better suited to assess the sustainability of biomass extraction over time, but was beyond the scope of our study.

4.4. Limitations

Some caveats need to be kept in mind when interpreting our study results. First, our study findings are based on a limited case and household sample in a specific socio-cultural, geographic and climatic context with distinct resource endowments. However, the importance of comparative research on different case studies to advance scientific disciplines has received much attention (Flyvbjerg 2006; Goertz 2017). To discuss interpretations that go beyond the individual case, we contextualize our research findings with selected prior case studies on households dependent on bioenergy (Table 7) and found reasonable agreement. Still, good reasons may exist why energy use in rural LMIC settings can deviate substantially from the values found in this specific situation. Domestic energy consumption depends on a variety of factors, for example household size, housing features, climate and seasonal variations, or social norms (Grabher et al. 2023; Stephenson 2018). Hence, extrapolations from case studies to different settings need to be viewed with caution.

Second, gender plays an enormous role in energy service provisioning, especially in rural household in LMIC settings (Clancy et al. 2003; Johnson et al. 2019; Zhang et al. 2022). However, this study focuses on households as the primary unit of analysis, so an analysis of these important intricacies was beyond the scope of the present work.

Third, our study derives allocation factors for energy carrier flows through appliances from a quantitative exercise conducted in focus group discussions. Additionally, we allocate energy flows from appliances to energy services by data on the frequency of energy services generated per appliance. We acknowledge that more precise methods for measuring energy consumption and their allocation to energy services may exist (Simons et al. 2017; Thomas et al. 2013; Aggarwal and Chandel 2022; Mekonnen et al. 2020). But the integration of these methods into our work were beyond the scope of the present study, given our focus on the household as the primary unit of analysis and the limited resources available for fieldwork. In any case, all our assumptions are transparent, hence progress in estimating such allocation factors will allow recalculation of the results. We endorse the use of adequate protocols to improve the measurement and allocation of energy flows along the complete service provisioning chain.

Fourth, our study is limited to only a fraction of total HANPP, i.e., the $HANPP_{ec}$ indicator. The reported $HANPP_{ec}$ focuses on energy carriers and neither includes human consumption nor animal feed beyond the measured amounts of dung. We use the $HANPP_{ec}$ indicator to gauge the scale of potential environmental pressure from biomass extraction for energy. However, more comprehensive HANPP accounts would be required for a robust assessment (as discussed in 4.3). In our case, this is especially relevant for forests, where wood fuel is the single most important extracted material. In addition, the applied land cover data is derived from satellite imagery. Yet the correct attribution of remote sensing data to land cover classes is challenging (Khalifa et al. 2018; Kassawmar et al. 2018). In the study region, only small areas with dense tree cover remain as forests, and only marginal (often communal) lands are used for dedicated grazing. Thus, most biomass is sourced from land used for crop production. In fact, in the local context cropland is used as additional grazing land for long periods between agricultural campaigns.

Finally, eliciting households' perceptions about environmental impact risks biased responses. We attempted to limit bias effects by providing pictorial diagrams to facilitate the respondent's decision on the appropriate level of response. Additionally we triangulated our results with qualitative interview data, which confirms the environmental concerns highlighted in the quantitative assessment. Nevertheless, quantitative assessments of environmental impacts based on household perceptions need to be viewed with caution.

5. Conclusion

Our case study findings reveal that an average household mobilizes 84 GJ/hh/yr (15 GJ/cap/yr) of biomass from the local environment, almost all by harvesting within the village boundaries. About 86% of domestic energy is used for three main energy services: space heating, food and drinking water preparation. Two-thirds of bioenergy consumption are covered by fuelwood and charcoal, crop residues and dung make up the rest. Three-stone fireplaces and charcoal stoves remain the most important conversion appliances. Family size, landholdings and livestock assets can all have a significant relevance for household energy service provision and energy consumption.

Communities attribute disquieting levels of deforestation, erosion, soil fertility loss to their bioenergy extraction. At the same time, rural households in LMIC are likely to remain dependent on biomass energy in foreseeable future. The potential negative socio-economic and ecological impacts of domestic bioenergy dependency merit intensified efforts towards a rapid transition to cleaner, more sustainable energy sources. In the short term, ICS may open an avenue to reduce bioenergy consumption: ICS-adopting households are associated with about 20% lower fuelwood and dung consumption, and display a 12% lower energy consumption overall, according to our research findings. Nevertheless, alternative ways for the generation of vital energy services should be prioritised. Opportunities to exploit solar, wind, hydropower or geothermal energy exist in the studied area. Our research suggests that a major fraction of bioenergy, including fuelwood and dung, is extracted from land used for agriculture. Remaining forest stands and dedicated grazing land may be at risk of depletion, but data with better spatial resolution would be required to assess linkages to bioenergy extraction. Practicable methods to collect data on the location of biomass removal are needed to assess environmental impacts.

Our study emphasises the importance of a source-to-service perspective on material and energy flows of rural energy systems. The systematic linkages of stocks, flows and services allow to identify changes in efficiency and wellbeing that are relevant for biomass-dependent households. Improving our knowledge about the location of biomass removal is key to relate energy consumption to environmental impacts. Case study research in rural LMIC contexts needs to adopt conventions to quantify mass and energy flows which are commensurate. In this way, case study results could be more easily integrated to create accounts of energy systems across scales, thus amplifying policy relevance of interdisciplinary case-based research. If energy scholarship progresses towards these milestones, it will be better poised to support the transition to more sustainable energy systems in rural areas of LMIC. Moreover, the design of policy interventions and innovations to improve the provision of energy services may benefit from such efforts.

References

Accenture (2012): Enhancing Markets for Delivery of Improved Cookstove Development and Promotion Support in Ethiopia. Market Analysis, Recommendations and Program Plan. Edited by Accenture (UK) Limited, checked on 8/30/2020.

Aggarwal, R. K.; Chandel, Shyam Singh (2022): A comprehensive review of four decades of thermally efficient biomass cookstove initiatives for sustainable development in India. In *International Journal of Ambient Energy* 43 (1), pp. 1–17. DOI: 10.1080/01430750.2022.2086915.

Alemayehu, Atsede Ghidey; Gebreeyesus, Aregawi; Palladino, Giuseppe; Setti, Marco (2020): Behavioral precursors in the innovation-decision process: The case of bioenergy in Ethiopia. In *Energy Strategy Reviews* 30, p. 100499. DOI: 10.1016/j.esr.2020.100499.

Allen, Vivien Gore; Batello, Caterina; Berretta, E. J.; Hodgson, John; Kothmann, Mort; Li, Xianglin et al. (2011): An international terminology for grazing lands and grazing animals. In *Grass and forage science* 66 (1), p. 2.

Arneth, Almut; Olsson, Lennart; Cowie, Annette; Erb, Karl-Heinz; Hurlbert, Margot; Kurz, Werner A. et al. (2021): Restoring Degraded Lands. In *Annu. Rev. Environ. Resour.* 46 (1), pp. 569–599. DOI: 10.1146/annurev-environ-012320-054809.

Balaj, G.; Sharma, Gagandeep; Sai, Shiva Jayanth R. (2022): Forest cover in India: A victim of technicalities. In *Ecological Economics* 193, p. 107306. DOI: 10.1016/j.ecolecon.2021.107306.

Baltruszewicz, Marta; Steinberger, Julia K.; Ivanova, Diana; Brand-Correa, Lina I.; Paavola, Jouni; Owen, Anne (2021): Household final energy footprints in Nepal, Vietnam and Zambia: composition, inequality and links to well-being. In *Environ. Res. Lett.* 16 (2), p. 25011. DOI: 10.1088/1748-9326/abd588.

Barnes, Douglas F.; Floor, Willem M. (1996): Rural Energy in Developing Countries: A Challenge for Economic Development. In *Annu. Rev. Energy. Environ.* 21 (1), pp. 497–530. DOI: 10.1146/annurev.energy.21.1.497.

Barton, Erin M.; Pearsall, Douglas R.; Currie, William S. (2020): Human appropriated net primary productivity as a metric for land use planning: a case study in the US Great Lakes region. In *Landscape Ecol* 35 (6), pp. 1323–1339.

Bazilian, Morgan; Nussbaumer, Patrick; Eibs-Singer, Christine; Brew-Hammond, Abeeku; Modi, Vijay; Sovacool, Benjamin et al. (2012): Improving Access to Modern Energy Services: Insights from Case Studies. In *The Electricity Journal* 25 (1), pp. 93–114. DOI: 10.1016/j.tej.2012.01.007.

Bechtel, William (1986): Integrating Scientific Disciplines. Case Studies from the Life Sciences. Dordrecht: Springer Netherlands.

Berhanu, Mesfin; Jabasingh, S. Anuradha; Kifile, Zebene (2017): Expanding sustenance in Ethiopia based on renewable energy resources – A comprehensive review. In *Renewable and Sustainable Energy Reviews* 75, pp. 1035–1045. DOI: 10.1016/j.rser.2016.11.082.

Beyene, Abebe D.; Koch, Steven F. (2013): Clean fuel-saving technology adoption in urban Ethiopia. In *Energy Economics* 36, pp. 605–613. DOI: 10.1016/j.eneco.2012.11.003.

Bhattarai, Tara N. (1998): Charcoal and its Socio-Economic Importance in Asia. Prospects for Promotion. Edited by RWDEP. Pontianak, Indonesia, checked on 4/19/2022.

Bittermann, W.; Suvorov, M. (2012): Quality standard for statistics on wood fuel consumption of households. (taking into account the relative importance for the 20-20-20 goals). Working Group 2: Methodology. CA-RES. Available online at https://ec.europa.eu/eurostat/documents, checked on 9/6/2022.

Bose, Ranjan Kumar; Purit, Charu; Joshi, Veena (1991): Energy profiles of three un-electrified villages in Eastern Uttar Pradesh of India. In *Biomass & bioenergy* 1 (2), pp. 99–109. DOI: 10.1016/0961-9534(91)90032-8.

Bouzarovski, Stefan; Petrova, Saska (2015): A global perspective on domestic energy deprivation: Overcoming the energy poverty–fuel poverty binary. In *Energy Research & Social Science* 10, pp. 31–40. DOI: 10.1016/j.erss.2015.06.007.

Brand-Correa, Lina I.; Martin-Ortega, Julia; Steinberger, Julia K. (2018): Human Scale Energy Services: Untangling a 'golden thread'. In *Energy Research & Social Science* 38, pp. 178–187. DOI: 10.1016/j.erss.2018.01.008.

Brandt, Martin; Tucker, Compton J.; Kariryaa, Ankit; Rasmussen, Kjeld; Abel, Christin; Small, Jennifer et al. (2020): An unexpectedly large count of trees in the West African Sahara and Sahel. In *Nature* 587 (7832), pp. 78–82. DOI: 10.1038/s41586-020-2824-5.

Brouwer, Inge D.; Hoorweg, Jan C.; van Liere, Marti J. (1997): When households run out of fuel: Responses of rural households to decreasing fuelwood availability, Ntcheu District, Malawi. In *World Development* 25 (2), pp. 255–266. DOI: 10.1016/S0305-750X(96)00100-3.

Brunner, Paul H.; Rechberger, Helmut (2016): Practical handbook of material flow analysis: CRC press.

Capeau, Bart; Dercon, Stefan (1998): Prices, local measurement units and subsistence consumption in rural surveys. An econometric approach with an application to Ethiopia. Centre for the Study of African Economies, Oxford University. Oxford (WPS, 98/10).

Carmona, Luis Gabriel; Whiting, Kai; Haberl, Helmut; Sousa, Tânia (2021): The use of steel in the United Kingdom's transport sector: A stock–flow–service nexus case study. In *Journal of Industrial Ecology* 25 (1), pp. 125–143. DOI: 10.1111/jiec.13055.

Chandyo, Ram K.; Schwinger, Catherine; Ranjitkar, Suman; Hysing, Mari; Ulak, Manjeswori; Shrestha, Merina et al. (2022): Biomass fuel use for cooking in Nepalese families and child cognitive abilities, results from a community-based study. In *Environmental Research* 212, p. 113265. DOI: 10.1016/j.envres.2022.113265.

Chen, Feifei; Qiu, Huanguang; Zhang, Jun (2022): Energy consumption and income of the poor in rural China: Inference for poverty measures. In *Energy Policy* 163, p. 112865. DOI: 10.1016/j.enpol.2022.112865.

Clancy, Joy S.; Skutsch, M.; Batchelor, S. (2003): The Gender-Energy-Poverty Nexus. Finding the energy to address gender concerns in development. DFID project CNTR998521. Available online at http://ris.utwente.nl/ws/files/5134277/Clancy99gender.pdf, checked on 8/18/2023.

Conway, Declan; van Garderen, Emma Archer; Deryng, Delphine; Dorling, Steve; Krueger, Tobias; Landman, Willem et al. (2015): Climate and southern Africa's water–energy–food nexus. In *Nature Clim Change* 5 (9), pp. 837–846. DOI: 10.1038/nclimate2735.

Cotruvo, J. A.; Trevant, C. (2000): Safe drinking water production in rural areas: a comparison between developed and less developed countries. In *Schriftenreihe des Vereins fur Wasser-, Boden- und Lufthygiene* 108, pp. 93–123.

Creutzig, Felix; Ravindranath, N. H.; Berndes, Göran; Bolwig, Simon; Bright, Ryan; Cherubini, Francesco et al. (2015): Bioenergy and climate change mitigation: an assessment. GCB Bioenergy, 7(5), 916-944. In *GCB Bioenergy* 7 (5), pp. 916–944. DOI: 10.1111/GCBB.12205.

Crewett, W.; Bogale, A.; Korf, B. (2008): Land Tenure in Ethiopia: Continuity and Change, Shifting Rulers, and the Quest For State Control. Continuity and Change, Shifting Rulers, and the Quest for State Control: International Food Policy Research Institute (CAPRi Working Paper, 91).

Daioglou, Vassilis; van Ruijven, Bas J.; van Vuuren, Detlef P. (2012): Model projections for household energy use in developing countries. In *Energy* 37 (1), pp. 601–615.

Delina, Laurence L. (2017): Accelerating Sustainable Energy Transition(s) in Developing Countries. The challenges of climate change and sustainable development: Routledge (earthscan).

Ding, Wenguang; Xu, Luan; Ye, Weifeng (2014): A comparative study of bioenergy consumption and CO 2 emissions in Tibetan region of China. In *Renewable Energy* 71, pp. 344–350. DOI: 10.1016/j.renene.2014.05.044.

Dresen, Elisabeth; DeVries, Ben; Herold, Martin; Verchot, Louis; Müller, Robert (2014): Fuelwood Savings and Carbon Emission Reductions by the Use of Improved Cooking Stoves in an Afromontane Forest, Ethiopia. In *Land* 3 (3), pp. 1137–1157. DOI: 10.3390/land3031137.

Erb, Karl-Heinz; Gingrich, Simone (2022): Biomass—Critical limits to a vital resource. In *One Earth* 5 (1), pp. 7–9. DOI: 10.1016/j.oneear.2021.12.014.

ESA CCI (2017): ESA CCI LAND COVER – S2 prototype Land Cover 20m map of Africa 2016. Edited by ESA Climate Change Initiative. Available online at https://2016africalandcover20m.esrin.esa.int/download.php, updated on 11/5/2022, checked on 11/5/2022.

Eurostat (2013): Manual for statistics on energy consumption in households. Luxembourg: Publications Office of the European Union (Eurostat Theme Collection).

Eurostat (2018): Economy-wide material flow accounts. Handbook. 2018 edition. Luxembourg: Publications Office of the European Union (Manuals and guidelines). Available online at https://ec.europa.eu/eurostat/documents/3859598/9117556/KS-GQ-18-006-EN-N.pdf/b621b8ce-2792-47ff-9d10-067d2b8aac4b.

FAO (1983): Wood fuel surveys. Rome. Available online at https://www.fao.org/3/Q1085E/q1085e00.htm#Contents, updated on 2/17/2021, checked on 8/23/2022.

FAO (2017): How to Include the Woodfuel Supplementary Module into Existing Surveys and Derive Woodfuel Indicators. Food and Agriculture Organization. Available online at https://www.fao.org/3/ca6445en/ca6445en.pdf, checked on 4/10/2022.

Fetzel, Tamara; Niedertscheider, Maria; Haberl, Helmut; Krausmann, Fridolin; Erb, Karl-Heinz (2016): Patterns and changes of land use and land-use efficiency in Africa 1980–2005: an analysis based on the human appropriation of net primary production framework. In *Reg Environ Change* 16 (5), pp. 1507–1520. DOI: 10.1007/s10113-015-0891-1.

Fischer-Kowalski, Marina; Singh, Simron Jit; Lauk, Christian; Remesch, Alexander; Ringhofer, Lisa; Grünbühel, Clemens M. (2011a): Sociometabolic transitions in subsistence communities: Boserup revisited in four comparative case studies. In *Human Ecology Review*, pp. 147–158.

Fischer-Kowalski, Marina; Krausmann, Fridolin; Giljum, Stefan; Lutter, Stephan; Mayer, Andreas; Bringezu, Stefan et al. (2011b): Methodology and indicators of economy-wide material flow accounting: State of the art and reliability across sources. In *Journal of Industrial Ecology* 15 (6), pp. 855–876.

Fishman, Tomer; Schandl, Heinz; Tanikawa, Hiroki; Walker, Paul; Krausmann, Fridolin (2014): Accounting for the Material Stock of Nations. In *Journal of Industrial Ecology* 18 (3), pp. 407–420. DOI: 10.1111/jiec.12114.

Flyvbjerg, Bent (2006): Five Misunderstandings About Case-Study Research. In *Qualitative Inquiry* 12 (2), pp. 219–245. DOI: 10.1177/1077800405284363.

Fuchs, Doris; Steinberger, Julia; Pirgmaier, Elke; Lamb, William; Brand-Correa, Lina; Mattioli, Giulio; Cullen, Jonathan (2021): A corridors and power-oriented perspective on energy-service demand and needs satisfaction. In *Sustainability: Science, Practice and Policy* 17 (1), pp. 163–173. DOI: 10.1080/15487733.2021.1912907.

Fullerton, Duncan G.; Bruce, Nigel; Gordon, Stephen B. (2008): Indoor air pollution from biomass fuel smoke is a major health concern in the developing world. In *Transactions of the Royal Society of Tropical Medicine and Hygiene* 102 (9), pp. 843–851. DOI: 10.1016/j.trstmh.2008.05.028.

Gao, Yan; Skutsch, Margaret; Paneque-Gálvez, Jaime; Ghilardi, Adrian (2020): Remote sensing of forest degradation: a review. In *Environ. Res. Lett.* 15 (10), p. 103001. DOI: 10.1088/1748-9326/abaad7.

GEA (2012): Global energy assessment. toward a sustainable future. Edited by Thomas B. Johansson, Anand Prabhakar Patwardhan, Nebojša Nakićenović, Luis Gomez-Echeverri: Cambridge University Press.

Gebreegziabher, Zenebe; van Kooten, G. C.; van Soest, D. (2017): Technological innovation and dispersion: Environmental benefits and the adoption of improved biomass cookstoves in Tigrai, northern Ethiopia. In *Energy Economics* 67, pp. 337–345. DOI: 10.1016/j.eneco.2017.08.030.

Gill-Wiehl, A.; Ray I.; Kammen, Daniel M. (2021): Is clean cooking affordable? A review. In *Renewable and Sustainable Energy Reviews* 151, p. 111537. DOI: 10.1016/j.rser.2021.111537.

Goertz, Gary (2017): Multimethod research, causal mechanisms, and case studies. An integrated approach. Princeton, New Jersey: Princeton University Press.

Gould, Carlos F.; Jha, Shaily; Patnaik, Sasmita; Agrawal, Shalu; Zhang, Alice Tianbo; Saluja, Sonakshi et al. (2022): Variability in the household use of cooking fuels: The importance of dishes cooked, non-cooking end uses, and seasonality in understanding fuel stacking in rural and urban slum communities in six north Indian states. In *World Development* 159, p. 106051. DOI: 10.1016/j.worlddev.2022.106051.

Grabher, Harald (2017): Trends in the human appropriation of net primary production for Ethiopia between 1961 and 2013 and their impacts from a national and local perspective. Thesis. University of Klagenfurt. Available online at http://ubdocs.uni-klu.ac.at/open/hssvoll/AC14500160.pdf.

Grabher, Harald (2021): HANPP trajectories for Ethiopia reveal recent agricultural efficiency gains but high grazing intensity. In *Environ Dev Sustain*. DOI: 10.1007/s10668-020-00814-x.

Grabher, Harald F.; Rau, Henrike; Ledermann, Samuel T.; Haberl, Helmut (2023): Beyond cooking: An energy services perspective on household energy use in low and middle income countries. In *Energy Research & Social Science* (97), pp. 1–12. DOI: 10.1016/j.erss.2023.102946.

Grünbühel, Clemens M.; Haberl, Helmut; Schandl, Heinz; Winiwarter, Verena (2003): Socioeconomic metabolism and colonization of natural processes in SangSaeng village: Material and energy flows, land use, and cultural change in northeast Thailand. In *Human Ecology* 31 (1), pp. 53–86.

Guta, Dawit Diriba (2014): Effect of fuelwood scarcity and socio-economic factors on household bio-based energy use and energy substitution in rural Ethiopia. In *Energy Policy* 75, pp. 217–227. DOI: 10.1016/j.enpol.2014.09.017.

Haas, Reinhard; Nakicenovic, Nebojsa; Ajanovic, Amela; Faber, Thomas; Kranzl, Lukas; Müller, Andreas; Resch, Gustav (2008): Towards sustainability of energy systems: A primer on how to apply the concept of energy services to identify necessary trends and policies. In *Energy Policy* 36 (11), pp. 4012–4021.

Haberl, Helmut (2001): The energetic metabolism of societies part I: accounting concepts. In *Journal of Industrial Ecology* 5 (1), pp. 11–33.

Haberl, Helmut (2013): Net land-atmosphere flows of biogenic carbon related to bioenergy: towards an understanding of systemic feedbacks. In *GCB Bioenergy* 5 (4), pp. 351–357. DOI: 10.1111/gcbb.12071.

Haberl, Helmut; Erb, Karl-Heinz; Krausmann, Fridolin (2014): Human Appropriation of Net Primary Production: Patterns, Trends, and Planetary Boundaries. In *Annu. Rev. Environ. Resour.* 39 (1), pp. 363–391. DOI: 10.1146/annurev-environ-121912-094620.

Haberl, Helmut; Erb, Karl-Heinz; Krausmann, Fridolin; Bondeau, Alberte; Lauk, Christian; Müller, Christoph et al. (2011): Global bioenergy potentials from agricultural land in 2050: Sensitivity to climate change, diets and yields. In *Biomass & bioenergy* 35 (12), pp. 4753–4769. DOI: 10.1016/j.biombioe.2011.04.035.

Haberl, Helmut; Fischer-Kowalski, Marina; Krausmann, Fridolin; Winiwarter, Verena (Eds.) (2016): Social ecology. Society-nature relations across time and space. Switzerland: springer (Human-Environment Interactions, volume 5).

Haberl, Helmut; Schmid, Martin; Haas, Willi; Wiedenhofer, Dominik; Rau, Henrike; Winiwarter, Verena (2021): Stocks, flows, services and practices: Nexus approaches to sustainable social metabolism. In *Ecological Economics* 182, p. 106949. DOI: 10.1016/j.ecolecon.2021.106949.

Haberl, Helmut; Sprinz, Detlef; Bonazountas, Marc; Cocco, Pierluigi; Desaubies, Yves; Henze, Mogens et al. (2012): Correcting a fundamental error in greenhouse gas accounting related to bioenergy. In *Energy Policy* 45-222 (5), pp. 18–23. DOI: 10.1016/j.enpol.2012.02.051.

Haberl, Helmut; Wiedenhofer, Dominik; Erb, Karl-Heinz; Görg, Christoph; Krausmann, Fridolin (2017): The Material Stock–Flow–Service Nexus: A New Approach for Tackling the Decoupling Conundrum. In *Sustainability* 9 (7), p. 1049. DOI: 10.3390/su9071049.

Haile, Kiflu; Sandewall, Mats; Urgessa, Kaba (2009): Wood fuel demand and sustainability of supply in South-Western Ethiopia, case of Jimma town. In *Research J. of Forestry* 3 (2), pp. 29–42. DOI: 10.3923/rjf.2009.29.42.

Han, Xiao; Wei, Chu (2021): Household energy consumption: state of the art, research gaps, and future prospects. In *Environ Dev Sustain* 23 (8), pp. 12479–12504. DOI: 10.1007/s10668-020-01179-x.

Hansfort, Sofie Louise; Mertz, Ole (2011): Challenging the Woodfuel Crisis in West African Woodlands. In *Hum Ecol* 39 (5), pp. 583–595. DOI: 10.1007/s10745-011-9417-8.

Harris, Ian; Osborn, Timothy J.; Jones, Phil; Lister, David (2020): Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. In *Scientific data* 7 (1), p. 109. DOI: 10.1038/s41597-020-0453-3.

Hoffmann, Harry; Uckert, Götz; Reif, Constance; Müller, Klaus; Sieber, Stefan (2015): Traditional biomass energy consumption and the potential introduction of firewood efficient stoves: insights from western Tanzania. In *Reg Environ Change* 15 (7), pp. 1191–1201. DOI: 10.1007/s10113-014-0738-1.

Hoogwijk, Monique; Faaij, André; van den Broek, Richard; Berndes, Göran; Gielen, Dolf; Turkenburg, Wim (2003): Exploration of the ranges of the global potential of biomass for energy. In *Biomass & bioenergy* 25 (2), pp. 119–133. DOI: 10.1016/S0961-9534(02)00191-5.

Hurni, Hans (1998): Agroecological Belts of Ethiopia. Explanatory notes on three maps at a scale of 1:1,000,000. Edited by Centre for Development and Environment. University of Berne. Berne Switzerland, checked on 5/23/2022.

Hurni, K.; Zeleke, G.; Kassie, M.; Tegegne, B.; Kassawmar, T.; Teferi, E. et al. (2015): Economics of Land Degradation (ELD) Ethiopia Case Study. Soil Degradation and Sustainable Land Management in the Rainfed Agricultural Areas of Ethiopia: An Assessment of the Economic Implications. Report for the Economics of Land Degradation Initiative. Bern. Available online at http://www.eld-initiative.org/#p2012, checked on 12/19/2016.

IEA (2022): World energy outlook 2022. revised edition. With assistance of Laura Cozzi, Tim Gould. Available online at iea.org, checked on 12/30/2022.

Imran, Muhammad; Zahid, Azlan; Mouneer, Salma; Özçatalbaş, Orhan; Ul Haq, Shamsheer; Shahbaz, Pomi et al. (2022): Relationship between Household Dynamics, Biomass Consumption, and Carbon Emissions in Pakistan. In *Sustainability* 14 (11), p. 6762. DOI: 10.3390/su14116762.

IPCC (2015): Climate change 2014: mitigation of climate change. Edited by O. Edenhofer, et al.: Cambridge University Press.

Jackson, Hasan; Prince, Stephen D. (2016): Degradation of net primary production in a semiarid rangeland. In *Biogeosciences* 13 (16), pp. 4721–4734. DOI: 10.5194/bg-13-4721-2016.

Jetter, J.; Kariher, P. (2009): Solid-fuel household cook stoves: Characterization of performance and emissions. In *Biomass & bioenergy* 33 (2), pp. 294–305. DOI: 10.1016/j.biombioe.2008.05.014.

Jeuland, Marc; Fetter, T. Robert; Li, Yating; Pattanayak, Subhrendu K.; Usmani, Faraz; Bluffstone, Randall A. et al. (2021): Is energy the golden thread? A systematic review of the impacts of modern and traditional energy use in low- and middle-income countries. In *Renewable and Sustainable Energy Reviews* 135, p. 110406. DOI: 10.1016/j.rser.2020.110406.

Jin, Jianjun; He, Rui; Kuang, Foyuan; Wan, Xinyu; Ning, Jing (2019): Different sources of rural household energy consumption and influencing factors in Dazu, China. In *Environmental science and pollution research international* 26 (21), pp. 21312–21320. DOI: 10.1007/s11356-019-05439-w.

Johnson, Nathan G.; Bryden, Kenneth M. (2012): Energy supply and use in a rural West African village. In *Energy* 43 (1), pp. 283–292. DOI: 10.1016/j.energy.2012.04.028.

Johnson, Oliver W.; Gerber, Vanessa; Muhoza, Cassilde (2019): Gender, culture and energy transitions in rural Africa. In *Energy Research & Social Science* 49, pp. 169–179. DOI: 10.1016/j.erss.2018.11.004.

Jonsson, Daniel K.; Gustafsson, Stina; Wangel, Josefin; Höjer, Mattias; Lundqvist, Per; Svane, Örjan (2011): Energy at your service: highlighting energy usage systems in the context of energy efficiency analysis. In *Energy Efficiency* 4 (3), pp. 355–369. DOI: 10.1007/s12053-010-9103-5.

Kalt, Gerald; Wiedenhofer, Dominik; Görg, Christoph; Haberl, Helmut (2019): Conceptualizing energy services: A review of energy and well-being along the Energy Service Cascade. In *Energy Research & Social Science* 53, pp. 47–58. DOI: 10.1016/j.erss.2019.02.026.

Karcagi-Kováts, Andrea; Tóth-Szita, Klára; Kuti, István (2018): The structure of socio-economic metabolism and its drivers on household level in Hungary. In *Journal of Cleaner Production* 172, pp. 758–767. DOI: 10.1016/j.jclepro.2017.10.220.

Kassa, Henok; Dondeyne, Stefaan; Poesen, Jean; Frankl, Amaury; Nyssen, Jan (2017): Impact of deforestation on soil fertility, soil carbon and nitrogen stocks: the case of the Gacheb catchment in the White Nile Basin, Ethiopia. In *Agriculture, Ecosystems & Environment* 247, pp. 273–282. DOI: 10.1016/j.agee.2017.06.034.

Kassawmar, Tibebu; Eckert, Sandra; Hurni, Kaspar; Zeleke, Gete; Hurni, Hans (2018): Reducing landscape heterogeneity for improved land use and land cover (LULC) classification across the large and complex Ethiopian highlands. In *Geocarto International* 33 (1), pp. 53–69. DOI: 10.1080/10106049.2016.1222637.

Kaygusuz, K. (2011): Energy services and energy poverty for sustainable rural development. In *Renewable and Sustainable Energy Reviews* 15 (2), pp. 936–947. DOI: 10.1016/j.rser.2010.11.003.

Khalifa, Muhammad; Elagib, Nadir Ahmed; Ribbe, Lars; Schneider, Karl (2018): Spatio-temporal variations in climate, primary productivity and efficiency of water and carbon use of the land cover types in Sudan and Ethiopia. In *The Science of the total environment* 624, pp. 790–806. DOI: 10.1016/j.scitotenv.2017.12.090.

Kissinger, Meidad; Damari, Yuval (2021): Household metabolism: Integrating socio-economic characteristics and lifestyles on individual and national scales as a mean for advancing environmental management. In *Journal of environmental management* 279, p. 111526. DOI: 10.1016/j.jenvman.2020.111526.

Kituyi, Evans; Marufu, Lackson; Huber, Beate; O. Wandiga, Shem; O. Jumba, Isaac; O. Andreae, Meinrat; Helas, Günter (2001): Biofuel consumption rates and patterns in Kenya. In *Biomass & bioenergy* 20 (2), pp. 83–99. DOI: 10.1016/S0961-9534(00)00072-6.

Kowsari, Reza; Zerriffi, Hisham (2011): Three dimensional energy profile. In *Energy Policy* 39 (12), pp. 7505–7517. DOI: 10.1016/j.enpol.2011.06.030.

Krausmann, Fridolin; Erb, Karl-Heinz; Gingrich, Simone; Haberl, Helmut; Bondeau, Alberte; Gaube, Veronika et al. (2013): Global human appropriation of net primary production doubled in the 20th century. In *Proceedings of the National Academy of Sciences of the United States of America* 110 (25), pp. 10324–10329. DOI: 10.1073/pnas.1211349110.

Krausmann, Fridolin; Schandl, Heinz; Eisenmenger, Nina; Giljum, Stefan; Jackson, Tim (2017): Material Flow Accounting: Measuring Global Material Use for Sustainable Development. In *Annu. Rev. Environ. Resour.* 42 (1), pp. 647–675. DOI: 10.1146/annurev-environ-102016-060726.

Kshirsagar, M. P.; Kalamkar, V. S. (2014): A comprehensive review on biomass cookstoves and a systematic approach for modern cookstove design. In *Renewable and Sustainable Energy Reviews* 30, pp. 580–603. DOI: 10.1016/j.rser.2013.10.039.

Kumar, Manoj; Kumar, Sachin; Tyagi, S. K. (2013): Design, development and technological advancement in the biomass cookstoves: A review. In *Renewable and Sustainable Energy Reviews* 26, pp. 265–285. DOI: 10.1016/j.rser.2013.05.010.

Langniss, Ole; Ince, David (2004): Solar water heating. In *Refocus* 5 (3), pp. 18–21. DOI: 10.1016/S1471-0846(04)00137-4.

Lemaire, Xavier (2018): Solar home systems and solar lanterns in rural areas of the Global South: What impact? In *WIREs Energy Environ.* 7 (5). DOI: 10.1002/wene.301.

Liu, Gang; Lucas, Mario; Shen, Lei (2008): Rural household energy consumption and its impacts on eco-environment in Tibet: Taking Taktse county as an example. In *Renewable and Sustainable Energy Reviews* 12 (7), pp. 1890–1908. DOI: 10.1016/j.rser.2007.03.008.

Liu, Siyu; Brandt, Martin; Nord-Larsen, Thomas; Chave, Jerome; Reiner, Florian; Lang, Nico et al. (2023): The overlooked contribution of trees outside forests to tree cover and woody biomass across Europe.

Liu, Wenling; Spaargaren, Gert; Heerink, Nico; Mol, Arthur P.J.; Wang, Can (2013): Energy consumption practices of rural households in north China: Basic characteristics and potential for low carbon development. In *Energy Policy* 55, pp. 128–138. DOI: 10.1016/j.enpol.2012.11.031.

Loo, Jennifer D.; Hyseni, Lirije; Ouda, Rosebel; Koske, Selline; Nyagol, Ronald; Sadumah, Ibrahim et al. (2016): User Perspectives of Characteristics of Improved Cookstoves from a Field Evaluation in Western Kenya. In *International journal of environmental research and public health* 13 (2), p. 167. DOI: 10.3390/ijerph13020167.

Lung, Mark A.; Espira, Anton (2019): A large-scale, village-level test of wood consumption patterns in a modified traditional cook stove in Kenya. In *Energy for Sustainable Development* 49, pp. 11–20. DOI: 10.1016/j.esd.2018.12.004.

Malla, Sunil; Timilsina, Govinda R. (2014): Household Cooking Fuel Choice and Adoption of Improved Cookstoves in Developing Countries: A Review. World Bank Group (Policy Research Working Paper, 6903).

Marufu, L.; Ludwig, J.; Andreae, M.O; Lelieveld, J.; Helas, G. (1999): Spatial and temporal variation in domestic biofuel consumption rates and patterns in Zimbabwe: implications for atmospheric trace gas emission. In *Biomass & bioenergy* 16 (5), pp. 311–332. DOI: 10.1016/S0961-9534(99)00010-0.

Matthews, G. A. (2011): Integrated vector management. Controlling vectors of malaria and other insect vector borne diseases. Chichester, West Sussex, U.K., Ames, Iowa: Wiley-Blackwell.

Mekonnen, Alemu; Beyene, Abebe; Bluffstone, Randall Ames; Dissanayake, Sahan; Gebreegziabher, Zenebe; LaFave, Daniel et al. (2020): Improved Biomass Cookstove Use in the Longer Run-Results from a Field Experiment in Rural Ethiopia. In *World Bank Policy Research Working Paper* (9272).

Mekonnen, Dawit; Bryan, Elizabeth; Alemu, Tekie; Ringler, Claudia (2017): Food versus fuel: examining tradeoffs in the allocation of biomass energy sources to domestic and productive uses in Ethiopia. In *Agricultural Economics* 48 (4), pp. 425–435. DOI: 10.1111/agec.12344.

Modi, Vijay; McDade, Susan; Lallement, Dominique; Saghir, Jamal (2005): Energy Services for the Millennium Development Goals. In *Energy services for the millennium development goals*.

Mondal, Md Alam Hossain; Bryan, Elizabeth; Ringler, Claudia; Mekonnen, Dawit; Rosegrant, Mark (2018): Ethiopian energy status and demand scenarios: Prospects to improve energy efficiency and mitigate GHG emissions. In *Energy* 149, pp. 161–172. DOI: 10.1016/j.energy.2018.02.067.

Mondal, Md. Alam Hossain; Bryan, Elizabeth; Ringler, Claudia; Rosegrant, Mark (2017): Ethiopian power sector development: Renewable based universal electricity access and export strategies. In *Renewable and Sustainable Energy Reviews* 75, pp. 11–20. DOI: 10.1016/j.rser.2016.10.041.

Motghare, Kalyani A.; Rathod, Ajit P.; Wasewar, Kailas L.; Labhsetwar, Nitin K. (2016): Comparative study of different waste biomass for energy application. In *Waste Management* 47, pp. 40–45. DOI: 10.1016/j.wasman.2015.07.032.

Mugabowindekwe, Maurice; Brandt, Martin; Chave, Jérôme; Reiner, Florian; Skole, David L.; Kariryaa, Ankit et al. (2023): Nation-wide mapping of tree-level aboveground carbon stocks in Rwanda. In *Nature Clim Change* 13 (1), pp. 91–97. DOI: 10.1038/s41558-022-01544-w.

Nansaior, A.; Patanothai, A.; Rambo, A.T.; Simaraks, S. (2013): The sustainability of biomass energy acquisition by households in urbanizing communities in Northeast Thailand. In *Biomass & bioenergy* 52, pp. 113–121. DOI: 10.1016/j.biombioe.2013.03.011.

Niu, Hewen; He, Yuanqing; Desideri, Umberto; Zhang, Peidong; Qin, Hongyi; Wang, Shijin (2014): Rural household energy consumption and its implications for eco-environments in NW China: A case study. In *Renewable Energy* 65, pp. 137–145. DOI: 10.1016/j.renene.2013.07.045.

Niu, Shuwen; Li, Zhen; Qiu, Xin; Dai, Runqi; Wang, Xiang; Qiang, Wenli; Hong, Zhenguo (2019): Measurement of effective energy consumption in China's rural household sector and policy implication. In *Energy Policy* 128, pp. 553–564. DOI: 10.1016/j.enpol.2019.01.016.

Noll, Dominik; Lauk, Christian; Haas, Willi; Singh, Simron Jit; Petridis, Panos; Wiedenhofer, Dominik (2022): The sociometabolic transition of a small Greek island: Assessing stock dynamics, resource flows, and material circularity from 1929 to 2019. In *J of Industrial Ecology* 26 (2), pp. 577–591. DOI: 10.1111/jiec.13206.

Pachauri, Shonali; Cherp, Aleh (2011): Energy security and energy access: distinct and interconnected challenges. In *Current Opinion in Environmental Sustainability* 3 (4), pp. 199–201. DOI: 10.1016/j.cosust.2011.07.006.

Pahla, G.; Mamvura, T. A.; Ntuli, F.; Muzenda, E. (2017): Energy densification of animal waste lignocellulose biomass and raw biomass. In *South African Journal of Chemical Engineering* 24, pp. 168–175. DOI: 10.1016/j.sajce.2017.10.004.

Pauliuk, Stefan; Müller, Daniel B. (2014): The role of in-use stocks in the social metabolism and in climate change mitigation. In *Global Environmental Change* 24, pp. 132–142. DOI: 10.1016/j.gloenvcha.2013.11.006.

Peng, Dailiang; Zhang, Bing; Wu, Chaoyang; Huete, Alfredo R.; Gonsamo, Alemu; Lei, Liping et al. (2017): Country-level net primary production distribution and response to drought and land cover change. In *The Science of the total environment* 574, pp. 65–77. DOI: 10.1016/j.scitotenv.2016.09.033.

Pratiti, R.; Vadala, D.; Kalynych, Z.; Sud, P. (2020): Health effects of household air pollution related to biomass cook stoves in resource limited countries and its mitigation by improved cookstoves. In *Environmental Research* 186, p. 109574. DOI: 10.1016/j.envres.2020.109574.

Pricope, Narcisa Gabriela; Cassidy, Lin; Gaughan, Andrea Elizabeth; Salerno, Jonathan David; Stevens, Forrest Robert; Hartter, Joel et al. (2020): Addressing Integration Challenges of Interdisciplinary Research in Social-Ecological Systems. In *Society & Natural Resources* 33 (3), pp. 418–431. DOI: 10.1080/08941920.2019.1680783.

Ravindra, Khaiwal; Kaur-Sidhu, Maninder; Mor, Suman (2021): Transition to clean household energy through an application of integrated model: Ensuring sustainability for better health, climate and environment. In *The Science of the total environment* 775, p. 145657. DOI: 10.1016/j.scitotenv.2021.145657.

Reddy, B. Sudhakara (2015): Access to modern energy services: An economic and policy framework. In *Renewable and Sustainable Energy Reviews* 47, pp. 198–212.

Ringhofer, Lisa (2009): Fishing, foraging and farming in the Bolivian Amazon: On a local society in transition: Springer Science & Business Media.

Roux, Nicolas; Kaufmann, Lisa; Bhan, Manan; Le Noe, Julia; Matej, Sarah; Laroche, Perrine et al. (2022): Embodied HANPP of feed and animal products: Tracing pressure on ecosystems along trilateral livestock supply chains 1986-2013. In *The Science of the total environment* 851 (Pt 2), p. 158198. DOI: 10.1016/j.scitotenv.2022.158198.

Sahakian, Marlyne; Erkman, S. (2016): Understanding household food metabolism: relating micro-level material flow analysis to consumption practices. In *Journal of Cleaner Production* 125, pp. 44–55. DOI: 10.1016/j.jclepro.2016.03.055.

Schaphoff, Sibyll; Bloh, Werner von; Rammig, Anja; Thonicke, Kirsten; Biemans, Hester; Forkel, Matthias et al. (2018): LPJmL4 – a dynamic global vegetation model with managed land – Part 1: Model description. In *Geosci. Model Dev.* 11 (4), pp. 1343–1375. DOI: 10.5194/gmd-11-1343-2018.

Simon, Gregory L.; Peterson, Cody (2019): Disingenuous forests: A historical political ecology of fuelwood collection in South India. In *Journal of Historical Geography* 63, pp. 34–47. DOI: 10.1016/j.jhg.2018.09.003.

Simons, Andrew M.; Beltramo, Theresa; Blalock, Garrick; Levine, David I. (2017): Using unobtrusive sensors to measure and minimize Hawthorne effects: Evidence from cookstoves. In *Journal of Environmental Economics and Management* 86, pp. 68–80. DOI: 10.1016/j.jeem.2017.05.007.

Singh, Simron J.; Haas, Willi (2016): Complex Disasters on the Nicobar Islands. In Helmut Haberl, Marina Fischer-Kowalski, Fridolin Krausmann, Verena Winiwarter (Eds.): Social ecology. Society-nature relations across time and space. Switzerland: springer (Human-Environment Interactions, volume 5), pp. 523–542.

Singh, Simron Jit (2010): Local studies manual: A researcher's guide for investigating the social metabolism of local rural systems. Vienna: Inst. of Social Ecology (Social Ecology Working Paper, 120). Available online at https://www.aau.at/wp-content/uploads/2016/11/working-paper-120-web.pdf.

Singh, Simron Jit; Grünbühel, Clemens M.; Schandl, Heinz; Schulz, Niels (2001): Social metabolism and labour in a local context: changing environmental relations on Trinket Island. In *Population and Environment* 23 (1), pp. 71–104.

Singh, Simron Jit.; Fischer-Kowalski, Marina; Chertow, Marian (2020): Introduction: The Metabolism of Islands. In *Sustainability* 12 (22), p. 9516. DOI: 10.3390/su12229516.

Song, Conghe; Bilsborrow, Richard; Jagger, Pamela; Zhang, Qi; Chen, Xiaodong; Huang, Qingfeng (2018): Rural Household Energy Use and Its Determinants in China: How Important Are

Influences of Payment for Ecosystem Services vs. Other Factors? In *Ecological Economics* 145, pp. 148–159. DOI: 10.1016/j.ecolecon.2017.08.028.
Sovacool, Benjamin K. (2011): Conceptualizing urban household energy use: Climbing the “Energy Services Ladder”. In *Energy Policy* 39 (3), pp. 1659–1668. DOI: 10.1016/j.enpol.2010.12.041.
Sovacool, Benjamin K.; Martiskainen, Mari (2020): Hot transformations: Governing rapid and deep household heating transitions in China, Denmark, Finland and the United Kingdom. In *Energy Policy* 139, p. 111330. DOI: 10.1016/j.enpol.2020.111330.
Stephenson, Janet (2018): Sustainability cultures and energy research: An actor-centred interpretation of cultural theory. In *Energy research and social science*. DOI: 10.1016/J.ERSS.2018.05.034.
Strydom, Adél; Musango, Josephine Kaviti; Currie, Paul K. (2019): Conceptualizing Household Energy Metabolism: A Methodological Contribution. In *Energies* 12 (21), p. 4125. DOI: 10.3390/en12214125.
Tabuti, J.R.S.; Dhillion, S. S.; Lye, K. A. (2003): Firewood use in Bulamogi County, Uganda: species selection, harvesting and consumption patterns. In *Biomass and Bioenergy* 25 (6), pp. 581–596. DOI: 10.1016/S0961-9534(03)00052-7.
Tanikawa, Hiroki; Fishman, Tomer; Hashimoto, Seiji; Daigo, Ichiro; Oguchi, Masahiro; Miatto, Alessio et al. (2021): A framework of indicators for associating material stocks and flows to service provisioning: Application for Japan 1990–2015. In *Journal of Cleaner Production* 285, p. 125450. DOI: 10.1016/j.jclepro.2020.125450.
Tanner, Andrew M.; Johnston, Alison L. (2017): The Impact of Rural Electric Access on Deforestation Rates. In *World Development* 94, pp. 174–185. DOI: 10.1016/j.worlddev.2016.12.046.
Thomas, Evan A.; Barstow, Christina K.; Rosa, Ghislaine; Majorin, Fiona; Clasen, Thomas (2013): Use of remotely reporting electronic sensors for assessing use of water filters and cookstoves in Rwanda. In *Environmental science & technology* 47 (23), pp. 13602–13610. DOI: 10.1021/es403412x.
Top, N. (2004): Variation in woodfuel consumption patterns in response to forest availability in Kampong Thom Province, Cambodia. In *Biomass & bioenergy* 27 (1), pp. 57–68. DOI: 10.1016/j.biombioe.2003.10.008.
Torres-Rojas, Dorisel; Lehmann, Johannes; Hobbs, Peter; Joseph, Stephen; Neufeldt, Henry (2011): Biomass availability, energy consumption and biochar production in rural households of Western Kenya. In *Biomass and Bioenergy* 35 (8), pp. 3537–3546. DOI: 10.1016/j.biombioe.2011.05.002.
Wang, Mingxia; Zhang, Chao; Yang, Ming; Li, Yingmei (2020): Material flows and in-use stocks of durable goods in Chinese urban household sector. In *Resources, Conservation and Recycling* 158, p. 104758. DOI: 10.1016/j.resconrec.2020.104758.
Warde, Paul (2019): Firewood consumption and energy transition: a survey of sources, methods and explanations in Europe and North America. In *HIST AGRAR* (77), pp. 7–32. DOI: 10.26882/histagrar.077e02w.
Wassie, Yibeltal T.; Adaramola, Muyiwa S. (2019): Potential environmental impacts of small-scale renewable energy technologies in East Africa: A systematic review of the evidence. In *Renewable and Sustainable Energy Reviews* 111, pp. 377–391. DOI: 10.1016/j.rser.2019.05.037.
Whiting, Kai; Carmona, Luis Gabriel; Brand-Correa, Lina; Simpson, Edward (2020): Illumination as a material service: A comparison between Ancient Rome and early 19th century London. In *Ecological Economics* 169, p. 106502. DOI: 10.1016/j.ecolecon.2019.106502.
Whiting, Kai; Carmona, Luis Gabriel; Carrasco, Angeles (2021): The resource service cascade: A conceptual framework for the integration of ecosystem, energy and material services. In *Environmental Development*, p. 100647. DOI: 10.1016/j.envdev.2021.100647.

WHO (2018): World health statistics 2018. Monitoring health for the SDGs. Geneva: World Health Organization.
Win, Zar Chi; Mizoue, Nobuya; Ota, Tetsuji; Kajisa, Tsuyoshi; Yoshida, Shigejiro; Oo, Thaung Naing; Ma, Hwan-ok (2018): Differences in consumption rates and patterns between firewood and charcoal: A case study in a rural area of Yedashe Township, Myanmar. In *Biomass & bioenergy* 109, pp. 39–46. DOI: 10.1016/j.biombioe.2017.12.011.
WLRC Ethiopia (2018): Map Server Ethiopia: Thematic and Geographic Overview, Field and Base Map Series. Release 3.0. With assistance of University of Bern CDE. Available online at www.mapserver-ethiopia.org, checked on 11/26/2022.
World Bank (2017): Converting Biomass to Energy: Washington, DC.
Xue, Bing; Xing, Ran; Chen, Xingpeng; Song, Lan; Wang, Yutao; Coffman, D'Maris; Mi, Zhifu (2020): Rural household energy consumption of farmers and herders in the Qinghai-Tibet Plateau. In *Energy* 192, p. 116649. DOI: 10.1016/j.energy.2019.116649.
Yalew, Amsalu Woldie (2022): Environmental and economic accounting for biomass energy in Ethiopia. In *Energ Sustain Soc* 12 (1). DOI: 10.1186/s13705-022-00356-2.
Zanuncio, Antônio José Vinha; Carvalho, Amélia Guimarães; Trugilho, Paulo Fernando; Monteiro, Thiago Campos (2014): Extractives and energetic properties of wood and charcoal. In *Rev. Árvore* 38 (2), pp. 369–374. DOI: 10.1590/S0100-67622014000200018.
Zhang, Alice Tianbo; Patnaik, Sasmita; Jha, Shaily; Agrawal, Shalu; Gould, Carlos F.; Urpelainen, Johannes (2022): Evidence of multidimensional gender inequality in energy services from a large-scale household survey in India. In *Nat Energy*. DOI: 10.1038/s41560-022-01044-3.
Zhang, Yanjie; Pan, Ying; Li, Meng; Wang, Zhipeng; Wu, Junxi; Zhang, Xianzhou; Cao, Yanan (2021): Impacts of human appropriation of net primary production on ecosystem regulating services in Tibet. In *Ecosystem Services* 47, p. 101231.
Zheng, Xinye; Wei, Chu; Qin, Ping; Guo, Jin; Yu, Yihua; Song, Feng; Chen, Zhanming (2014): Characteristics of residential energy consumption in China: Findings from a household survey. In *Energy Policy* 75, pp. 126–135. DOI: 10.1016/j.enpol.2014.07.016.
Zika, Michael; Erb, Karl-Heinz (2009): The global loss of net primary production resulting from human-induced soil degradation in drylands. In *Ecological Economics* 69 (2), pp. 310–318. DOI: 10.1016/j.ecolecon.2009.06.014.
Zulu, Leo C.; Richardson, Robert B. (2013): Charcoal, livelihoods, and poverty reduction: Evidence from sub-Saharan Africa. In *Energy for Sustainable Development* 17 (2), pp. 127–137. DOI: 10.1016/j.esd.2012.07.007.