Summer 6-21-2020

Quantifying the environmental impacts of cookstove transitions A societal exergy analysis based model of energy consumption and forest stocks in Honduras

Noah Ver Beek
Calvin University

Elvin Vindel
Carnegie Mellon University

Matthew K. Heun
Calvin University

Paul E. Brockway
University of Leeds

energies

MDPI

Article

Quantifying the Environmental Impacts of Cookstove Transitions: A Societal Exergy Analysis Based Model of Energy Consumption and Forest Stocks in Honduras

Noah Ver Beek [1,*], Elvin Vindel [2], Matthew Kuperus Heun [1] and Paul E. Brockway [3]

1 Engineering Department, Calvin University, 3201 Burton St. SE, Grand Rapids, MI 49546, USA; mkh2@calvin.edu
2 Civil and Environmental Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, USA; evindel@andrew.cmu.edu
3 Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK; p.e.brockway@leeds.ac.uk
* Correspondence: noah.m.verbeek@gmail.com; Tel.: +1-(616)-406-6031

Received: 14 May 2020; Accepted: 9 June 2020; Published: 20 June 2020

check for updates

Abstract: Unsustainable consumption of biofuels contributes to deforestation and climate change, while household air pollution from burning solid biofuels in homes results in millions of premature deaths globally every year. Honduras, like many low and medium Human Development Index countries, depends on primary solid biofuels for more than 30% of its primary energy supply (as of 2013). We conducted a societal exergy analysis and developed a forest stock model for Honduras for 1971–2013 and used the results to model an energy transition from traditional wood stoves to either improved efficiency wood cookstoves or modern fuel cookstoves (using Electricity or Liquefied petroleum gas) over the period 2013–2050. The exergy analysis and forest model enabled quantification of the environmental tradeoffs between the improved efficiency and fuel switching scenarios. We find that the continued reliance on wood within both the existing and improved wood cookstove scenarios would exhaust forest stocks by 2050, though improved efficiency could reduce national greenhouse gas emissions. Modern fuel cookstoves would reduce household air pollution, emissions, and deforestation. However, the best alternative to successfully reduce household air pollution, GHG emissions, and deforestation is a rapid switch to electric stoves with significant investment in renewable-based electricity.

Keywords: societal exergy analysis; forest stocks; Honduras; cookstoves; wood stoves; biofuels; low HDI countries; medium HDI countries

1. Introduction

1.1. The Importance of Energy

Energy plays a critical role in the modern world. Prior to the industrial revolution, technology and knowledge limitations restricted energy supplies to fuels with low energy density. At that time, most energy came from either human or animal labor or wood fuels [1], both of which are limited, low-density options: muscle work is limited by the number and strength of humans and animals, and wood fuels are limited by the available forest area. (Hereafter, wood fuels will be referred to as primary solid biofuels, or PSBs, in accordance with the IEA definition of PSBs as “woody materials generated by industrial process or provided directly by forestry and agriculture (firewood, wood chips, bark, sawdust, shavings, chips, sulphite, lyes, also known as black liquor, animal materials/wastes, and other solid biofuels" [2].)

Over time, technologies were developed to extract and use high energy density fossil fuels, such as coal and oil. Muscle work and PSBs have been replaced by fossil fuels in most of the world's economy, and energy is more accessible and affordable than ever.

Most countries have transitioned to rely on modern (primarily fossil) fuels to provide the bulk of their energy needs. However, many low and medium Human Development Index (HDI) countries—primarily in Sub-Saharan Africa, South and East Asia, and Central America—still rely heavily on PSBs [3]. (Hereafter low and medium HDI countries are referred to as "lower-HDI countries.") As of 2012, nearly half of the world's population depended on solid fuels for household cooking and heating, with PSBs serving as the main source of energy for approximately 80% those who rely on solid fuels [3].

As shown in Figure 1, a high consumption fraction of PSBs (measured relative to total primary energy supply, TPES) is associated with low HDI; nearly all countries with an HDI less than 0.4 rely on PSBs for more than half of their primary energy supply.

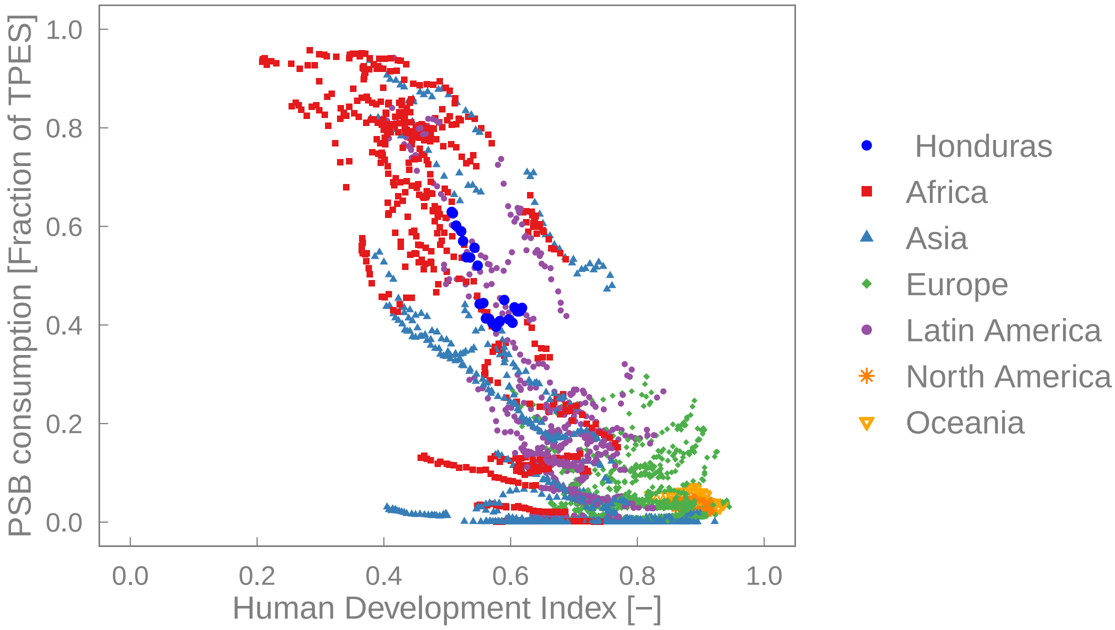

Figure 1. PSBs (as a fraction of the Total Primary Energy Supply, TPES) vs. Human Development Index (1990–2013) [4]. Countries generally move from top-left to bottom-right through time.

1.2. Impacts of Primary Solid Biofuel Consumption

Serious health, energy, environmental, and economic impacts are associated with the consumption of PSBs in residential settings. The following sections examine each impact in turn.

1.2.1. Health

The negative health impacts associated with the use of wood stoves are well documented. As PSBs burn, they release carbon dioxide (CO_2), carbon monoxide, particulate matter, and other hazardous chemicals, such as benzene and hydrocarbons [3]. The chemicals and particulate matter remain in living areas as Household Air Pollution (HAP), causing respiratory infections, pulmonary diseases, high blood pressure, and lung cancer, resulting in an estimated 1.9 million premature deaths worldwide each year [3,5–8]. The greatest risk is borne by already vulnerable populations and those who spend the most time in proximity to PSB burning stoves. Young children and mothers are particularly at risk [9].

1.2.2. Energy Cost

The point-of-use energy efficiency of the traditional wood stove common in lower-HDI countries (~13%) is approximately half that of the improved wood stoves promoted by many groups (~25%). (The efficiency of standard and improved cookstoves was taken from [10,11], then adjusted for Honduras after conversations with researchers at the Zamorano Improved Stove Certification Center (CEEM).) The lower efficiency of a traditional wood stove means that more time must be spent gathering fuel to supply a basic household need (heat for cooking), a task that generally falls to women. With deforestation, the distances to wood sources increase, and even more time must be expended in gathering firewood. Improved wood stoves, Liquid Petroleum Gas (LPG), and electric stoves can provide higher point-of-use efficiencies than traditional stoves.

1.2.3. Environmental Costs

Two main environmental costs are associated with high rates of PSB consumption. First, forest regrowth occurs slowly and, when wood is harvested at rates above the regrowth rate, unsustainable deforestation occurs, increasing rates of soil erosion, destroying natural habitats, and causing loss of biodiversity. In many areas, the rates of consumption of PSBs far outstrip forest regrowth. A 2015 report [12] estimated that, globally, between 27% and 34% of wood fuel harvesting is unsustainable, although, in some regions of Asia and Africa, up to 90% of wood fuels are harvested unsustainably. Second, burning unsustainably harvested wood fuels results in net positive greenhouse gas (GHG) emissions, as more carbon is released by burning than can be reabsorbed through forest regrowth.

1.2.4. Economic Costs

The combined effect of the previous three impacts of PSB consumption can have large economic costs. Hutton et al. [9] found that halving the population without access to modern fuels or improved woodfuel stoves would generate between $90 billion and $105 billion each year in economic benefits globally. Economic benefits arise from reduced healthcare costs and increased productivity gains from improved health, time savings with modern fuels or reduced fuel use, and local and global environmental benefits.

1.3. Interactions between the United Nations Sustainable Development Goals and PSBs

In 2015, the United Nations (UN) adopted the Sustainable Development Goals (SDGs) that the organization hopes to achieve by 2030. The purpose of the SDGs is to "…shift the world on to a sustainable and resilient path" [13]. Among the goals adopted in the 2015 UN Resolution, the four most relevant to PSB consumption are:

- Goal 3: "ensure healthy lives and promote well-being for all at all ages."
- Goal 7: "ensure access to affordable, reliable, sustainable and modern energy for all."
- Goal 12: "ensure sustainable consumption and production patterns."
- Goal 15: "protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss." [13]

Unsustainable PSB consumption works against SDGs 3, 7, 12, and 15. The use of PSBs in the home increases levels of HAP and causes infections and diseases, as discussed in Section 1.2.1. As shown in Sections 1.2.2 and 1.2.3, when rates of PSB consumption are high, consumption patterns become unsustainable, forests are degraded, and the energy supply chain can become unreliable. A reduction in the use of PSBs could slow unsustainable consumption patterns and prevent the health problems that are associated with the use of PSBs, furthering progress on SDGs 3, 7, 12, and 15. Beyond these goals, Batchelor et al. [14] show the beneficial impact of a shift away from traditional fuels could have on SDGs 1 (No Poverty), 2 (Zero Hunger), 4 (Quality Education), 5 (Gender Equality), 8 (Decent Work and Economic Growth), 11 (Sustainable Cities and Communities), and 13 (Climate Action).

1.4. Research Aim and Structure

Clearly, continued widespread residential use of traditional wood stoves (with high rates of PSB consumption) is harmful and unsustainable, but what are the alternatives? Both (a) improved (but still wood-fired) cookstove efficiency and (b) switching to modern fuels (fossil fuels and electricity) have been proposed, but tradeoffs exist. Both improved efficiency and fuel switching are believed to reduce HAP exposure. But, by how much, and what are the tradeoffs between these alternatives?

This paper aims to answer the question: what are the environmental tradeoffs between improved cookstove efficiency and fuel switching for residential cooking in lower-HDI countries? The answer to this question will play a crucial role in whether Honduras and other lower-HDI countries can meet the SDGs discussed in Section 1.3.

Other research has examined the costs and benefits of cookstove interventions in Latin America in general and in Honduras specifically. Flores et al. [15] recently conducted a cost-benefit analysis of an improved efficiency intervention with and without LPG in Honduras from 2016 to 2030. Our paper complements the work of Flores et al. by extending to a wider range of fuel replacements and by considering three key environmental impacts: national level emissions, forest stock depletion, and to a lesser extent, HAP. We use a societal exergy analysis and linked forest stock model to evaluate an improved efficiency scenario and a fuel switching scenario over the period 2013–2050. To our knowledge, this is the first application of societal exergy analysis to the problem of PSB consumption in lower-HDI countries.

The rest of the paper is organized, as follows: Section 2 introduces Honduras as a case study and examines some of its characteristics. Section 3 discusses the analysis methods used to create forecasting models and PSB consumption scenarios for Honduras. Section 4 highlights results from the societal exergy analysis and forecasting scenarios and discusses limitations and suggestions for future work. Section 5 summarizes some of the implications for Honduran society, and, by extension, for neighboring countries.

2. Honduras as a Case Study

2.1. Honduran Primary Solid Biofuel Consumption

Among lower-HDI countries with a deep historic dependence on PSBs, Honduras provides an appealing case study. Honduras demonstrates both (a) the undesirability of PSB consumption for cooking and (b) the tradeoffs that exist between improved efficiency and fuel switching alternatives (The tradeoffs between climate and forest stocks we identified above are not unique to Honduras. E.g., Cameron et al. [16] analyzed economic tradeoffs of cookstoves for South Asia, neglecting forest stocks.)

Honduras remains heavily dependent on PSBs today, as shown in Figure 2. But Honduras is transitioning away from PSBs. In 1971, 63% of the Total Primary Energy Supply (TPES) for Honduras came from PSBs. By 2013, the consumption of PSBs had dropped to 43% of TPES, but was still the single largest fuel source for the country [17].

A 2015 analysis [12] estimated that approximately 46% of Honduran wood fuel harvesting is non-renewable, meaning that for every tree that grows to maturity in Honduras, approximately two are cut down for firewood or building material. The high rate of non-renewable biofuel consumption is contributing to a rate of deforestation of 2.1% annually between 2000 and 2010 [18].

Fossil fuel consumption has displaced some of the PSB consumption in Honduras, but not to the same extent as in other countries. By comparison, El Salvador, another lower-HDI country that borders Honduras, saw the proportion of PSBs in TPES fall from 75% in 1971 to less than 25% as of 2013 [17]. El Salvador accomplished its reduction in PSB consumption in part through subsidies to encourage poor families to switch to liquid petroleum gas (LPG) [19]. As of 2016, 86% of the population in El Salvador relied on modern fuels and technologies for cooking [20]. (The WHO refers to LPG and Electricity as "Clean Fuels and Technologies;" however, the word "clean" implies a reduction in emissions, which may or may not result from a transition to LPG and Electric cookstoves. Therefore, we use the term "modern fuels" to refer to liquid petroleum gas (LPG) and Electricity.)

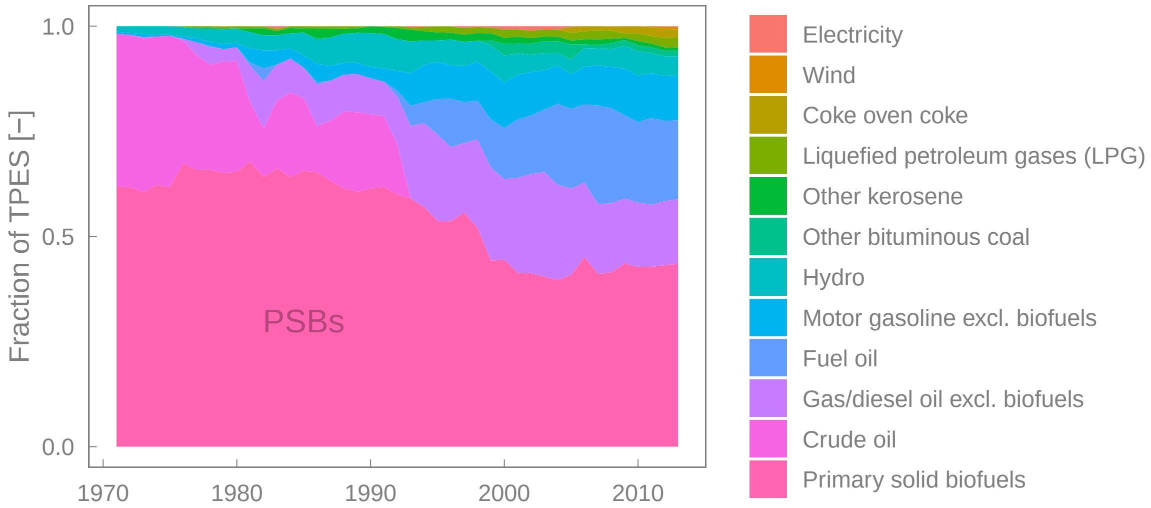

Figure 2. Sources of primary energy for Honduras from 1971 to 2013 [17]. (Electricity is considered to be a primary energy source due to net imports on the interconnected Central American electricity market.)

The detrimental health effects of high levels of PSB consumption outlined in Section 1.2 are clearly evident in Honduras. The World Health Organization (WHO) estimates that, in 2016, the Household Air Pollution (HAP) attributable death rate for Honduras was 25 per 100,000 persons. In contrast, the HAP-attributable death rate in El Salvador was 15 per 100,000 persons (40% lower than Honduras), a difference largely attributable to El Salvador's transition away from PSB consumption for cooking [20]. Public health campaigns in the 1980s led many households in Honduras to install chimneys on their stoves [21], but HAP-attributable death rates have remained high.

Not only does Honduras exhibit the challenges inherent in PSB consumption for cooking, it also faces the difficult decision of how a cookstove transition should be carried out. In their cost-benefit analysis study, Hutton et al. [9] found that a cookstove intervention in the region of the Americas including Honduras would yield a total annual benefit of between $12.3 and $32.2 per person, depending on the type and extent of the intervention. Savings result from reduced health costs, increased productivity (due to improved health), and reduced time spent cooking and gathering and collecting firewood, which outweigh the increased fuel cost and the cost of producing and distributing improved stoves. Similarly, Flores et. al. [15] found that implementing an improved cookstove strategy is significantly cheaper than non-implementation, while the implementation of an improved efficiency strategy with additional LPG is more expensive than non-implementation.

To expand on the cost-benefit analysis, it is valuable to examine the environmental and health impacts, along with the economic. A conversion to more efficient woodstoves could result in cost savings while reducing forest degradation and GHG emissions; but, given economic and population trends, how much would efficiency improvements actually help? Alternatively, an intervention to swap PSB cookstoves for modern fuel (such as LPG or electricity) cookstoves would reduce forest degradation, but may result in an increase in GHG emissions through the distribution, consumption, and generation of modern fuels.

2.2. Residential Cooking in Honduras

Despite trends towards better stoves, the majority of Hondurans still use a traditional wood stove similar to the one shown in Figure 3a. However, high-efficiency cookstoves, such as the one shown in Figure 3b, have been promoted by many groups, including the World Bank, the UN, and the Clean Cooking Alliance (CCA, formerly the Global Alliance for Clean Cookstoves). The Honduran government, together with various non-governmental organizations and neighboring countries, is choosing the improved efficiency (IE) alternative, investing millions of dollars to procure and install high-efficiency cookstoves throughout the country [22]. Improved cookstoves use chimneys, better insulation, and modern designs to provide better burning characteristics when compared to traditional stoves. Improved cookstoves achieve more-complete combustion of PSBs and reduce household air pollution and particulate matter emissions, as illustrated in Figure 4b [23].

(**a**) Traditional Wood Stove (**b**) Improved Wood Stove

Figure 3. Traditional-style stove commonly used in Honduras, in comparison with the Improved cookstove model (Ecofogon) being distributed by the Honduran government. Pictures taken by author N.V.B. at the Improved Cookstove Evaluation Center (CEEM) at the University of Zamorano, Honduras.

In the Honduran Nationally Appropriate Mitigation Actions (NAMAs) published in November of 2015, the Honduran government established the goal of installing 1.125 million improved stoves by 2030. [24]. However, the reduced primary energy demand of improved cookstoves (resulting from increased efficiency) does not ensure adoption. In a 2011 survey, 77% of traditional stove users in Honduras indicated that they would like an improved stove, while 46% of users who already had an improved stove indicated that they would like a better one due to issues with reliability, maintenance, or lack of use [21]. Many people with improved stoves ultimately return to a traditional stove due to better perceived performance or unfamiliarity with new technology, which indicates a lack of satisfaction with improved cookstoves technology. In Honduras, approximately one in five recipients of improved stoves do not use the new technology [15]. In addition, field measurements of point-of-use emissions of improved stoves indicate that particulate matter reductions may be lower than laboratory tests would suggest [6]. Finally, improved cookstoves may ultimately do nothing more than delay the inevitable; although the higher efficiency may temporarily reduce demand for PSBs, the growing population and economy (and associated increase in energy consumption) could eventually overwhelm any gains from higher efficiency, leading to a return to unsustainable consumption patterns.

A second alternative to traditional wood stoves, the use of either Liquid Petroleum Gas (LPG) or electric stoves (modern fuel sources), should also be considered. A transition away from PSB and toward modern fuels could completely reduce unsustainable biofuel consumption and decrease energy consumption and particulate matter emissions by increasing cooking efficiency, albeit at the expense of replacing PSBs with other unsustainable fuels (e.g., LPG and diesel).

To accurately compare various stove types used in Honduras, the energy flows from initial (primary) fuel source to the desired (useful) heat output must be well understood. Sankey diagrams can be used to illustrate energy flows, using lines whose widths are proportional to the magnitude of the energy flow. Figure 4a shows the efficiency of heat production from a traditional wood stove common in Honduras. Figure 4b–d show example Sankey diagrams for improved wood stoves (e.g., Ecofogones), LPG stoves, and Electric stoves, respectively.

(**a**) Traditional Wood Stove (**b**) Improved Wood Stove

(**c**) LPG Stove (**d**) Electric Stove

Figure 4. Sankey Diagram for a traditional wood stove and three higher efficiency alternatives. (**a**) shows the efficiency of heat production from a traditional wood stove common in Honduras, while (**b**–**d**) show the efficiency of improved wood stoves (e.g., Ecofogones), LPG stoves, and Electric stoves, respectively.

3. Methods and Data

This section describes two aspects of our analysis: historical analysis and future analysis. For the historical analysis, Section 3.1.1 summarizes the method used to conduct a complete societal exergy analysis for Honduras, including the residential sector, which is the focus of this study. Section 3.1.2 details how final energy carriers in the residential sector were allocated to useful energy products. Subsequently, Sections 3.2.1–3.2.4 outline the methods used to forecast useful energy consumption from 2013 to 2050, fuel production efficiencies, primary and final energy requirements, and CO_2 emissions, respectively, for three scenarios: Current Technology (CT), Improved Efficiency (IE), and Fuel Switching (FS).

3.1. Historical Analysis

A historical analysis of the Honduran energy sector was first conducted to provide a base for forecasting future scenarios. The historical analysis used Societal Exergy Analysis methods to allocate primary and final energy to end uses to calculate useful energy supplied to the Honduran economy.

3.1.1. Societal Exergy Analysis in Honduran Residential Sector

A comprehensive analysis approach that accounts for the entire Energy Conversion Chain (ECC) is needed to study the energy and emissions trade-offs of different cooking fuels. Societal Exergy Analysis is a tool that aids in the analysis of the ECC from primary to useful forms of exergy [25–27]. Exergy is "the maximum amount of *work* that a subsystem can do on its surroundings as it approaches thermodynamic equilibrium reversibly" [28]. In any transformation process, energy is conserved but exergy is destroyed through the generation of entropy. An analysis that is based on exergy accounts more fully for the value of energy, since it is exergy, as the capacity to do work, which provides energy services and drives economic activity [29].

We studied energy and exergy in the Honduran residential sector at three stages: (a) Primary, the initial energy carrier (e.g., wood, oil, natural gas); (b) Final, energy sold to consumers (e.g., charcoal, electricity); and (c) Useful, the energy carrier which is ultimately used for some purpose (e.g., heat for cooking). The distinctions among Primary, Final, and Useful stages allows for rigorous analysis by including both what the end user actually wants (heat for cooking) and how they get it (electricity, wood, or natural gas). The distinction between energy and exergy further allows for an analysis of the usable part of each energy flow while excluding the portion of the energy that will be wasted due to thermodynamic losses. The efficiency with which Primary energy is converted into Useful Exergy (thermodynamic efficiency) has been shown to be a key driver in economic growth [30].

A societal exergy analysis of the Honduran economy was conducted using methods outlined in recent papers by Heun et al. [25,26]. The analysis relies on primary and final energy data from the International Energy Agency (IEA) Extended Energy Balances [17], the UN Food and Agriculture Organization [31], and national censuses [32]. The IEA provides primary and final energy data by sector and fuel for more than 100 countries. Data by fuel and sector are available for Honduras starting in 1971. We focused further analysis on the residential sector and energy/exergy needs for cooking.

3.1.2. Allocation of Residential Final Energy to End Uses

Detailed analysis was conducted on the energy flows in the Residential sector. Figure 5 shows final energy carriers in the residential sector of Honduras from 1971 to 2013. Five final energy carriers are consumed in the residential Sector: kerosene, charcoal, Liquefied Petroleum Gas (LPG), electricity, and primary solid biofuels. Although electricity has provided a growing portion of the final energy for the residential sector(9.3% in 2013, up from 1.3% in 1971), the vast majority of the final energy in the residential sector in Honduras is still supplied by PSBs.

Because of its geographic location, the average monthly temperature in Honduras ranges from 22 °C to 25 °C [33]. Therefore, use of PSBs, charcoal, and LPG for domestic heating is largely unnecessary and, for the purpose of this analysis, is assumed negligible. The useful energy product from PSB consumption was assumed to be medium temperature heat (MTH, 100 °C) for home cooking.

Kerosene and electricity, on the other hand, can be used to produce more than one useful energy product. Kerosene is used for cooking, but, in some areas, is also used for lighting. Based on data from Heltberg [34], the Honduran Central Bank [32], and the personal experience of and interviews by authors N.V.B. and E.V., on average 77% of kerosene was estimated to be used for cooking, with the remaining 23% used for lighting. (The exact distribution depends on the year in question. Kerosene consumption for lighting is higher in rural areas, which are less likely to be electrified. As the rural population moved to urban centers, the ratio of consumption for lighting and cooking ranged from 30%/70% in 1971 to 20%/80% in 2013.)

Residential electricity was assumed to have six uses: refrigeration/air conditioning, electric stoves, water heaters, electric lights, televisions, and electric motors. Although electricity might be used for other purposes, all other uses were assumed to fit under one of the six principal uses. The allocation of energy use was calculated from Drigo et al. [35], Flores [36], and national censuses and surveys to predict trends in electricity use [32]. Although the exact distribution changes over the period studied, on average, 29% of electricity consumption was estimated for electric stoves, while 24%, 17%, 19%, 8%, and 2% was consumed for refrigeration/air conditioning, water heaters, electric lights, televisions, and electric motors, respectively.

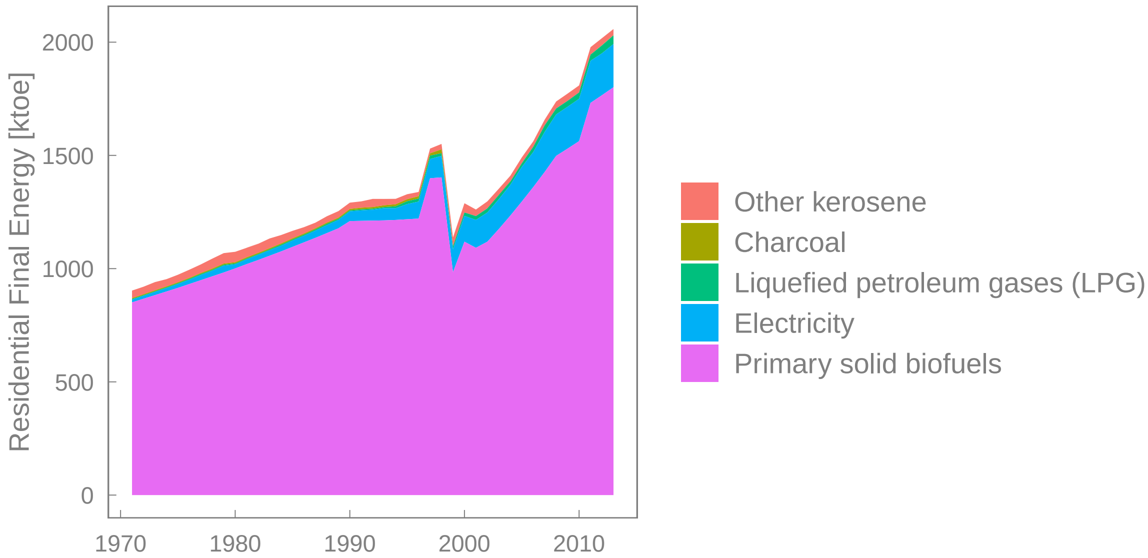

Figure 5. Final energy carriers for the Honduran residential sector (1971–2013) [17]. The discontinuity between 1998 and 1999 is attributed the impact of Hurricane Mitch and a change in energy accounting methods.

Finally, the portion of energy used for residential cooking with each of the different final-stage fuels was calculated using the percentages that are shown above, and the useful energy production was calculated using the final-to-useful energy efficiency of each of the stove types shown in Table 1.

Table 1. Primary-to-Final and Final-to-useful efficiency of traditional and improved PSB, charcoal, kerosene, LPG, and electric stoves.

Stove Type	Primary to Final (Production) Energy Efficiency	Final-to-Useful (Stove) Energy Efficiency
Charcoal	30.7% [17]	18% [37]
Kerosene	93.7% [1]	37.8% [38]
LPG	93.7%	45% [37]
Electric	∼58.5% [2]	70% [3]
Traditional PSB	100% [4]	13% [5]
Improved PSB	100%	21% (2013) to 25% (assumed 2050) [5]

[1] The efficiency of kerosene production is assumed to be roughly equal to that of LPG. Given the low quantity of kerosene used for residential cooking, the results are not highly sensitive to this value. [2] Efficiency of electricity production taken from IEA Extended Energy Balances [17]. Efficiency varies year over year, namely with hydroelectricity (100% efficiency by the Physical Content Method [39]). [3] From [40] and [41], adjusted for Honduras. [4] Energy expended in cutting and gathering PSBs is neglected; therefore, the primary and final energy content of the fuel is the same, because there is no transformation process occurring for PSBs. [5] The efficiency from [10] was used as a starting point and adjusted for Honduras after conversations with researchers at the Zamorano Improved Stove Certification Center (CEEM). Stove efficiency from the Zamorano CEEM mirrors efficiencies reported in a 2017 study of Ghana by Obeng et al. [11].

3.2. Energy Forecast

The societal exergy analysis that is described in Section 3.1.2 provides an estimate for the total useful energy used for residential cooking in Honduras each year from 1971 to 2013. The resulting useful energy requirement is the quantity of useful energy (as heat) that must be delivered to the economy to meet the nutritional needs of the population. By estimating the useful energy that will be required each year, it is possible to work upstream in the ECC to find the final and primary energy production required to deliver the useful energy that is demanded for cooking, as seen in Heun et al. [26]. Emissions, air pollution, and resource consumption are a function of the primary fuel type and the cookstove technology used to deliver the required useful energy.

Future energy consumption and emissions were forecast by (a) forecasting useful energy used in residential cooking from 2014 to 2050, (b) estimating fuel production efficiency for the five fuels in use in the residential cooking sector, (c) calculating primary and final energy requirements, and (d) calculating resulting CO_2 emissions from 2014 to 2050.

Three scenarios were evaluated for the purpose of this analysis: (a) a Current Technology (CT) scenario, where the proportions of the population cooking with PSBs, electricity, charcoal, kerosene, and LPG remains roughly constant into the future, with no change in stove efficiency; (b) an Improved Efficiency (IE) scenario, where all traditional stoves are gradually replaced with improved stoves, but the proportion of people using each fuel type stay at 2013 levels; and (c) a Fuel Switching (FS) scenario, in which PSBs are replaced by electricity and LPG.

3.2.1. Forecasting Useful Energy Consumption

The demand for cooking heat (useful energy) in Honduras was forecast from 2014 to 2050 using an exponential model, given in Equation (1):

$$U_t = A\mathrm{e}^{B(t-t_0)} \, , \tag{1}$$

where U_t is the useful energy at year t, and t_0 is the first year of the model fit. The values of A and B were found by the method of least squares by fitting to historical data while using the Generalized Reduced Gradient (GRG) non-linear optimization with the Excel Solver Add-On [42].

Three different fit types were generated from the historical data: a direct fit, a per capita fit, and a per GDP fit. The three fit types model an increase in energy consumption proportional to past trends, population growth, and economic growth, respectively. For the direct fit, the useful energy trend of the economy is fitted beginning in either 1971 or 1999 (direct 43-year and direct 14-year, respectively), due to the 1998 discontinuity, which altered the characteristics of the trend. The discontinuity is attributed in part to Hurricane Mitch and partially to changes in energy accounting methods that occurred over that period. (Mitch struck Honduras in 1998. In Honduras alone, it killed more than 5,500 and affected 1.5 million people [43].)

For the per capita fit, the per capita useful energy consumption (ktoe/person) was calculated from 1971 to 2013 using UN population data [44]. The per capita useful energy consumption pattern was convex, with an inflection point in 1999, possibly due to changes in the energy sector after hurricane Mitch and energy efficiency improvement programs that began in 1997 and 1998 [36]. To fit the most recent trends, the model fit begins after 1999. The model was then multiplied by the Honduran population forecast from the UN Population Prospects from 2013 to 2050 [44] to yield a total useful energy forecast.

The per GDP model was created by first forecasting the Honduran GDP from 2013 to 2050 based on historical output side GDP (GDPo) from the Penn World Tables [45,46]. The useful energy intensity (ktoe/USD) was calculated for each year from 1971 to 2013 and fit with Equation (1).

3.2.2. Fuel Production Efficiency

The efficiency of production of each of the five fuels under consideration was calculated based on historical data from the IEA and other sources. The primary-to-final efficiency of LPG production was calculated to be approximately 93.7%. (The Energy Return on Energy Invested (EROI) for LPG is approximately 15 [47]. The efficiency of LPG production is therefore $1/(1 + EROI) = 0.937$.) The efficiency of kerosene production was assumed to be equal to that of LPG, due to the small portion of kerosene cooking relative to overall energy consumption (<6% across all years studied). (The sensitivity of the model to the assumed value of primary-to-final efficiency of kerosene production is low.) Charcoal consists of PSBs that are collected and transformed to increase the energy density. The efficiency of the PSB-to-charcoal conversion in Honduras was taken from primary-to-final conversion efficiency reported in the IEA data from 1971 to 2013 [17]. The aggregate primary-to-final conversion efficiency of electricity is comprised of the weighted efficiency of converting the six primary energy sources (fuel oil, gas/diesel oil excl. biofuels, hydroelectric, primary solid biofuels, other bituminous coal, and wind) to electricity. Although included as a source of electricity, at their peak in 2012 PSBs accounted for just over 7% of the primary energy used to produce electricity, and PSB use for the production of electricity accounts for less than 3% of total PSB consumption.

The primary-to-final efficiency of electricity production in Honduras (by the IEA's Physical Content Method, PCM) varies from year to year and it is particularly dependent upon the quantity of hydroelectricity generated. However, between 1995 and 2013, the primary-to-final efficiency of electricity production remained centered around 58.5%, with a standard deviation of 6.6% [17]. The historical and projected primary-to-final efficiency for electricity is shown in Figure 6.

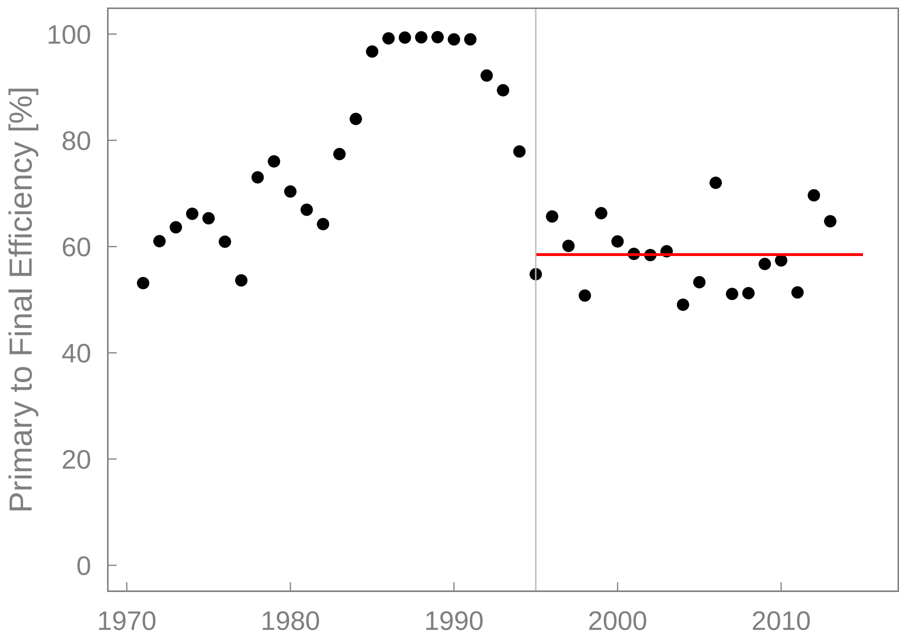

Figure 6. Primary-to-final efficiency for Electricity production in Honduras from 1971 to 2013. A horizontal line at 58.5% indicates the average efficiency from 1995 to 2013, which was assumed to be the primary-to-final efficiency of electricity production from 2013 to 2050.

Total primary energy consumption was calculated from the predicted final energy consumption and the primary-to-final conversion efficiency shown in Table 1.

3.2.3. Predicting Primary and Final Energy

Three energy consumption scenarios were forecast by the useful energy models in Section 3.2.1 and the efficiency of stoves and fuel production from Table 1 and Section 3.2.2.

Current Technology (CT)

The final energy demands for each year from 2014 to 2050 for the CT scenario were estimated by extending the consumption distribution (the relative portion of the population using charcoal, kerosene, LPG, PSB, and electricity) from the 2000–2013 time period out to 2050. The resulting useful energy for each of the five fuels was then converted to a final energy requirement while using the final-to-useful efficiency of the respective stove type. Primary energy consumption was calculated using primary-to-final efficiencies for each fuel.

Improved Efficiency (IE)

The improved efficiency scenario, the option being pursued by the Honduran government, replaces the current PSB cookstoves with improved cookstoves with higher final-to-useful efficiencies. The efficiency of improved cookstoves was 21% in 2013. We assumed an increase to 25% by 2050 due to technology improvements. The Current Technologies model was modified by linearly increasing the aggregate final-to-useful efficiency of PSB cookstoves, assuming complete adoption of improved cookstoves by 2050, to forecast the transition to improved stoves (i.e., by 2050, every household using PSBs for cooking will be using an improved cookstove). Because we are swimming upstream in the energy conversion chain, from useful to primary energy, the adoption of higher efficiency cookstoves does not affect the contribution of PSBs to total useful energy consumption; rather, it affects the primary and final energy consumption of PSB-burning cookstoves, without impacting primary and final energy consumption for other types of cookstoves.

Fuel Switching (FS)

Finally, in the FS scenario, PSB cookstoves are replaced with electric and LPG stoves, reaching 100% modern fuel usage by 2050. To model this transition, the useful energy output of PSBs as a percentage of total useful energy was linearly decreased from the level in 2013 (79%) to 0% in 2050. No energy was allocated to kerosene or charcoal, as their use was already negligible in 2013 (3% and 0.06% of final energy used for cooking, respectively). The useful energy output of LPG and Electric cookstoves was calculated based on Equation (2), as shown below for LPG:

$$U_{LPG} = (U_t - U_{PSB}) \frac{y_{LPG}}{y_{LPG} + y_{Elect}} , \tag{2}$$

where U_t is the aggregate useful energy for cooking in a given year, and subscripts denote the LPG or electric sector. The y values are the ratios of useful heat supplied to cooking from LPG and electricity as final energy carriers, which begin at 15% and 8%, respectively, in 2013 and increase linearly to 2050. The sensitivity of the forecast to the fuel (electric or LPG) was evaluated by forecasting a conversion to 100% electric in one instance and 100% LPG in the other. Primary and final energy consumption were calculated with the same primary-to-final and final-to-useful efficiencies shown in Table 1.

3.2.4. Forecasting CO_2 Emissions

Each scenario (CT, FS, and IE) will exhibit different CO_2 emissions characteristics. This section describes the methods used to forecast CO_2 emissions under each scenario.

The emissions calculations follow a modified version of the Greenhouse Gas Protocol for Cities from the World Resources Institute (WRI) [48]. In accordance with the protocol, emissions were calculated for three "scopes." Scope 1 includes point-of-use emissions from on-site burning of fuels. Scope 1 emissions from domestic cooking contribute to HAP and often have negative health effects.

Scope 2 emissions are direct emissions associated with the production of electricity, e.g. burning diesel to generate electric power. Finally, Scope 3 emissions are net indirect emissions, such as emissions associated with transportation of fuels, the construction of power plants, and re-absorption of carbon into forests. Note that Scope 3 emissions can be negative if the re-absorption of carbon by forests exceeds other Scope 3 emissions. Furthermore, and relevant to PSB consumption, deforestation appears as a net increase in Scope 3 emissions, while afforestation can provide a decrease in Scope 3 emissions. Total emissions are the sum of Scope 1, 2, and 3 emissions.

Scope 1 emissions were calculated for PSB, LPG, kerosene, and charcoal stoves. Due to a lack of information available for Honduras, emission factors (in units of metric tons of CO_2 per ktoe) were obtained from a 1999 study of CO_2 emissions factors in India [49].

Scope 2 emissions were calculated by estimating time series emissions factors for the Honduran electricity sector from 1971 to 2013, as shown in Figure 7. The emission factor for electricity is dependent on the fuel makeup of the electric sector. Fuel-specific emission factors from the IEA [17] and the Intergovernmental Panel on Climate Change (IPCC) Greenhouse Gas Emission Guidelines [50] were used to calculate the aggregate annual electric emission factor for each year in the period. Scope 2 emissions approached zero from 1986 to 1991, when hydro supplied most (if not all) of Honduran electricity. The Scope 2 emission factor then trended upward until 2000 and has remained relatively stable at approximately 3942 MT of CO_2 emissions per ktoe of electricity produced. The trend from 2000 to 2013 was linearly extended to 2050. With the development of renewable energy sources in Honduras, the CO_2 intensity of the Honduran electric sector has the potential to decrease beneath the linearly-extended trend. If a decrease were to occur, net CO_2 emissions will be lower than that predicted by our model for electric cookstoves.

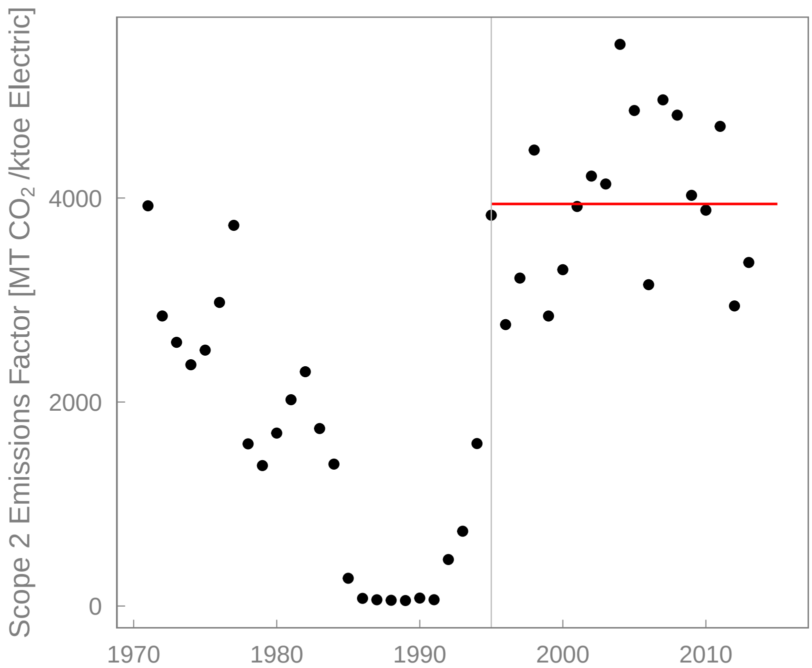

Figure 7. CO_2 emissions associated with electricity generation in Honduras from 1971 to 2013. Horizontal line at 3942 MT CO_2/ktoe of electricity indicates the average efficiency from 1995 to 2013, which was assumed to be the primary-to-final efficiency of electricity production from 2013 to 2050.

Scope 3 emissions for kerosene, LPG, and charcoal were taken from [51,52], and they are shown in the third column of Table 2. Indirect emissions factors for electricity were taken from a 2011 World Nuclear Association study [52] and used to create a Scope 3 emission time series for the electricity sector, while taking into account indirect emissions associated with the production of electricity, such as construction and maintenance of plants and fuel transportation and storage.

Finally, Scope 3 emissions for PSBs were calculated using the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Tier 1 analysis of Carbon Stocks [50]. The Scope 3 emissions for PSBs take into account the carbon that is absorbed into woody biomass by the forests. The quantity of carbon absorbed is dependent on the total forest area, which is, in turn, dependent on rates of forest regrowth. The IPCC Tier 1 analysis provides base level analysis of changes to carbon stocks while using average values of forest regrowth, energy content, and emissions factors in tropical forests [50].

Forest stocks for Honduras (in hectares) from 1990 to 2015 were taken from the FAO forest database [53] and converted to mass based on average forest density from an analysis of Honduran forests [54]. Forest regrowth was estimated to be 3.1 tons/ha-yr from Table 4.9 in the 2006 IPCC report [50]. The FAO stocks data provided information on total fuel wood removal, while the societal exergy analysis (Section 3.1.1) was used to estimate the fraction of total consumption for fuelwood or non-fuelwood uses.

Table 2. Scope 1, 2, and 3 Emissions Factors for Kerosene, LPG, PSB, Fuel Oil, Gas/Diesel, Hydroelectric, Coal, Wind, and Electricity (Average).

Energy Source	Scope 1 MT CO_2/ktoe	Scope 2 MT CO_2/ktoe	Scope 3 MT CO_2/ktoe
Kerosene	3154	0	2650
LPG	2704	0	3100
PSB	3977	0	Varies [1]
Electricity: Fuel Oil	0	3240	5284
Electricity: Gas/Diesel	0	3100	5424
Electricity: Hydroelectric	0	0	302
Electricity: Coal	0	3960	6367
Electricity: Wind	0	0	302
Electricity: Average	0	2590	4531

[1] Scope 3 emissions for PSBs are a function of the consumption rate and forest regrowth. As fuel wood consumption reduces forest stocks, the re-absorption of carbon into forests is affected, which alters the scope 3 emissions factor.

Trends in non-fuelwood uses of forests were assumed to continue from 2013 to 2050, while fuelwood uses of forests (for PSBs) were predicted by the PSB consumption models that are described above. The annual stocks, regrowth, and consumption could then be calculated and were used to estimate net emissions after regrowth and re-absorption were taken into account. For Scope 3 emissions, only fuelwood-associated emissions were taken into account by weighting the overall emissions by fuelwood consumption as a fraction of total wood consumption.

4. Results and Discussion

We applied the methods outlined to the Honduran Economy from 1971 to 2013 and projected energy consumption for residential cooking to 2050. The results are provided below, as they apply to (a) useful energy demand, (b) primary energy consumption, (c) forest stocks, and (d) CO_2 emissions. Detailed results can be found in Supplementary Materials [55].

4.1. Useful Energy Model

Figure 8 shows the four useful energy models generated in Section 3.2.1. The direct 43-year model shows the slowest growth over the time period studied (2% annually). The slow growth rate is likely due to the discrepancies in energy accounting prior to 1999. The per capita useful energy consumption model most rapidly increases from 2014 to 2040, with a declining rate of increase by 2050. Finally, the 14-year GDP and 14-year direct model rise in near lockstep from 2013 to 2050, at a rate of approximately 4.6% per year. The Direct 14-Year model was chosen for analysis, as this model agreed with the GDP projection and was reasonably close to the projections from the per Capita model. This model gives a useful energy projection of 1587 ktoe in 2050 and it was used as the basis for the primary energy projections.

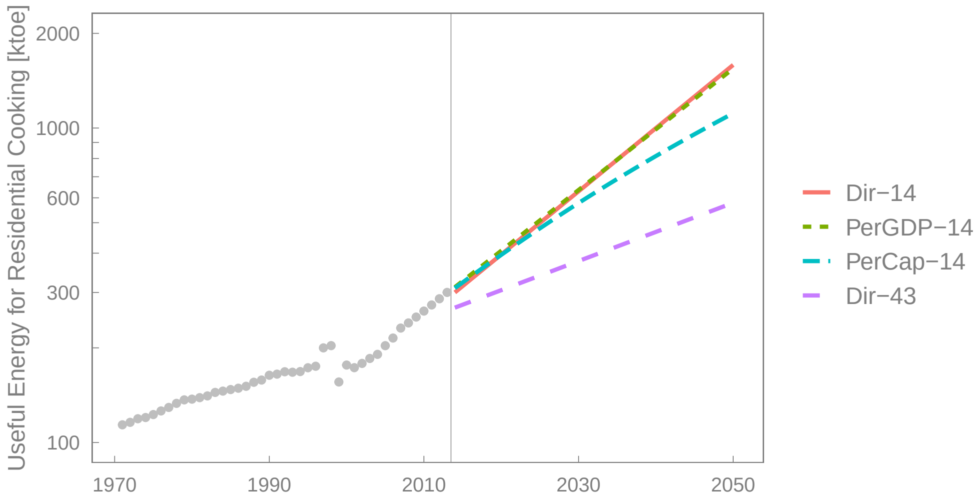

Figure 8. Four Models of Useful Energy for Residential Cooking in Honduras

4.2. *Primary Energy Consumption from Residential Cooking*

The primary energy needs for residential cooking in Honduras can be expected to significantly increase from 2013 to 2050, as shown in Figure 9. First, under the Current Technologies (CT) scenario, primary energy consumption would surpass 10,000 ktoe (92% from wood), more than a five-fold increase from 2013. The Improved Efficiency (IE) scenario fares somewhat better, with a three-fold increase in primary energy to just under 6,000 ktoe (90% from wood). The two Fuel Switching (FS) scenarios have much higher efficiencies, which translate to a primary energy demand in 2050 of about 3800 ktoe, being roughly double that of 2013.

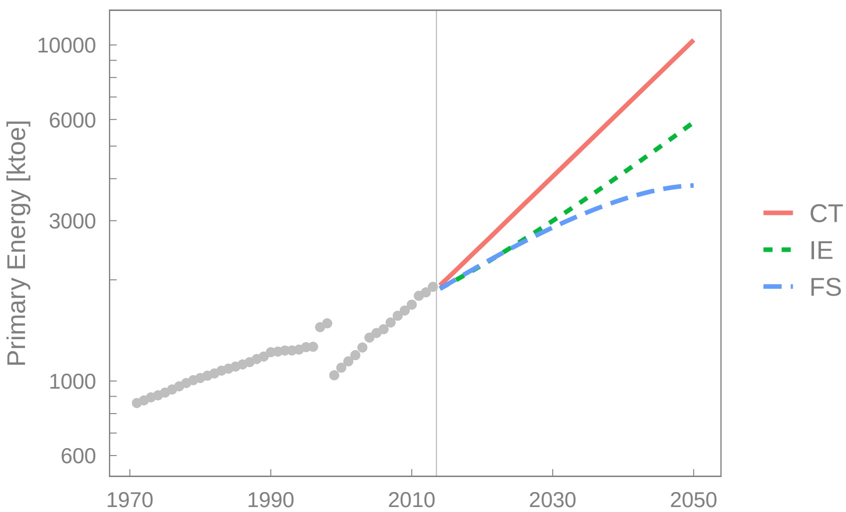

Figure 9. Primary Energy projections under the Current Technologies (CT), Fuel Switching (FS), and Improved Efficiency (IE) Scenarios. Vertical axis shown as logarithmic. Straight lines indicate exponential growth.

4.3. Reduction in Forest Stocks

In the year in which forest stocks are exhausted under the CT or IE scenarios, fuelwood demand will reach approximately 250,000 acres per year. (The energy content per acre of forest is taken from [1], which indicates both the energy content of wood and the mass of dry wood per acre of forest. The energy content of wood per acre is roughly 2,000,000 MJ/acre (0.048 ktoe/acre).) The high rate of deforestation under the CT and IE scenarios would remove all forests in Honduras by 2037 under CT and by 2048 under IE, as shown in Figure 10.

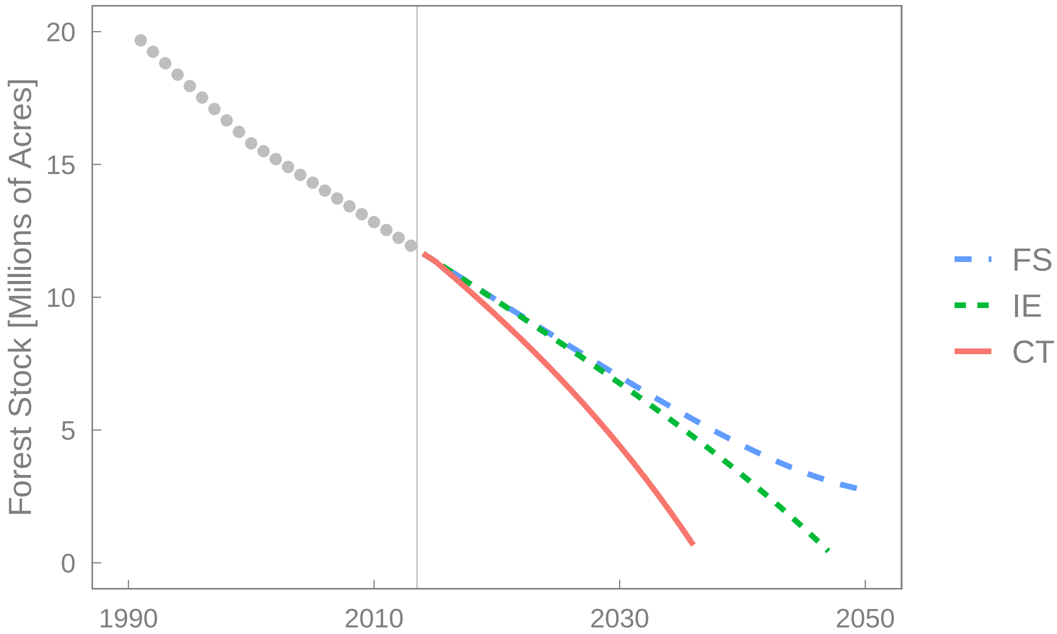

Figure 10. Forest stocks from 1990 to 2050 under the CT, IE, and FS scenarios

The projection that forests stocks would disappear does not account for an increase in the cost of PSBs, an inevitable effect of increased scarcity. Increasing PSB prices would force a reduction in non-fuelwood forest use and a transition to other cookstove technologies, such as LPG and electric. Nonetheless, a dramatic reduction in forest area is alarming and highlights the severity of the problem facing Honduras.

The Fuel Switching (FS) scenario is clearly better than Improved Efficiency (IE) as far as forest stocks are concerned. Although the cost of increased LPG or electric usage might be initially higher than CT [15], the long term benefits in health improvements and forest preservation may eventually outweigh these costs. In addition, we must consider the other dimension of the PSB tradeoff, CO_2 emissions.

4.4. CO_2 Emissions

Figure 11 shows CO_2 emissions related to domestic cooking for all three scenarios (CT, FS, and IE), for all three Scopes (1, 2, and 3), and for total emissions.

The Current Technologies (CT) scenario entails a dramatic increase in greenhouse gas emissions from domestic cooking in the next 30 years. By 2030, the total carbon dioxide (CO_2) emissions will have increased by a factor of 3.7. By 2050, they will have increased by a factor of 18. Although the Scope 3 emissions begin negative due to re-absorption into forests, over time increased demand for PSBs increases direct emissions (Scope 1) and indirect emissions (Scope 3), because deforestation decreases the rate of CO_2 re-absorption. The combined effect of Scope 1 and Scope 3 emissions leads to a rapid increase in net CO_2 emissions. The increased emissions from domestic cooking under the

CT scenario will not only exacerbate climate change concerns, but will also increase HAP levels and respiratory disease.

By 2050, the distribution of improved cookstoves under the Improved Efficiency (IE) scenario would reduce CO_2 emissions from cooking by 58% relative to business as usual (Figure 11). Even so, if all traditional wood stoves were replaced by improved efficiency stoves, CO_2 emissions would increase eight-fold from 2013 to 2050, a dramatic increase relative to today.

Finally, under the Fuel Switching (FS) scenario, if wood-burning stoves were gradually replaced by LPG stoves and/or electric stoves, by 2050 the total CO_2 emissions from cooking would be between seven and 12 times higher than 2013 levels. Under the Fuel Switching (FS) scenario, Scope 1 (point-of-use) emissions are quickly curbed to well below CT Scope 1 emissions. However, Scope 3 emissions quickly rise above 0, but by reducing rates of deforestation Scope 3 emissions increase at a slower rate than the CT scenario.

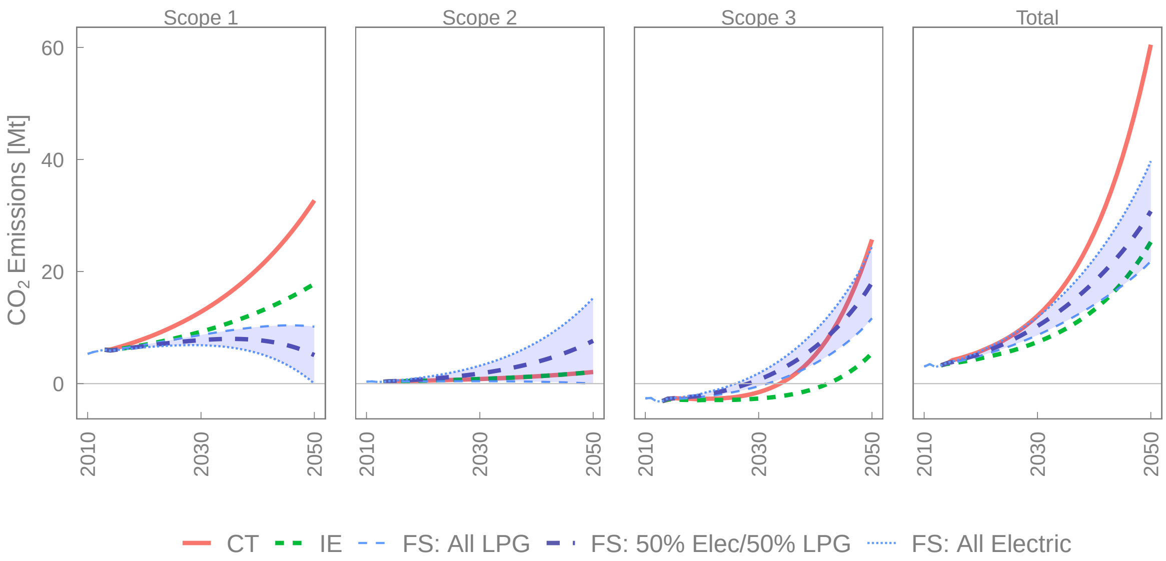

Figure 11. Scope 1, 2, 3, and Total emissions for three Scenarios of PSB Consumption in the Honduran Residential Cooking Sector. The shaded region represents the range of emissions for Fuel Switching between all electric and all LPG.

4.5. Limitations and Future Work

The model represented above has several limitations. First, the model is based on the data available for Honduras, supplemented with other data sources from similar countries where possible. In addition, the model does not account for the increased cost of fuelwood as forest stocks deplete. The increasing fuelwood price would naturally drive a transition to modern fuels. Therefore, we direct the attention of the reader to the model trajectory rather than the destination point. Finally, the model assumes a linear transition in stove types. The adoption of new stove types would likely follow an s-shaped technology adoption curve, with late adopters in remote areas without access to electricity or LPG lagging behind the remainder of the population.

Future work in this area could include: (a) analyzing other countries with high non-renewable biofuel consumption rates, such as Guatemala, Bangladesh, the Dominican Republic, and Haiti [12]; (b) determining Honduras-specific emissions factors for PSB, LPG, kerosene, and charcoal stoves (Section 3.2.4); (c) adopting a model for renewable electricity adoption in Honduras to project the emissions factor for electricity into the future (Section 3.2.4); (d) developing a "forest depletion fuel switching" scenario in which deforestation increases the cost for harvesting PSBs, leading to high fuelwood prices and economically-motivated fuel substitution away from PSBs; and, (e) adopting a Tier 2 or Tier 3 (localized) model of carbon stocks for forecasting Scope 3 emissions from PSB consumption.

5. Conclusions

Despite most countries relying heavily on modern fuels for the bulk of their energy needs, Primary solid biofuels still supply a significant portion of residential energy use. High levels of residential biofuel consumption can have serious health, energy, environmental, and economic impacts.

In combination, the societal exergy analysis and forest stock model outlined in Section 3 enable the quantification of the environmental impacts of remaining at the high PSB Current Technology (CT) scenario, versus transitioning to the Improved Efficiency (IE) and Fuel Switching (FS) scenarios, as shown in Section 4.

We confirm that the current path of the country, as shown in the Current Technologies (CT) scenario, is damaging to both the national and global ecosystem. The CT scenario projects more than a five-fold increase in fuelwood consumption and an 18-fold increase in national-level GHG emissions between 2013 and 2050.

Although the IE scenario might offer cost savings over CT, forecasting consumption to 2050 highlights the precarious position of Honduran forest stocks, which are depleted under either high-PSB scenario. We see that both alternative scenarios (improved efficiency, IE, and fuel switching, FS) offer improvements over the CT scenario, but each also has associated costs.

The IE scenario yields a 30 to 40% decrease in fuelwood consumption (prior to the exhaustion of forest stocks), and a 50 to 60% reduction in the national level emissions. However, rates of deforestation and fuelwood consumption are still high, such that forest stock exhaustion is delayed only by approximately a decade. In addition, improved cookstoves would do little to address the high rates of pulmonary disease and HAP-attributable deaths, especially among women and children.

The FS scenario, on the other hand, would both reduce rates of deforestation and all but eliminate HAP, reducing deaths that are associated with residential cooking, as occurred in El Salvador. However, relative to the IE scenario, a transition to modern fuels via the (50% LPG / 50% Electric) FS Scenario would cause higher overall GHG emissions at the national level, with associated global environmental impacts. A switch to 100% electricity would reduce rates of household air pollution, but, unless the country invests further in renewable electricity, the switch would do little to reduce overall GHG emissions. Conversely, a transition to LPG would decrease national-level GHG emissions, but would make the country more dependent on imported fossil fuels.

The Honduran government has not incentivized a transition to stoves that use modern fuels. Instead, the government has decided to focus on the IE scenario, investing millions into the construction and distribution of improved efficiency wood stoves, with little to no funding for fuel switching. In 2014, the government began to manufacture and distribute thousands of improved cookstoves, known as Ecofogones, and agreed to invest $20 million in improved cookstoves [22,56]. Personal experience and interviews by authors N.V.B. and E.V. show increasing interest in LPG and electric stoves in Honduras. However, many households, including those who received improved cookstoves, continue to use traditional stoves (including one case in which the traditional stove was built on top of an improved stove). The lack of adoption of improved cookstoves is due, in part, to the additional work that is needed to prepare woody biomass prior to burning, lack of training in operating and maintaining improved stoves, and a personal preference for traditional stoves.

The transition away from traditional wood stoves for cooking will occur in Honduras, as it has in many other countries. The forest stocks are being quickly depleted, causing irreversible damage to the natural environment. The Honduran government faces an ever more pressing dilemma between continuing to incentivize a transition to improved efficiency wood stoves (with a reduction in GHG emissions) or supporting modern fuel stoves (with a reduction in rates of deforestation).

Neither scenario is ideal and, although both result in a reduction of residential PSB consumption with associated health benefits, our analysis reveals a tradeoff between forest stock and climate.

The only pathway that might successfully address all three impacts (HAP, GHG emissions, and deforestation) is a rapid switch to electric stoves with a significant investment in renewable-based electricity to reduce emissions.

Supplementary Materials: The following are available online at http://www.mdpi.com/1996-1073/13/12/3206/s1.

Author Contributions: Conceptualization, N.V.B. and M.K.H.; methodology, N.V.B., M.K.H., and P.E.B.; software, N.V.B. and M.K.H.; validation, N.V.B., E.V., M.K.H., and P.E.B.; formal analysis, N.V.B. and M.K.H., and P.E.B.; investigation, N.V.B. and E.V.; resources, M.K.H. and P.E.B.; data curation, N.V.B., M.K.H., and P.E.B.; writing—original draft preparation, N.V.B. and M.K.H.; writing—review and editing, N.V.B., E.V., M.K.H., and P.E.B.; data visualization, N.V.B.; supervision, M.K.H.; project administration, M.K.H.; funding acquisition, M.K.H. and P.E.B. All authors have read and agreed to the published version of the manuscript.

Funding: Funding for this research was provided the Calvin University Engineering Department Program for Sustainability Engineering. We also acknowledge support for P.E.B. under EPSRC Fellowship award EP/R024251/1.

Acknowledgments: The authors would like to thank all of those who helped with the early stages of this research and provided data and insight into Honduran energy use. These include the Centro de Evaluación de Estufas Mejoradas (CEEM) at the Universidad Zamorano, the Dirección General de Biodiversidad (DiBio), the Comisión Administradora del Petróleo (CAP), the Banco Central de Honduras (BCH), the Instituto Nacional de Estadisticas (INE), and many others.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

CT	Current Technologies
CO_2	Carbon Dioxide
ECC	Energy Conversion Chain
FS	Fuel Switching
GHG	Greenhouse Gas
HAP	Household Air Pollution
HDI	Human Development Index
IE	Improved Efficiency
IEA	International Energy Agency
IPCC	Intergovernmental panel on climate change
LPG	Liquid Petroleum Gas
MTH	Medium Temperature Heat
PSB	Primary Solid Biofuels
SDG	Sustainable Development Goal
TPES	Total Primary Energy Supply
WHO	World Health Organization
U_{LPG}	Useful energy from LPG (or electric) sector
U_t	Useful energy at year t
y_{LPG}	Ratio of useful heat supplied by LPG
y_{elect}	Ratio of useful heat supplied by electricity

References

1. Heinberg, R.; Fridley, D. *Our Renewable Future: Laying the Path for One Hundred Percent Clean Energy*; Island Press: San Francisco, CA, USA, 2016.
2. International Energy Agency. World Energy Balances 2018 Edition: Database Documentation. Available online: http://wds.iea.org/wds/pdf/WORLDBAL_Documentation.pdf (accessed on 22 March 2019).

3. Ekouevi, K.; Tuntivate, V. *Household Energy Access for Cooking and Heating: Lessons Learned and the Way Forward*; A World Bank Study; World Bank: Washington, DC, USA, 2012. [CrossRef]
4. UNDP. *Human Development Report (2016)*; United Nations Development Programme: New York, NY, USA, 2012. Available online http://hdr.undp.org/en/data (accessed on 26 August 2018)
5. Joan Henkle DNS, R.; Mandzuk, C.; Emery, E.; Schrowe, L.; Sevilla-Martir, J. Global health and international medicine: Honduras Stove Project. *Hisp. Health Care Int.* **2010**, *8*, 36–46. [CrossRef]
6. Rosenthal, J.; Quinn, A.; Grieshop, A.P.; Pillarisetti, A.; Glass, R.I. Clean cooking and the SDGs: Integrated analytical approaches to guide energy interventions for health and environment goals. *Energy Sustain. Dev.* **2018**, *42*, 152–159. [CrossRef]
7. Fullerton, D.G.; Bruce, N.; Gordon, S.B. Indoor air pollution from biomass fuel smoke is a major health concern in the developing world. *Trans. R. Soc. Trop. Med. Hyg.* **2008**, *102*, 843–851. [CrossRef] [PubMed]
8. McCracken, J.P.; Smith, K.R.; Díaz, A.; Mittleman, M.A.; Schwartz, J. Chimney stove intervention to reduce long-term wood smoke exposure lowers blood pressure among Guatemalan women. *Environ. Health Perspect.* **2007**, *115*, 996–1001. [CrossRef] [PubMed]
9. Hutton, G.; Rehfuess, E.; Tediosi, F. Evaluation of the costs and benefits of interventions to reduce indoor air pollution. *Energy Sustain. Dev.* **2007**, *11*, 34–43. [CrossRef]
10. Jetter, J.; Zhao, Y.; Smith, K.R.; Khan, B.; Yelverton, T.; DeCarlo, P.; Hays, M.D. Pollutant emissions and energy efficiency under controlled conditions for household biomass cookstoves and implications for metrics useful in setting international test standards. *Environ. Sci. Technol.* **2012**, *46*, 10827–10834. [CrossRef] [PubMed]
11. Obeng, G.; Mensah, E.; Ashiagbor, G.; Boahen, O.; Sweeney, D. Watching the smoke rise up: Thermal efficiency, pollutant emissions and global warming impact of three biomass cookstoves in Ghana. *Energies* **2017**, *10*, 641. [CrossRef]
12. Bailis, R.; Drigo, R.; Ghilardi, A.; Masera, O. The carbon footprint of traditional woodfuels. *Nat. Clim. Chang.* **2015**, *5*, 266. [CrossRef]
13. United Nations. *Transforming Our World: The 2030 Agenda for Sustainable Development*; Division for Sustainable Development Goals: New York, NY, USA, 2015.
14. Batchelor, S.; Brown, E.; Scott, N.; Leary, J. Two Birds, One Stone—Reframing Cooking Energy Policies in Africa and Asia. *Energies* **2019**, *12*, 1591. [CrossRef]
15. Flores, W.C.; Bustamante, B.; Pino, H.N.; Al-Sumaiti, A.; Rivera, S. A National Strategy Proposal for Improved Cooking Stove Adoption in Honduras: Energy Consumption and Cost-Benefit Analysis. *Energies* **2020**, *13*, 921. [CrossRef]
16. Cameron, C.; Pachauri, S.; Rao, N.D.; McCollum, D.; Rogelj, J.; Riahi, K. Policy trade-offs between climate mitigation and clean cook-stove access in South Asia. *Nat. Energy* **2016**, *1*. [CrossRef]
17. International Energy Agency. *Extended World Energy Balances: World Energy Statistics and Balances (Database)*; International Energy Agency: Paris, France, 2018. [CrossRef]
18. Food and Agriculture Organization. State of the World's Forests: 2011. Available online: http://www.fao.org/3/a-i2000e.pdf (accessed on 4 June 2019).
19. Pan American Health Organization. Household Air Pollution—El Salvador Country Profile. Available online: https://www.paho.org/hq/dmdocuments/2016/HAP-Perfil-ElSalvador-spa.pdf (accessed on 4 June 2019).
20. Global Health Observatory Data Repository. 2018. World Health Organization: The 2018 Revision. Available online: http://apps.who.int/gho/data/node.home (accessed on 4 June 2019)
21. Wang, X.; Franco, J.; Masera, O.R.; Troncoso, K.; Rivera, M.X. *What Have We Learned about Household Biomass Cooking in Central America?* The World Bank: Energy Sector Management Assistance Program (ESMAP): Washington, DC, USA, 2013. Available online: http://documents.worldbank.org/curated/en/197301468231876909/pdf/762220Revised00kstove0FINALFULL0REV.pdf (accessed on 13 April 2019)
22. Honduras: USD 20 millones para EcoFogones. *Her*. 2014. Available online: https://www.elheraldo.hn/pais/770029-214/honduras-usd-20-millones-para-ecofogones (accessed on 10 November 2018).
23. Jagger, P.; Pedit, J.; Bittner, A.; Hamrick, L.; Phwandapwhanda, T.; Jumbe, C. Fuel efficiency and air pollutant concentrations of wood-burning improved cookstoves in Malawi: Implications for scaling-up cookstove programs. *Energy Sustain. Dev.* **2017**, *41*, 112–120. [CrossRef] [PubMed]

24. Ludeña, C.; Salomón, M.; Cocco, M.; Dannecker, C.; Grütter, J.; Zelaya, S. Identificación y priorización de Acciones Nacionales Apropiadas de Mitigación (NAMA) en los sectores de agricultura, transporte y eco-fogones en Honduras. *Banco Interamericano del Desarrollo* **2015**. Available online: https://publications.iadb.org/es/publicacion/15492/identificacion-y-priorizacion-de-acciones-nacionales-apropiadas-de-mitigacion (accessed on 15 June 2020).
25. Heun, M.K.; Brockway, P.E. Meeting 2030 primary energy and economic growth goals: Mission impossible? *Appl. Energy* **2019**. [CrossRef]
26. Heun, M.K.; Owen, A.; Brockway, P.E. A physical supply-use table framework for energy analysis on the energy conversion chain. *Appl. Energy* **2018**, *226*, 1134–1162. [CrossRef]
27. Brockway, P.E.; Barrett, J.R.; Foxon, T.J.; Steinberger, J.K. Divergence of trends in US and UK aggregate exergy efficiencies 1960–2010. *Environ. Sci. Technol.* **2014**, *48*, 9874–9881. [CrossRef]
28. Ayres, R.U. Eco-thermodynamics: economics and the second law. *Ecol. Econ.* **1998**, *26*, 189–209. doi:10.1016/S0921-8009(97)00101-8. [CrossRef]
29. Miller, J.; Foxon, T.; Sorrell, S. Exergy accounting: A quantitative comparison of methods and implications for energy-economy analysis. *Energies* **2016**, *9*, 947. [CrossRef]
30. Sakai, M.; Brockway, P.E.; Barrett, J.; Taylor, P. Thermodynamic efficiency gains and their role as a key 'engine of economic growth'. *Energies* **2019**, *12*, 110. [CrossRef]
31. Food and Agriculture Organization. Information Division. FAOSTAT: FAO Statistical Databases. Available online: http://www.fao.org/faostat/en/. (accessed on 14 April 2019).
32. Honduras en Cifras. 1996–2016. Banco Central de Honduras: Departamento de Estudios Económicos. Available online: https://www.bch.hn/honduras_en_cifras.php (accessed on 14 April 2019).
33. The World Bank. Climate Change Knowledge Portal: Honduras. Available online: Https://Climateknowledgeportal.Worldbank.Org/Country/Honduras (accessed on 1 June 2019).
34. Heltberg, R. *Household Fuel and Energy Use in Developing Countries: A Multi-Country Study*; World Bank: Washington, DC, USA, 2003; pp. 1–87.
35. Drigo, R.; Bailis, R.; Ghilardi, A.; Masera, O. *Analysis of Woodfuel Supply, Demand and Sustainability in Honduras*; Global Alliance Clean Cookstoves: Washington, DC, USA, 2015.
36. Flores, W. El sector energético de Honduras: Diagnóstico y política energética. 2010. Available online: http://www.sirih.org/uploaded/content/article/1738307773.pdf (accessed on 14 June 2018).
37. Afrane, G.; Ntiamoah, A. Analysis of the life-cycle costs and environmental impacts of cooking fuels used in Ghana. *Appl. Energy* **2012**, *98*, 301–306. [CrossRef]
38. Shrestha, J. *Efficiency Measurement of Biogas, Kerosene and LPG Stoves*; Center for Energy Studies: Tribhuvan University Institute of Engineering: Lalitpur, Nepal, 2001.
39. Sousa, T.; Brockway, P.E.; Cullen, J.M.; Henriques, S.T.; Miller, J.; Serrenho, A.C.; Domingos, T. The need for robust, consistent methods in societal exergy accounting. *Ecol. Econ.* **2017**, *141*, 11–21. [CrossRef]
40. Hager, T.J.; Morawicki, R. Energy consumption during cooking in the residential sector of developed nations: A review. *Food Policy* **2013**, *40*, 54–63. [CrossRef]
41. Research Into Action. *Product Trends and Manufacturer Insights for Residential Laundry, Cooking, and Refrigeration Appliances*; Technical Report; Research Into Action: Portland, OR, USA, 2015.
42. Walsh, S.; Diamond, D. Non-linear curve fitting using Microsoft Excel Solver. *Talanta* **1995**, *42*, 561–572. [CrossRef]
43. Morris, S.S.; Neidecker-Gonzales, O.; Carletto, C.; Munguía, M.; Medina, J.M.; Wodon, Q. Hurricane Mitch and the livelihoods of the rural poor in Honduras. *World Dev.* **2002**, *30*, 49–60. [CrossRef]
44. United Nations Population Division. *World Urbanization Prospects: The 2018 Revision*; Technical report; United Nations, New York, NY, USA, 2018. Available online: https://population.un.org/wup/ (accessed on 1 April 2019).
45. Feenstra, R.C.; Inklaar, R.; Timmer, M.P. The Next Generation of the Penn World Table. *Am. Econ. Rev.* **2015**, *105*, 3150–3182. [CrossRef]
46. Zeileis, A. pwt9: Penn World Table (Version 9.x), R package version 9.0-0; 2017 . Available online: https://CRAN.R-project.org/package=pwt9 (accessed on 10 July 2018).
47. Freise, J. The EROI of conventional Canadian natural gas production. *Sustainability* **2011**, *3*, 2080–2104. [CrossRef]

48. World Resources Institute. Global Protocol for Community-Scale Greenhouse Gas Emission Inventories. 2014. Available online: https://ghgprotocol.org/sites/default/files/standards/GHGP_GPC_0.pdf (accessed on 1 April 2019).
49. Zhang, J.; Smith, K.; Uma, R.; Ma, Y.; Kishore, V.; Lata, K.; Khalil, M.; Rasmussen, R.; Thorneloe, S. Carbon monoxide from cookstoves in developing countries: 1. Emission factors. *Chemosphere-Global Chang. Sci.* **1999**, *1*, 353–366. [CrossRef]
50. Eggleston, S.; Buendia, L.; Miwa, K.; Ngara, T.; Tanabe, K. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*; Institute for Global Environmental Strategies Hayama: Kanagawa, Japan, 2006; Volume 5. Available online: https://www.ipcc-nggip.iges.or.jp/public/2006gl/ (accessed on 1 April 2019).
51. Hammond, G.P.; O'Grady, Á. The implications of upstream emissions from the power sector. *Proc. Inst. Civ. Eng.* **2014**, *167*, 9–19. [CrossRef]
52. McIntyre, J.; Berg, B.; Seto, H.; Borchardt, S. Comparison of lifecycle greenhouse gas emissions of various electricity generation sources. *World Nucl. Assoc. (WNA) Rep.* **2011**. Available online: https://www.world-nuclear.org/uploadedFiles/org/WNA/Publications/Working_Group_Reports/comparison_of_lifecycle.pdf (accessed on 7 May 2019).
53. Food and Agriculture Organization. Forest Area (Sq. Km)—Honduras. Available online: Https://Data.Worldbank.Org/Indicator/Ag.Lnd.Frst.K2 (accessed on 4 June 2019).
54. Ramirez Zea, C.; Salgado Cruz, J. *Evaluación Nacional Forestal: Resultados del Inventario de Bosques y árboles 2005–2006*; TCP/HON/3001; Honduran Forestry Agenda, HON: Tegucigalpa, Honduras, 2006.
55. Ver Beek, N.; Vindel, E.; Heun, M.K.; Brockway, P.E. Supplementary materials for Quantifying the Environmental Impacts of Cookstove Transitions: A Societal Exergy Analysis Based Model of Energy Consumption and Forest Stocks in Honduras. Available online: https://doi.org/10.5518/828 (accessed on 18 June 2020).
56. Pan American Health Organization. Household Air Pollution—Honduras Country Profile. Available online: https://www.paho.org/hq/dmdocuments/2016/HAP-Perfil-Honduras-eng.pdf (accessed on 30 March 2019).