Solid biofuels residential energy consumption model

Concept note

March 2022

Authors:

ADAM Zakia [1] –Statistics Manager

ODOU Thierry [2] – Associated consultant

BETANCOURT Maria – Energy Analyst Intern

[1] Zakia.Adam@iea.org

[2] thierryodou@gmail.com

International Energy Agency

Table of contents

International Energy Agency

Introduction

The present concept note focuses on the production of reliable and accurate data for solid biofuels in a set of Sub-Saharan African countries. The African continent accounts for the consumption for about 50% of the solid biofuels consumed worldwide, having 82% of its population relying on it for heating and cooking. In Sub-Saharan Africa alone, roughly 95% of the population depends on solid biofuels in the form of fuelwood, charcoal and residues. Therefore, having accurate data sets to measure solid biofuel's share of the energy mix is key to developing policies and assessing sustainability goals. However, the continent suffers from a systematic lack of data, with the reported data often not harmonized across countries and collected from outdated surveys. In general, the IEA collects data primarily from statistical releases from national administrations and uses secondary sources and estimations to complement IEA data where official data are not available. Robust or recent energy demand data are hard to find, and in many cases, the level of detail is not sufficient to give a clear picture of energy consumption.
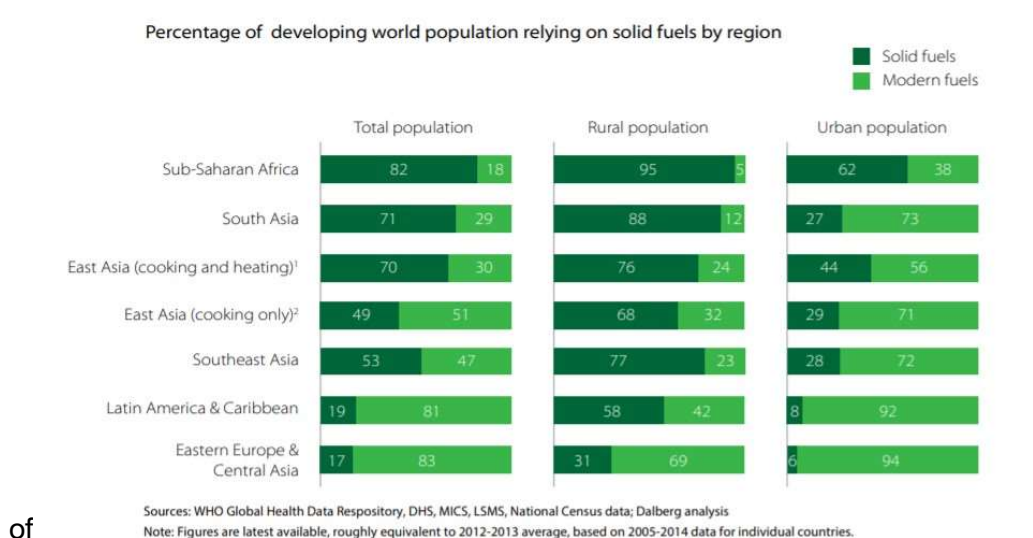
of

Figure 1: Percentage of developing world relying on solid biofuels (average 2012 – 2013) Source: The World Bank, 2014)

The International Energy Agency (IEA) is implementing a 4-year program co-funded by the European Commission titled "An Affordable and Sustainable Energy System for Sub-Saharan Africa". The programme aims to improve energy data management and long-term energy planning in 10 countries: Benin, Democratic Republic of Congo (DRC), Ethiopia, Ghana, Kenya, Nigeria, Rwanda, Senegal, Uganda and Zambia. The activities under the program include capacity development to reinforce in-country capabilities in energy information management, energy modelling, as well as measuring progress towards SDG-7, NDCs and other energy policy goals.

The programme activities also include a strong push for energy data improvement at the country level by cooperating directly with country administrations, identifying new data sources and particularly developing estimation tools for residential solid biofuels consumption.

International
Energy Agency

Solid biofuels remain the main source of energy for cooking purposes in Africa and are estimated to cover up to 90% of the energy mix in some African countries. We found three main categories used in the African continent, being wood (or the so-called fuelwood or firewood), charcoal and residues from the agricultural sector. Its demand has been growing along with the population, and it is expected to keep growing. Urbanisation is a phenomenon that has been taking place also and has been displacing fuelwood to be replaced with charcoal in urban areas. Thus, these fuels are still crucial in the energy mix in the country, and understanding the demand is essential to promote the energy transition. In Table 1, a rough panorama of the country is outlined (IEA, 2021a).

Table 1: Biomass and waste share in the 10 selected Sub-Saharan African countries

Biomass and waste share in total energy supply (TES) for selected Sub-Saharan countries, 2018

Selected country	Biomass share in total primary energy supply
Benin	51.60%
DRC	94.70%
Ethiopia	91.60%
Ghana	39%
Kenya	64.70%
Nigeria	74.80%
Rwanda	74.40%
Senegal	45.10%
Uganda	91.20%
Zambia	70.30%

Additionally, most of the energy mix is used for residential purposes. This is a result of low-income developing countries, in which the industry accounts for a little portion of the total energy demand. Moreover, the aforementioned countries consumed up to 90% of the energy at a residential level, in which 80% of the energy expenditure is burnt to satisfy the cooking demand (Garba & Bellingham, 2021).
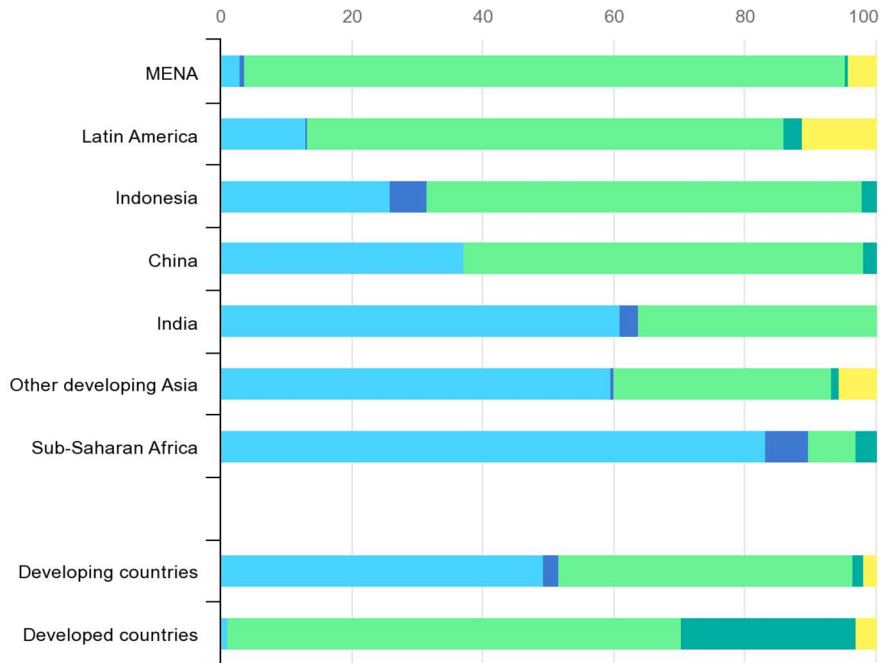
International
Energy Agency

Figure 2: Share population relying on different fuels, 2015 Source: (IEA, 2015)

The extended use of biomass to satisfy the energy needs in such countries has triggered a set of concerns in terms of health and environmental issues:

1. **Indoor air pollution:** Household air pollution (HAP) is the second most common cause of disability and the third one in avoidable deaths. The EPA has determined that the standardised use of solid biomass in burning processes for cooking and heating purposes release large amounts of pollutants, like particulate matter (PM), nitrogen oxides (NOx), carbon monoxide (CO), sulphur dioxide (SO2), lead, mercury, and other 187 hazardous air pollutants (Partnership for Policy Integrity, 2011).
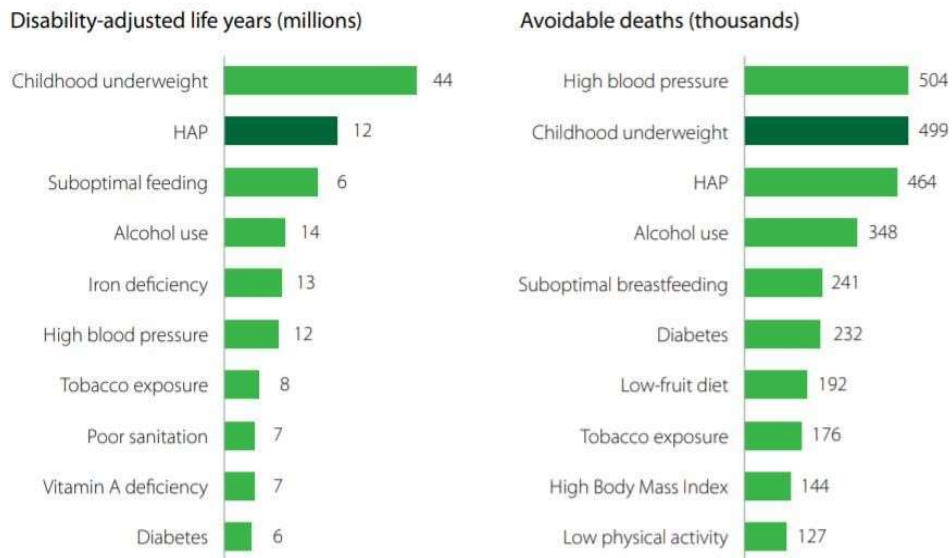
Note: As of the latest World Health Organization/Global Burden of Disease (WHO/GBD) analysis using 2012 data, the estimated number of HAP deaths in SSA stands at 581,000, suggesting that HAP may become the leading regional risk factor for mortality once the GBD data is fully revised for 2013-14.

Sources: 2010 Global Burden of Disease (available at http://www.healthmetricsandevaluation.org); Dalberg analysis.

Figure 3: WHO's an estimation of top 10 causes DALY and avoidable deaths in Sub-Saharan Africa Source: (The World Bank, 2014)

2. **Environmental effects:** Deforestation and increase in GHG emission is also a strong consequence of the traditional use of biomass. Africa is one of the biggest producers of charcoal, accounting for 64% of its production worldwide (UNEP, 2019). Charcoal is the most common fuel derived from fuelwood. Therefore, as the urban population and income grow, so does the demand for charcoal. Additionally, most of the production of charcoal in Africa is carried out using traditional stoves and inefficient technologies (Lambe et al., 2015).

3. **Gender issues:** in most of the Sub-Saharan African countries, biomass collection is a task that falls on women. On the one hand, the total extra time that encompasses collecting and cooking hours mean women have fewer available hours for education and other productive activities. On the other hand, there is a big issue related to physical safety in conflict zones and extreme geographical locations (Lambe et al., 2015).

4. **Economic:** Additionally, the use of biomass brings some economic losses linked to the man labour hours spent in biomass collection and extra time of cooking with traditional devices and fuels. According to a World Bank study (2014), more than 40 million worker years are wasted each year on fuelwood gathering and slow biomass cooking (UNEP, 2019).

Activity	Low (Full adoption of higher-performing biomass stoves)	Mid (Tier 3–4 gasifier biomass stoves at the top of the range)	High (Intermediate Tier 2–3 rocket stoves at the bottom of the range)
Mortality from household air pollution	0.3	3.5	6.8
Morbidity from HAP	0.2	0.7	1.1
Other health conditions (burns, eye problems)	0.1	0.8	1.5
Total health	0.6	5.0	9.4
Spending on solid fuels	0.4	3.8	7.3
Time wastage (fuel collection)	0.6	6.5	12.4
Time wastage (cooking)	3.3	10.2	17.2
Total economic	4.2	20.6	36.9
GHG emissions (fuel consumption)	0.2	2.1	3.9
GHG emissions (charcoal production)	0.2	0.7	1.2
Deforestation	0.2	3.5	6.7
Total environment	0.6	6.3	11.9
Total all categories	5.4	31.8	58.2

Figure 4: Economic losses and opportunity costs associated with solid biofuel dependence in Sub-Saharan Africa in 2010 Source: (Lambe et al., 2015).

The Sustainable Development Goals (SDG)

Data on solid biofuels are crucial to assess the completion of **National Determined Contribution (NDCs)** and the progress on the **Sustainable Development Goals (SDGs).**

The collection of solid biofuels data will enable the African countries to track the policies in place, the efforts made by each country to comply with international agreements such as the Paris agreement and to track the sustainable initiatives and policies implemented. However, the data is not readily available, there are not reachable new studies and countries have not included a comprehensive methodology. This has led different organisations such as the IEA to estimate these quantities using only macro-economic trends like GDP and population.

Clean cooking is associated with a set of sustainable development goals, as it is entangled in a set of social, economic variables. The SDG7, related to the access to clean energies is the goal with a higher relation with this matter. In fact, in the sustainable development scenario, the goal for 2030 is to accomplish a 100% share in clean cooking fuel access[3].

Hence, different initiatives are promoting the adoption of modern fuels. The most common transitioning fuels are kerosene (an intermediate fuel) and LPG (a modern fuel). The standards could also be achieved using improved cookstoves (ICS), devices with higher efficiencies and lower-emitting rates (WHO et al., 2018).

---

[3] It is worthy to mention that clean fuels are defined in terms of air quality guideline defined by the WHO. This means, the term is related to indoor pollution, and not in terms of GHG (WHO et al., 2018).

International
Energy Agency

Drivers of biomass demand

- Population growth: in developing countries where the residential energy demand is satisfied using solid biofuels, the increase of the population derives from a correlated growth of these fuels' demand.

- Urbanisation: Predominant rural countries tend to have a higher share of solid biomass in the energy matrix. Conversely, in the Sub-Saharan African countries, the urbanisation phenomena have a positive effect on the charcoal demand, triggering an increase in the biofuels demand.

- Income growth: the spread and user adoption of technologies are highly dependable on the income of the demanding households. This concept is defined in the literature as the energy ladder. The energy ladder theory postulates that as income increases, households shift from traditional biomass and other solid fuels to more modern and efficient cooking fuels such as kerosene, LPG, and electricity. Therefore, the energy ladder has solid biofuels, such as fuelwood and charcoal at the bottom, nonliquid fuels such as gas and oil in the middle, and electricity at the top (Alinaitwe, 2021).

Figure 1.5. Transition from use of biomass fuels to use of modern fuels
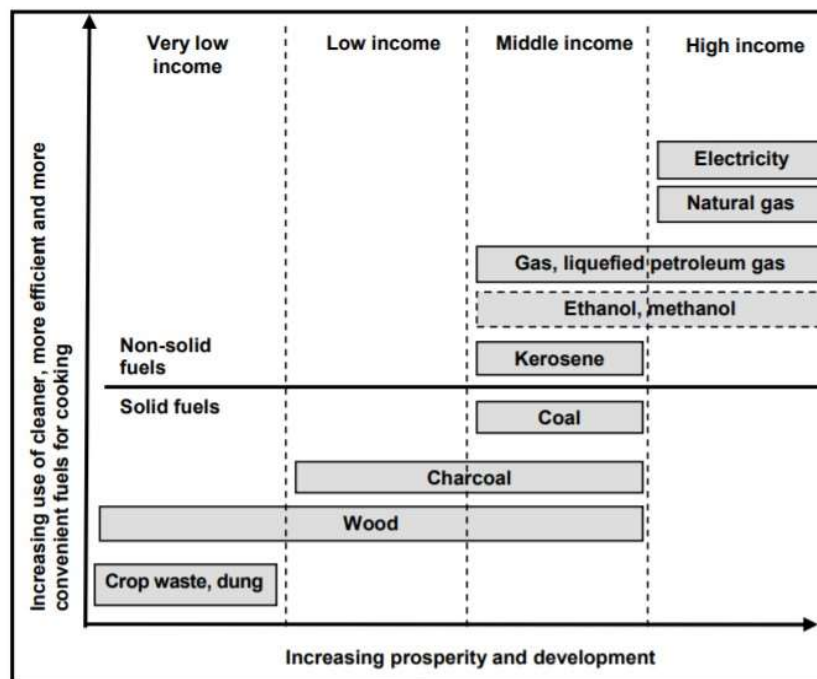
From WHO (2006) (Figure 2: The energy ladder: household energy and development inextricably linked)
Note: Ethanol and methanol are rarely, if ever, used.
Dash: estimate

Figure 5: Energy ladder Source: (The International Agency for Research on Cancer, 2010)

- Education level: awareness of the harmful effect and alternative fuels are crucial to change fuels choices in developing countries. Additionally, a decrease in the time used in fuelwood collection means an increase in available hours, deriving in higher education enrolment rates, especially for women.

Harmonisation of variables and conversion of units

One of the main issues on the solid biofuels' reported data is the units and definition in which the data are published and reported.

- **Net Calorific Value (NCV):** the "net" energy content, which excludes the energy lost to produce water vapour during combustion (IEA, 2021b). This value is used then, for converting reported amounts from physical to energy units. To guarantee harmonisation, all the fuels must be in energy units, on a net basis instead of a gross one. It is highly dependable on a different set of parameters. The most important variable is humidity, which is inversely proportional to its calorific value. Additionally, the humidity on fuelwood is dependable on a set of different factors such as storage time, size of the collected matter and the different species. Finally, the NCV is correlated with seasonal variations of humidity in tropical countries, correlating with charcoal demand (Atteridge et al., 2013).
- **Improved Cooking Stoves (ICS) efficiencies:** the penetration of improved cooking stoves have an effect in reducing the demand input energy, as it has roughly twice the efficiency of a traditional device (The International Agency for Research on Cancer, 2010).

Table 2:Typical efficiencies of cooking fuels

Fuel source	Energy content (MJ/kg)	Typical conversion efficiency[a] (%)	Useful energy at final consumption stage of cooking (MJ/kg)	Approximate quantity of fuel necessary to provide 5 GJ of useful energy for cooking (kg)
Liquefied petroleum gas	45.5	60	27.3	180
Natural gas	38 [MJ/m³]	60		219 [m³]
Kerosene (pressure)	43.0	55	23.6	210
Kerosene (wick)	43.0	35	15.1	330
Biogas (60% methane)	22.8 [MJ/m³]	60		365 [m³]
Charcoal (efficient stoves)	30.0	30	9.0	550
Charcoal (traditional stoves)	30.0	20	6.0	830
Bituminous coal	22.5	25	5.6	880
Fuelwood (efficient stoves), 15% moisture	16.0	25	4.0	1250
Fuelwood (traditional stoves), 15% moisture	16.0	15	2.4	2000
Crop residue (straw, leaves, grass), 5% moisture	13.5	12	1.6	3000
Dung, 15% moisture	14.5	12	1.7	2900

From Sullivan & Barnes (2006)
[a] The typical conversion efficiency for charcoal, fuelwood and kerosene is based on their respective stove types.

International Energy Agency

Since the socio-cultural variables act like barriers in the fuel switching, it is quite relevant to get data about the real penetration of the stoves in the African countries. Some studies reveal most of the Sub-Saharan countries continue with a high prevalence of traditional cooking stoves.
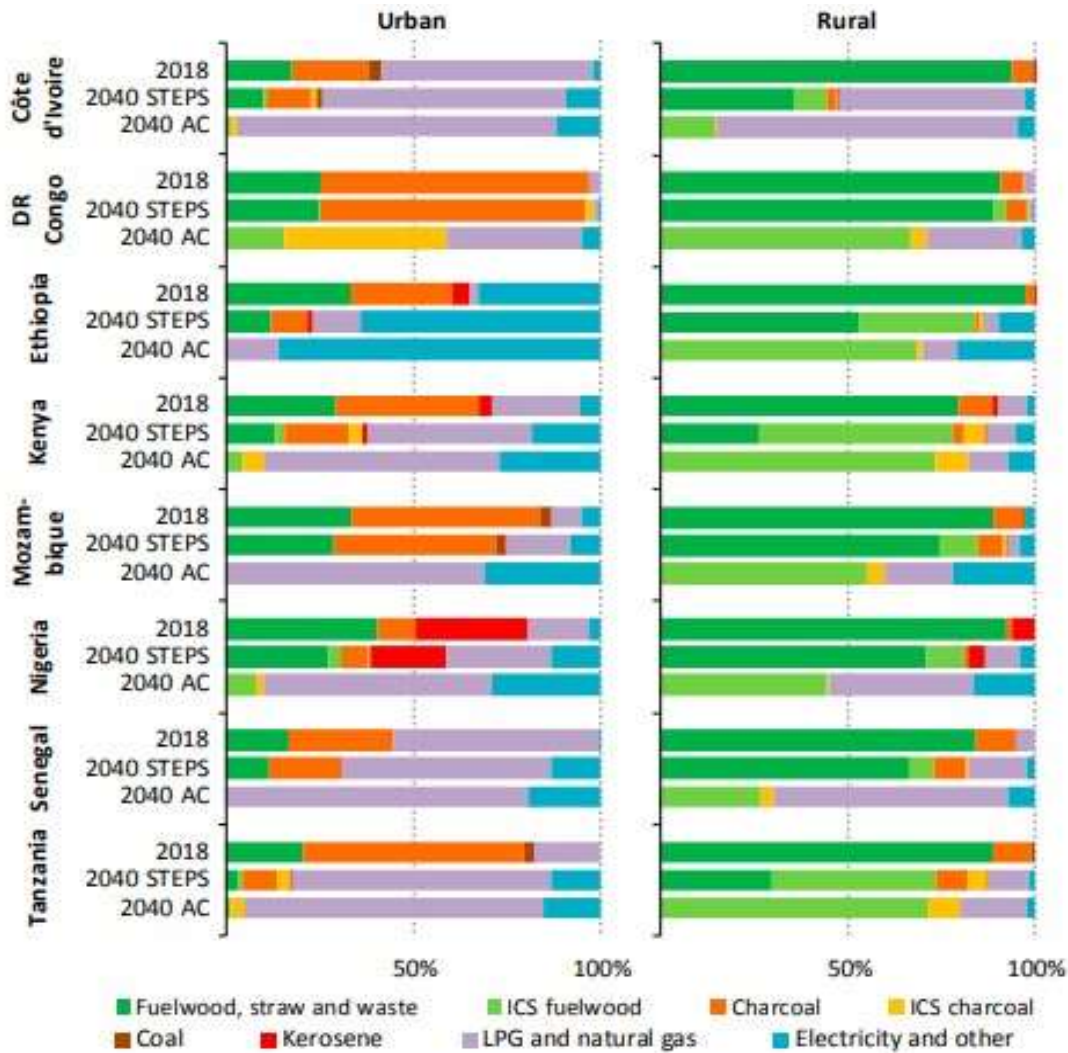

Figure 6: Primary fuels used for cooking in selected Sub-Saharan countries in the Stated Policies Scenario and Africa Case, 2018 and 2040

Variables considered for performing a comprehensive model

Defining key variables that are crucial to determine the demand in developing countries.

Demographic variables	• Population size • Urbanisation indicators • Health indicators • Well-being indicators
Geographical variables	• Deforestation rate • Climate variables • Available and used plant species
Technology variables	• ICS efficiency and penetration rate • Wood to charcoal tranformation kilns • Emissions generated by devices
Economic variables	• Income indicators • Transitioning fuels price, production and imports • Subsidies • Energy intensity
Social variables	• Non-energy uses of residual crops • Non-energy uses of animal waste • Cooking preferences • Cooking reliance in different fuels

Figure 7: Key variables in the demand for biofuels

Data challenges

A comprehensive model will take into account the set of variables aforementioned. This however presents a great challenge in terms of the availability of the data. To create a strong framework suitable for the whole set of selected countries, some of the variables have been taken out as there are not enough reliable sources. Hence, the model is a good start to verify and get reliable data, but also propose a challenge to the national institutions amongst the countries to collect more on-field information and get better accuracy.

Model scope

This user-friendly model can help national energy officials and statisticians and IEA data managers to estimate the solids biofuel consumption at a household level in the 14 selected Sub-Saharan African countries. It is important to emphasize that our aim is not to replace official data with the estimations from the model. Primary data collection should remain the priority for countries and this tool should serve as a check and could be used as a tool to enable discussions on the data.

- The model aims to **verify** and **estimate** the solid biofuel residential demand for each country to improve the data quality.
- The final interface is **user-friendly** and developed in a very common environment. To avoid technical complications, the model has been developed on Microsoft Excel and programmed in Visual Basic.
- The model enables users to assess the impact of policies, goals and international agreements, creating **scenarios.**

Methodology

The underlying estimation model adopted is based on a hybrid approach combining top-down and bottom-up methodologies to take advantage of available data and modelling limitations.

The primary determining factor in estimating solid biofuels residential energy consumption is demographic nature characteristics, in particular, the population and the number of households disaggregated in urban and rural areas (Farzaneh, 2019).

Therefore, on one hand, the top-down approach is used to select the predictors that drive specific consumption per fuel type and demography characteristic setting (Urban/rural). In that regard, various indicators are collected from diverse sources including but not limited to the IEA (International Energy Agency) databases, the World Bank Sustainable Development Indicators[4], the World Urbanization Prospects 2018[5], World Health Organization indicators[6], the United Nations Global SDG Indicators Database and others official databases and literature. Specifically, the goal at the end of the top-down is to derive indicators that explain Urban/rural household consumption for firewood and charcoal in the region.

In prediction modelling, interest is often to determine the most important predictors that should be included in a reduced, parsimonious model. This can be achieved by performing variable selection, in which optimal predictors are identified based on statistical characteristics such as importance or accuracy (Jaime Lynn Speisera, Michael E. Millerb, Janet Toozec, 2020).

More than hundreds (100) of variables have been gathered. To reduce dimensionality and to find the most important variables that drive household-specific consumption per fuel type, three advanced features selection methods (BORUTA, Random Forest, xgboost method) are used.

---

[4] https://databank.worldbank.org/source/world-development-indicators
[5] https://population.un.org/wup/
[6] https://www.who.int/data/gho/data/indicators

Boruta is a feature ranking and selection algorithm based on random forests algorithm. The algorithm is designed as a wrapper around a Random Forest classification algorithm. It iteratively removes the features which are proved by a statistical test to be less relevant than random probes (Kursa & Rudnicki, 2010).

XGBoost provides the best score for every element, shows the significance of each element to prepare the model, and creates another tree with gradient direction (Satapathy et al., 2019; Wang, 2019). Random forests (RF) are a collection of classification and regression trees which are simple models using binary splits on predictor variables to determine outcome predictions (BREIMAN, 2001; Jaime Lynn Speisera, Michael E. Millerb, Janet Toozec, 2020). RF provides the best score for each feature, shows the importance of each feature to train the model, and generates a new tree by maximizing the label purity within these subsets. This statistical significance of identifiers can de directly used for feature selection (Satapathy et al., 2019).

A combination of the results of these methods has been adopted to have a good confidence level. This step is critical in the modelling process to avoid redundant features as we are in the situation of high dimensionality space and to build high performing model. A subset of the top 10 variables has been selected in each case.

Beforehand, a country is selected as a proxy to drive the feature selection procedure. Countries such as Angola, South Africa, Botswana, Senegal and Morocco were selected based on the progress they made in access to clean cooking fuel and quality of data (not estimated and later evaluated. Average household consumption for charcoal and firewood are computed using country data from IEA databases on solid biofuel consumption for charcoal and firewood, and demography data as follows:

$$Q_{daily} = \frac{E_{solid\ biofuels}}{NH * Pop * NCV_{solid\ biofuels}} * \frac{1}{365}$$

In which $E_{solid\ biofuel}$ is the total energy supply in the residential sector per type of fuel, NH is the number of households, Pop for the population and NCV is the Net Calorific Value.

The units mass per household generated from this calculation is then compared with acceptable household biofuels consumption across the continent. This range are determined by gathering information from literature and report. Angola is later selected as a reference country among others since the average urban/rural household consumption computed stands within the acceptable average range. The comparison table is annexed to the concept note (Household specific **consumption per fuel type of references countries** Table 3).

Furthermore, a multi-linear regression (MLR) predictive model is fit with data from the country of proxy and all the 14 most significant predictors derived above. To have an optimised size of model with fewer variables, a quality criterion is applied to select the small predictors possible that leads to the best Adjusted R-Squared. The Adjusted R-Squared helps penalise for additional predictors and can decrease with added predictors. One model is then determined for each household's charcoal/firewood consumption in urban/rural areas. Model coefficients and accuracy are shown in the annexe (Model output).

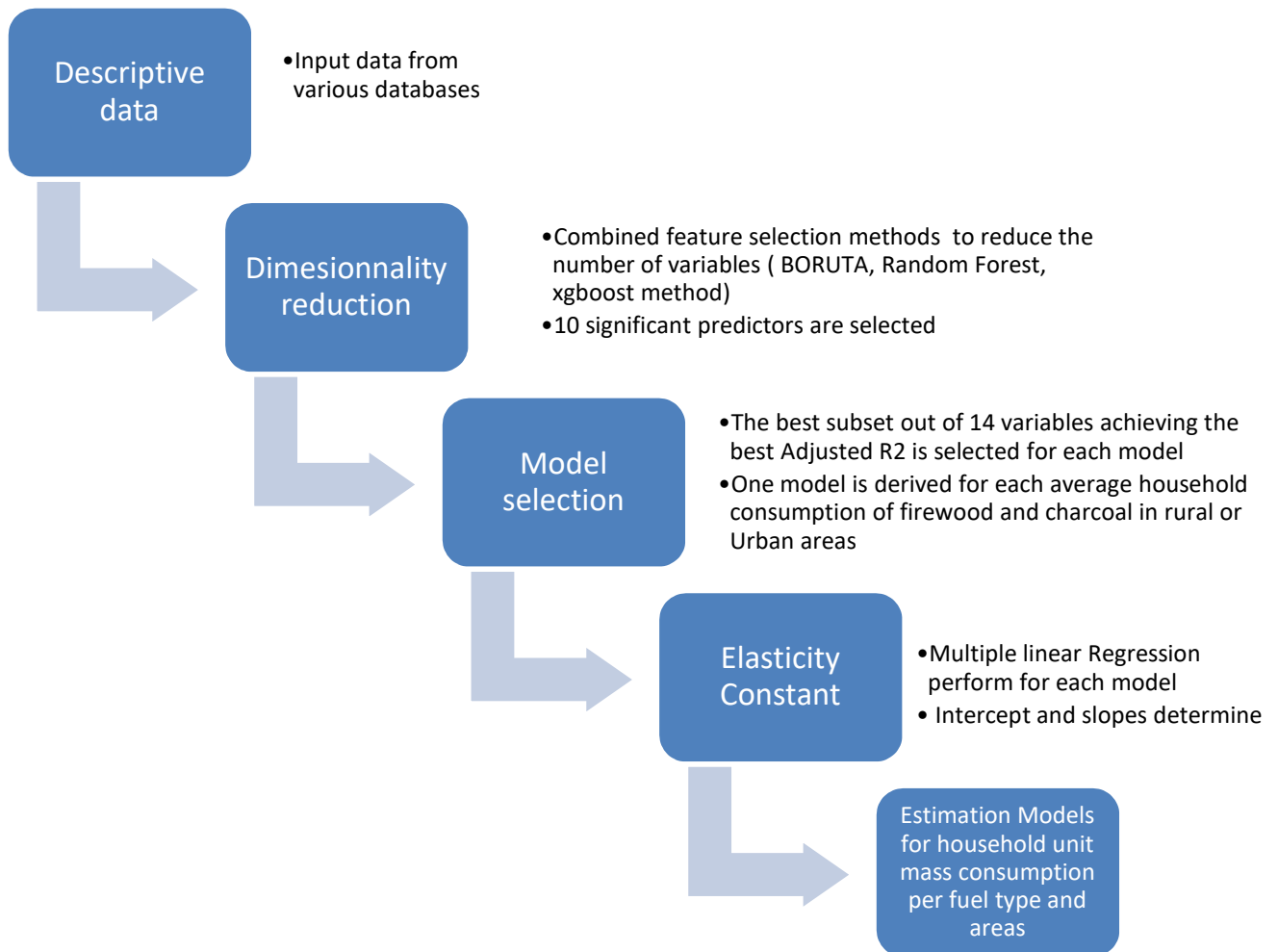The chart below describes the steps explained above.

Figure 8: Pre-analysis: Top-down approach steps

At the end of this process, four models (equations) is developed providing the unit mass estimation of household consumption per fuel type (firewood and charcoal) and areas (Urban or Rural). **The pre-analysis study is done in R software which source code can be provided from this link.** Model equations and coefficients are in the annexe.

This estimation is then populated on the entire national population knowing the demography data representing the bottom-up approach. The consideration of technical and technological values (efficiency of stoves and net calorific values) are taken into account to compute the energy consumption per end-uses and fuel type used. The energy consumption per end-uses and fuel type is computed as follow:

$$E_0 = \sum_i \sum_j (NH * \% NH_i * EFuel_{ij}) \quad and \quad NH = \frac{Pop}{\theta},$$

$$E_0 = \sum_i \sum_j \sum_k \sum_l (NH * \% SH_i * Euse_{ijkl}) \quad and \quad NH = \frac{Pop}{\theta},$$

Where **NH** is total number of households, **SH$_i$** is the share of household type (%), **EFuel** is the energy consumption for each type of fuel and per household type (TJ /Household). **θ** refers to the average household size (person/household), **i** refer to demographical nature (urban or rural

area), **j** refers to the type of solid fuels: firewood, charcoal, agriculture residues. **Euse** refers to the energy consumption per end-uses where **k** refers to the type of end-uses (heating, cooling, lighting) and **l** refers to the type of stoves technology.

$EFuel_{ij} = NCV_j * Q_{ij}$, where **Q** is the mass units need per fuel (Kg/year) and NCV in MJ/Kg

$Euse_{ijkl} = NCV_j * Q_{ijkl}$, where **Q** is the mass units need per fuel, end-uses and per technology (Kg/end-uses/technology/year).

The conceptual framework below summarizes the modelling approach. The modelling process of the Solid biofuels (SBE) Model overview is illustrated as follows:
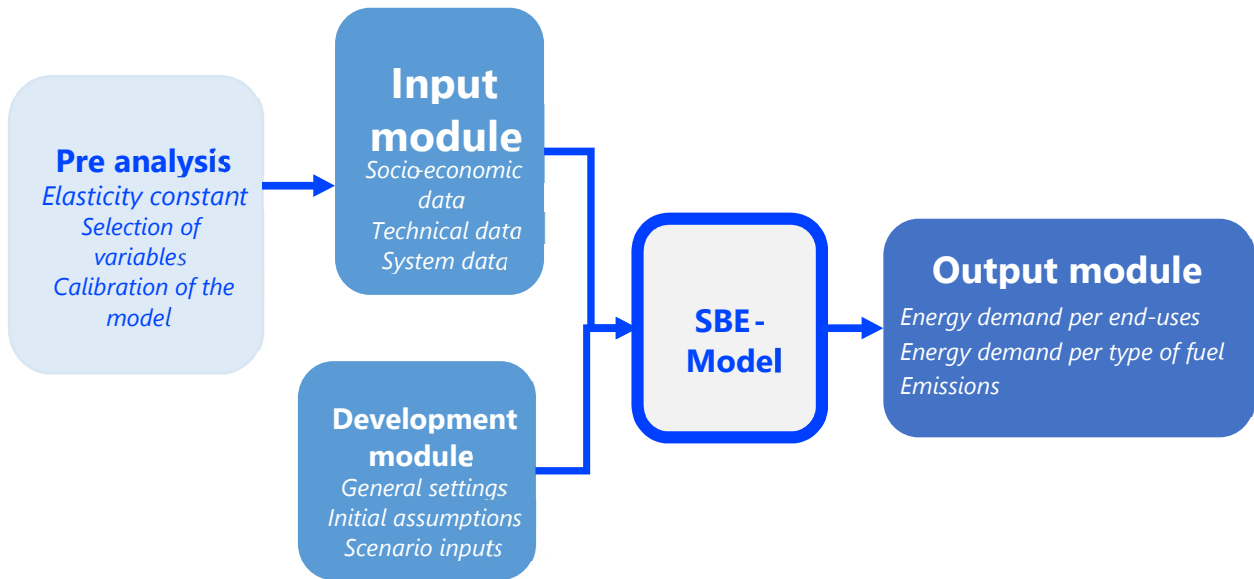
Figure 9: Model concept note

Modules

The model has been conceived to be an Excel worksheet file, in which the user can add the relevant inputs to get personalised and accurate results. It is separated into several worksheets to facilitate ease of navigation. These worksheets can be accessed from the landing page (''Control Board'' Worksheet).
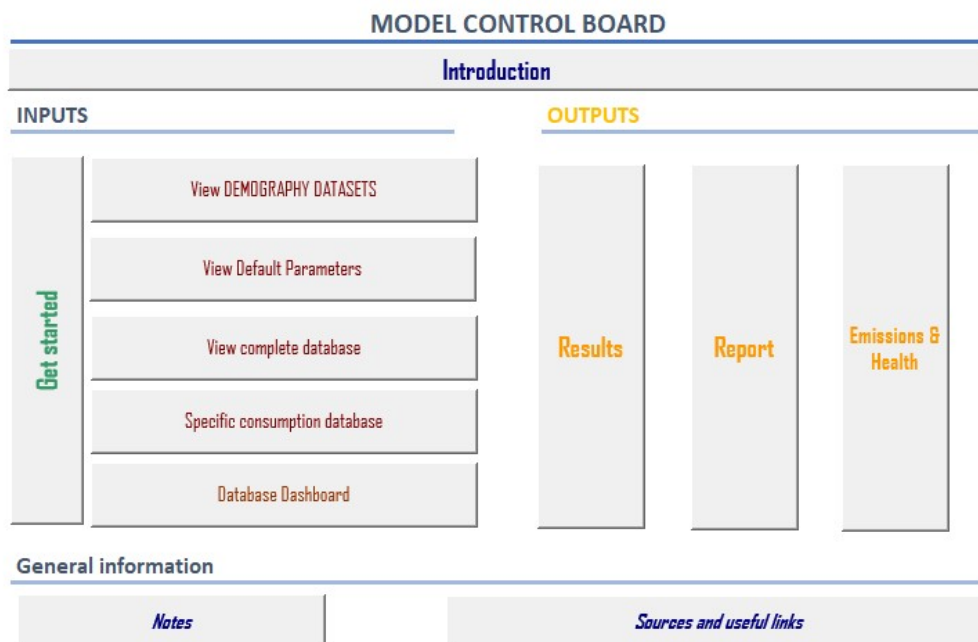
Figure 10: Model landing page

Most important sheets are visible to users and the table hereafter summarises their content. The sheets are grouped into Inputs, outputs and General Information. The worksheet colour difference represents the type of information or analysis performed in each sheet.

Table 3: Model general worksheet description

Model Worksheet	Description
General information	
INTRO	Provide baseline information about the context of the project, objectives, short introduction to the modelling approach, data collected and person of contact for further information.
NOTES	Inform user about model version history and update and orientation on colour code used in the model. Pre-computed values Entry cells
References	Informs on the different sources of data and links to access the database and institution that provide it.
Model outputs and display	
Control Board	The landing page of the model with a control board with several buttons to access the different features and modules of the model.
Dashboard	Help user to have a quick view of certain descriptive parameters trend about a country and compare various countries.
EmissionsHealth	Provides an estimate of the emission by greenhouses gases and fuel type using energy consumption estimated in the **"Compute" worksheet**. This calculation is based on default emission factors by fuel type for stationary combustion in the residential per unit of mass/TJ. Reference emission factors and sources are provided in the "Default Param" worksheet where users set entry parameters.
Report	A summary of the analysis computed in the "Compute" worksheet with key graph showing historical consumption, future projection and emissions. **Export to pdf** feature provided for printing purposes to support communication materials.
Model Inputs	
Default Param	It encompasses default parameters and assumptions considered in the model including the Net Calorific Value

	(NCV), emission factors, share of the end-uses activities of total consumption, conversion unit, and model Intercept and slopes coefficients. Limited access is given to the user in modifying some entries. • NCV: a value for fuelwood of moisture of 20% (on a wet basis) is assumed, as the IRENA guideline proposes, low moisture charcoal with a value of approximately 33.33 GJ/tonne (IRENA, 2019). The residues are assumed to be from herbaceous crops, Miscanthus spp. With moisture of 15% following the same guidelines. • Share of agricultural residues: 5% of firewood and charcoal consumption. This number can be modified to have a more accurate estimation. • Share of household biofuels consumption per end-uses: the percentage used for the main three activities (cooking, heating and lighting) is derived from different sources and literature. The source is provided next to each row. • Emissions factors: following the IPCC guideline and in coherence with the IEA emissions team, a set of factors are fixed to calculate the total emissions. References for these factors are provided and users can update these values.
Demography_World	Provides demography dataset derived from the 2018 revision of World Urbanization Prospects[7], which contains the latest estimates of the urban and rural populations from 1950 to 2018 and projections to 2050. These estimates can be updated by the user for the country of estimation and as new information is available. The model uses this estimate for the estimation at the country level and per area of the demand.
database_raw	Access to the entire database of the model expects the demography separated and concatenated by column as published by primary sources per year and country.
model_fit	Contains a subset of the **"database_raw" worksheet** with the most significant predictors derived from the pre-analysis where feature selection analysis is performed. The model runs majorly using data in this worksheet.
Model Run	
Compute	It is the core of the excel model and where all the computations are made given user inputs. For an initial start, the user can select the desired country, output unit and run the model. Historical estimation of solid biofuels consumption

[7] World Urbanization Prospects - Population Division - United Nations. (1950–2050). [Dataset]. https://population.un.org/wup/

| | at the national level per fuel type and end-uses and future projection based on various scenarios can be performed. Scenarios include the Sustainable Development Scenario (SDS)[8] and Stated Policies Scenario (STEPS)[9].

The user can adjust several variables to perform some sensitivity analysis and to study future demand as well as compare two countries or to a base scenario. |
|---|---|
| **Future_dat** | Excel worksheet which contains sensitivity variables for the future projection. |

Running the model

Users can get started with the model from the **"control board" worksheet** and click directly on the button **"Get started"** which lead to the **"Compute" worksheet.**
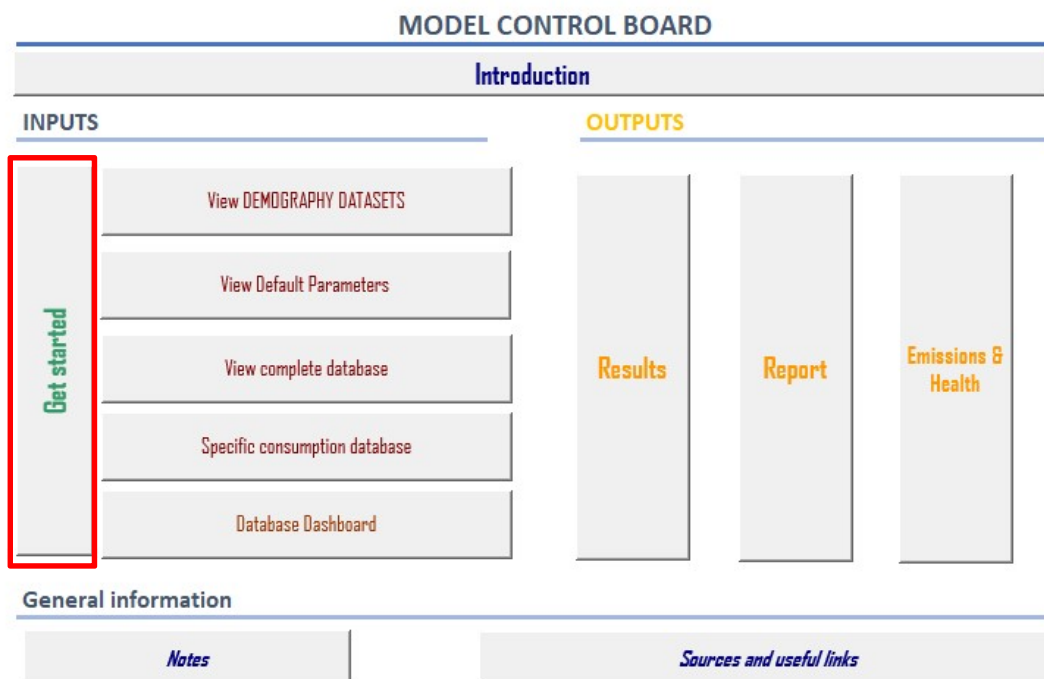
Figure 11: Control board and get started

Before that users can adjust default parameters by clicking in **"View Default Parameters"** from the control board or directly going to the **"Default Param"** worksheet. The calorific values constant, the share of agricultural residues, emission factors and end-uses share percentage can be updated to suit user requirements before getting started.

---

[8] https://www.iea.org/reports/world-energy-model/sustainable-development-scenario-sds

[9] https://www.iea.org/reports/world-energy-model/stated-policies-scenario-steps

Figure 12: Default parameters worksheet

Historical estimation of solid biofuels consumption per fuel type and end-uses

Once redirected to the **"Compute"** worksheet, the user can choose a country of modelling from the drop-down menu as well as choosing outputs energy unit.
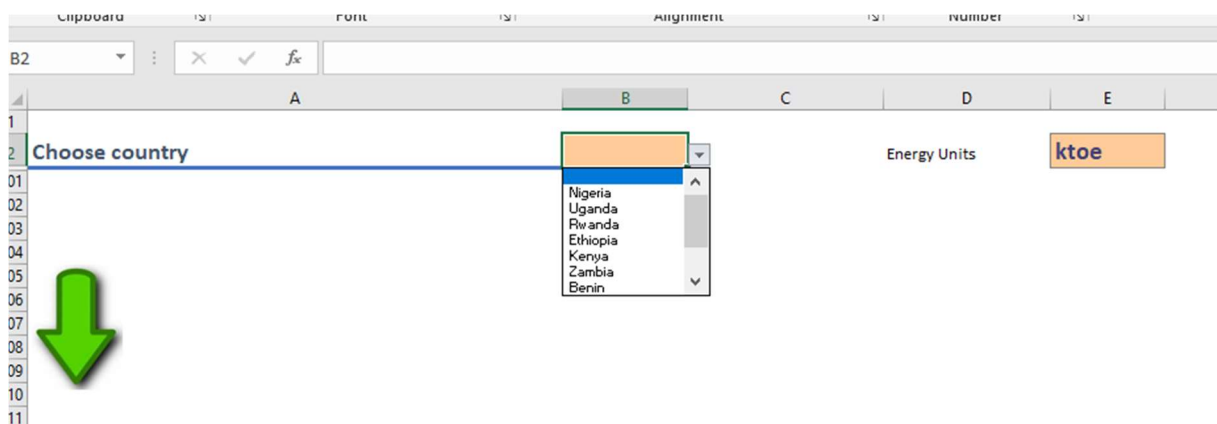
Figure 13: Model starting point

The model does not perform any calculation if the country is not indicated otherwise it will prompt a message to invite to choose a country.
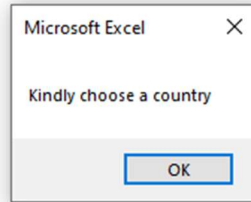
Figure 14: Message prompt in case of no country indicated

The model calculation is performed in Visual Basic for Applications (VBA) language and any user actions trigger some macros that run in the background. The code is written in a way to permits rapid computation.

The model is designed to compute directly the historical estimation of the solid biofuels by end-uses and fuel type. Based on the country selected the model runs on background and display values in cells. It takes a few seconds to calibrate and provide the estimation depending on the speed of the computer.
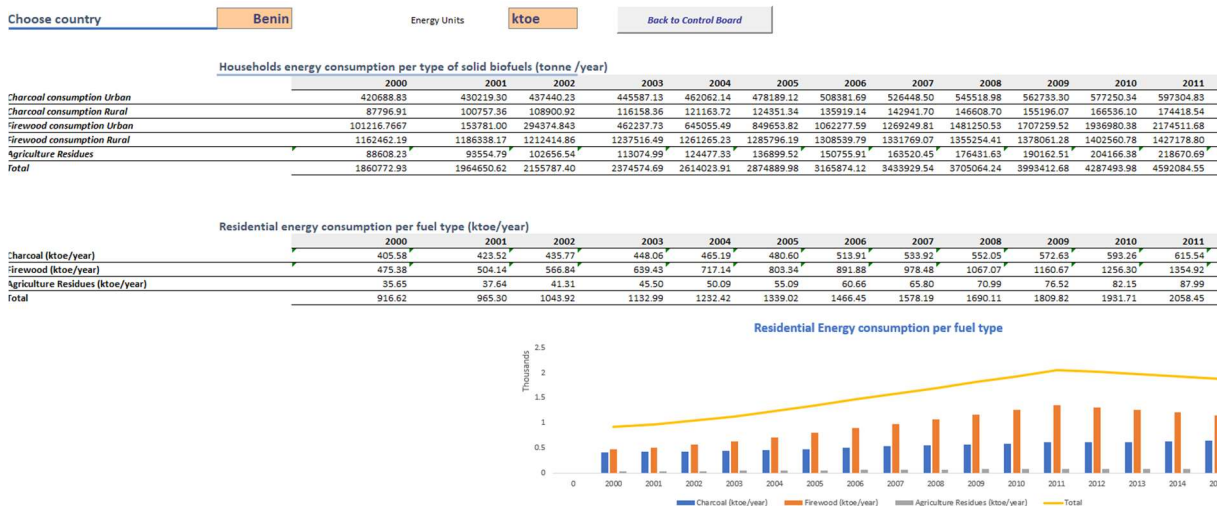
Figure 15: Historical solid biofuels consumption per fuel type output of the model

It provides firstly residential energy consumption per fuel type in rural and urban areas in unit mass (tonne/year) from 2000 to 2015 and later the energy consumption using NCV set in **"Default Param"** worksheet and others default parameters. At the same time, it computes as

International
Energy Agency

well the consumption per end -uses in particular cooking, heating and lighting as shown in the figure below.

Residential energy consumption per end uses (ktoe/year)	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
ooking (ktoe/year)	0.014	0.014	0.015	0.017	0.018	0.020	0.022	0.023	0.025	0.027	0.029	0.030
eating (ktoe/year)	0.008	0.008	0.009	0.010	0.011	0.011	0.013	0.014	0.014	0.016	0.017	0.018
ghting (ktoe/year)	0.000	0.000	0.000	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
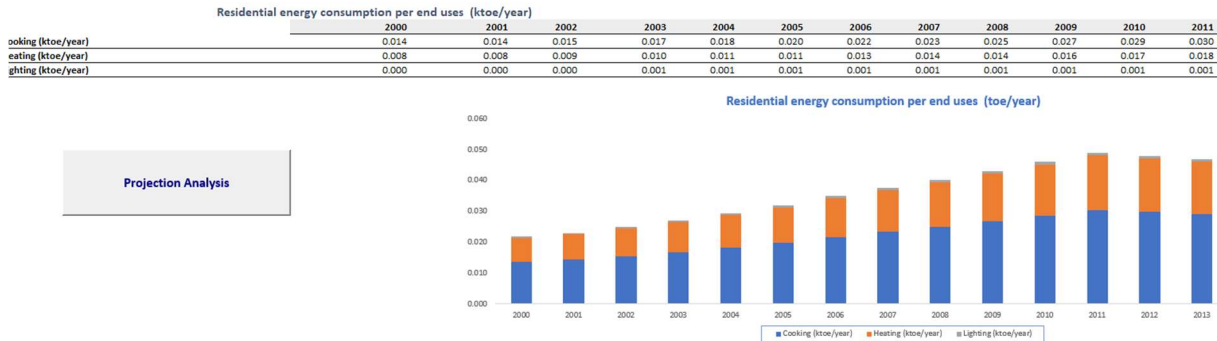
Figure 16: Historical solid biofuels consumption per end-uses - output of the model

Projection analysis

Next to the chart of the residential consumption per end-uses on the left-hand side, a button is available to initiate the Projection analysis.
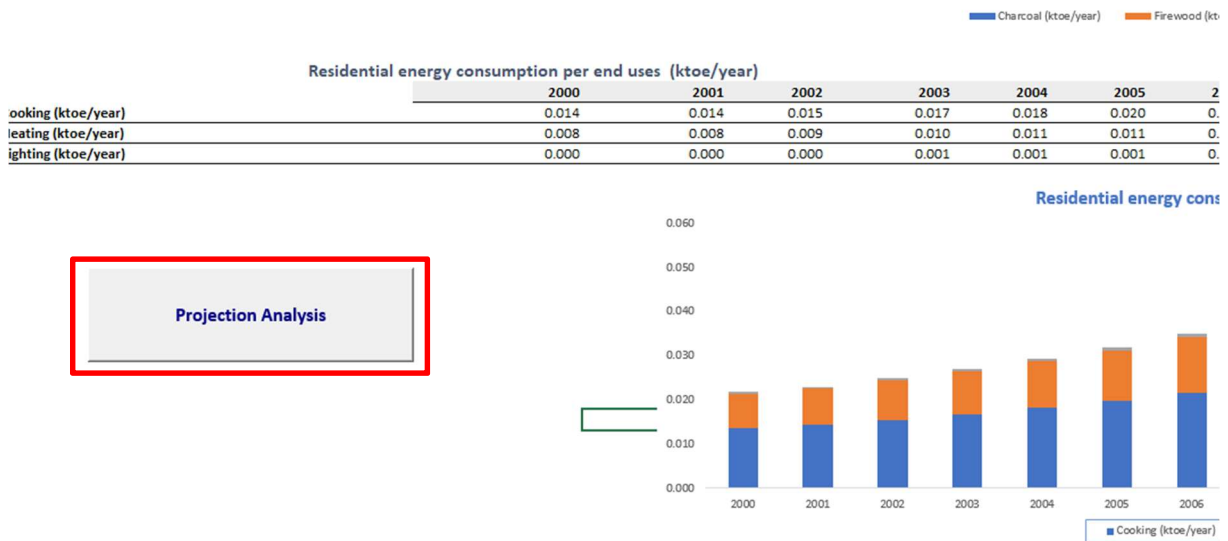
Figure 17: Starting the projection analysis

This section of the model helps the user to project future consumption based on a set of variables and trends in the next decades 2020, 2030, 2040 and 2050. For each set of variables, the user can play with a set scenario that generates future estimates by 2050 on which the model will run to provide future estimates. Hereafter the presentation of each type of scenario is available in the drop-down list of variables.

International
Energy Agency

Table 4: Scenario description

Scenario	Description
User-defined	This option allows the user to set values in between decades that suit the requirement of the particular exercise or progress expected for the country of analysis. *However, in this option, the user must pay attention to the values set for the variables with the asterisk sign (*). For these variables, the values for each decade represents the growth rate to be observed this decade and the previous one and not the annual growth rate in between these decades.*
STEPS	Future pathway of the variable by 2050 following the Stated Policies Scenario (STEPS) of the IEA.
SDS	Future pathway of the variable by 2050 following the Sustainable Development Scenario (SDS) of the IEA.
Linear	The future pathway of the variable by 2050 is based on linear forecast using Excel FORECAST.ETS function calculates or predicts a future value based on existing (historical) values. Historical values of variables here are in the **"model_fit"** or **"database_raw"** worksheet.
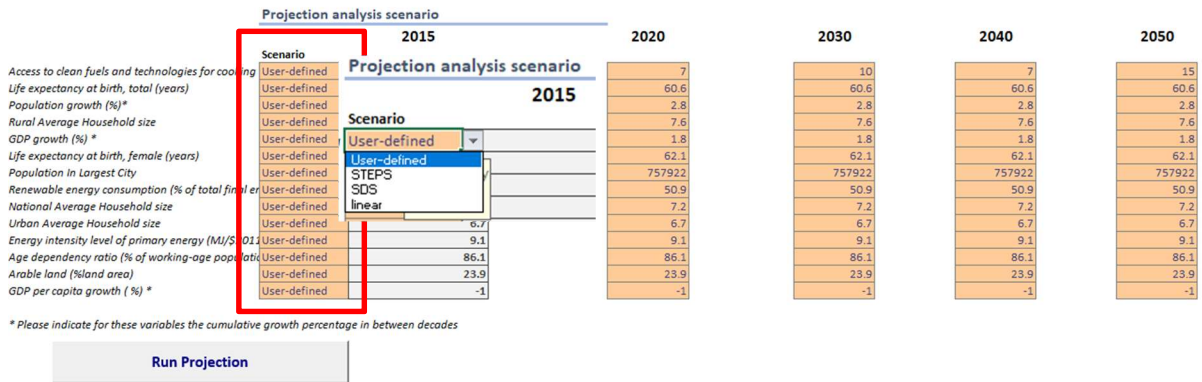
Figure 18: Scenario settings - screenshot

Given the user choice of scenario, the future values are predicted and filled in the cells automatically and stored in the **"future_dat"** worksheet from ROW1 to ROW15. The user can manually update each row that suits best for the analysis.

Figure 19: Scenario setting time series generation in Future_dat worksheet

After all the setting is done, the button [Run Projection] helps to run the projection and outputs will be generated as in the figure below. Firstly, it shows the unit mass consumption followed by the energy consumption in energy unit preference selected at the beginning of the exercise and then a graphic showing the trend per fuel type.

Residential energy consumption per fuel type (ktoe/year)

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Charcoal	27285709.15	27474968.87	28234742.29	28880143.55	29508196.26	30573213.80	36686588.96	37953423.54	39227516.39	40547044.36
Firewood	48155757.19	45396043.25	42624422.70	39482988.42	36093581.64	334550389.21	418713094.61	472987267.67	530842536.23	592996747.54
Agriculture Residues	3263670.13	3120851.70	2991787.06	2840059.50	2674632.52	18663268.69	23318578.45	26253170.67	29379466.59	32736820.37
Total	78705136.47	75991863.82	73850952.05	71203191.47	68276410.41	383786871.70	478718262.03	537193861.88	599449519.21	666280612.27

|	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Charcoal (ktoe/year)	649.66	654.17	672.26	687.62	702.58	727.93	873.49	903.65	933.99	965.41
Firewood (ktoe/year)	1146.57	1080.86	1014.87	940.07	859.37	7965.49	9969.36	11261.60	12639.11	14118.97
Agriculture Residues (ktoe/year)	77.71	74.31	71.23	67.62	63.68	444.36	555.20	625.08	699.51	779.45
Total	1873.93	1809.33	1758.36	1695.31	1625.63	9137.78	11398.05	12790.33	14272.61	15863.82
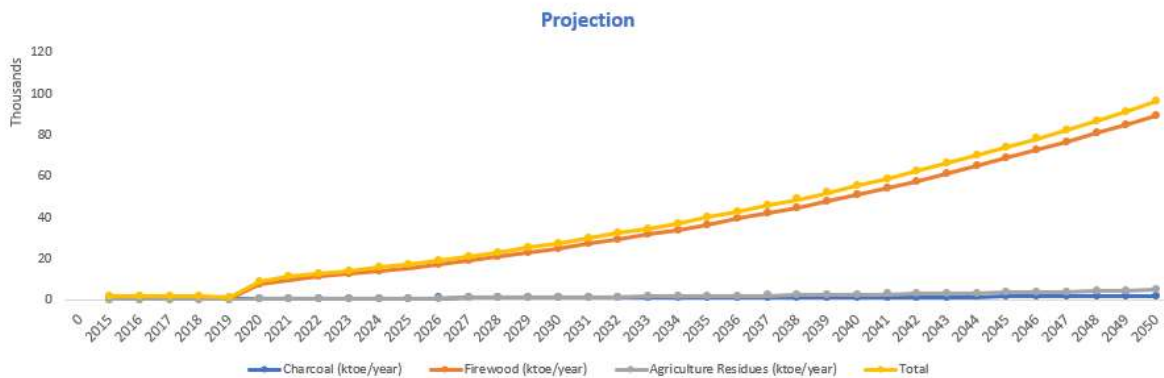
Figure 20: Model projection output

This process can be iterated as many times as possible by the user.

Comparison analysis

Under this section, the user can perform as in the projection analysis a long-term forecast. In addition, this functionality allows to compare two countries or compare the same country with an improved scenario by changing the several options in the scenario drop-down list per variable.

The button **comparative analysis** is at the left of the projection graph.
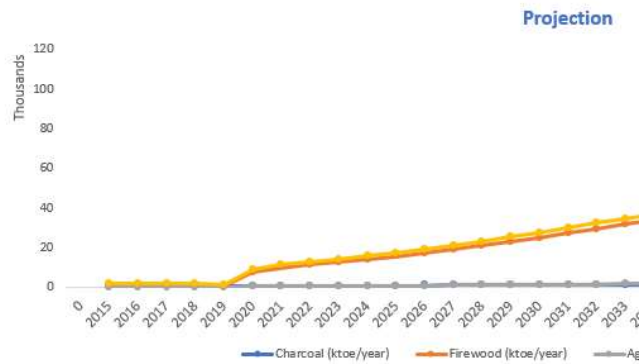
Figure 21: Starting comparative analysis

As it is a new analysis the user needs to select the country of comparison and optionally provide a name for this analysis or choose the same country to compare two scenarios. Once the selection is completed, the projection tab is displayed with the variables and scenario to be performed.

Figure 22: Set comparative analysis scenario and compute analysis

Like the projection analysis, the user can set the scenarios for each variable. Given the user choice of scenario, the future values are predicted and filled in the cells automatically and stored in the **"future_dat" worksheet** from ROW18 to ROW32. The user can manually update each row that suits best for the analysis.

Then the user can compute the analysis with the next button on the right-hand of the settings tab (highlighted red in the figure above) will launch in the background a macro and display a graph to show the output.
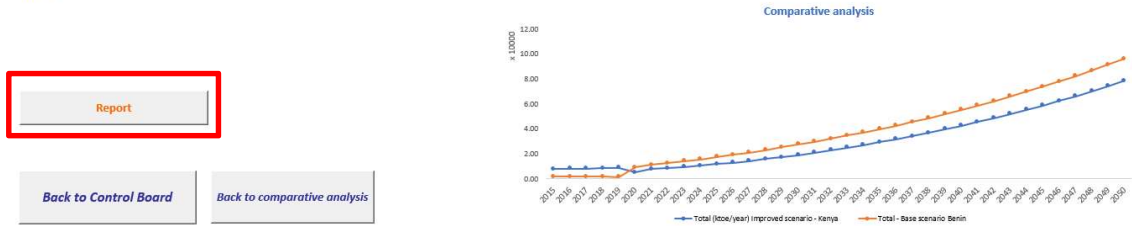
International
Energy Agency

Figure 23: Comparative analysis output

This process is not limited and can be re-iterated as many times as possible.

Emissions

Emissions are directly computed as users is computing the historical and future consumption of solid biofuels and stored them in the **"EmissionsHealth" worksheet.** The worksheet communicates directly with the **"Compute"** worksheet to reflect changes. We obtained solid biofuels emissions by end-uses and per fuel type. Here below is a screenshot of the content of the sheet.

Figure 24: Model emissions output

Dashboard

The dashboard shows the trend of several variables and provided with time and country slicer for additional comparison and displays.
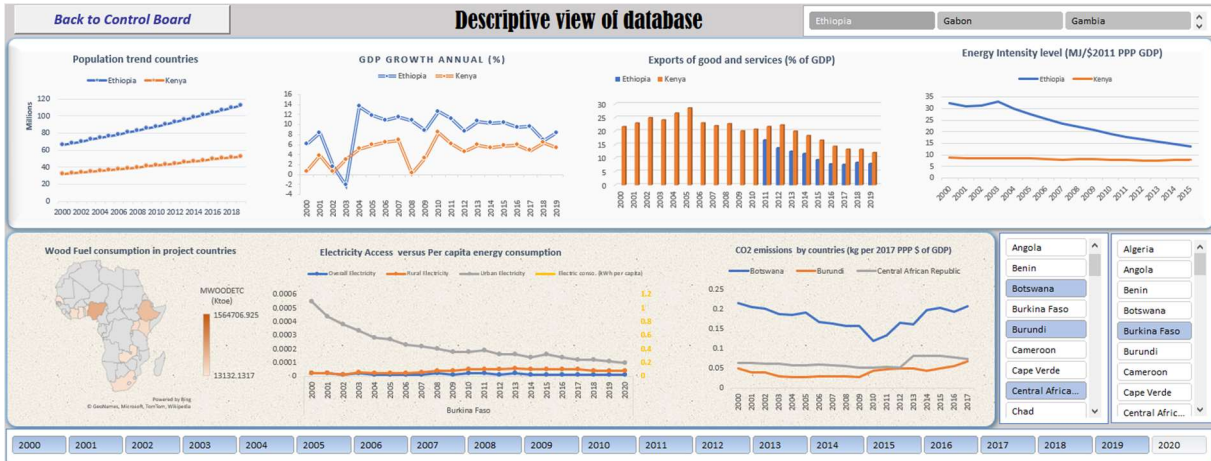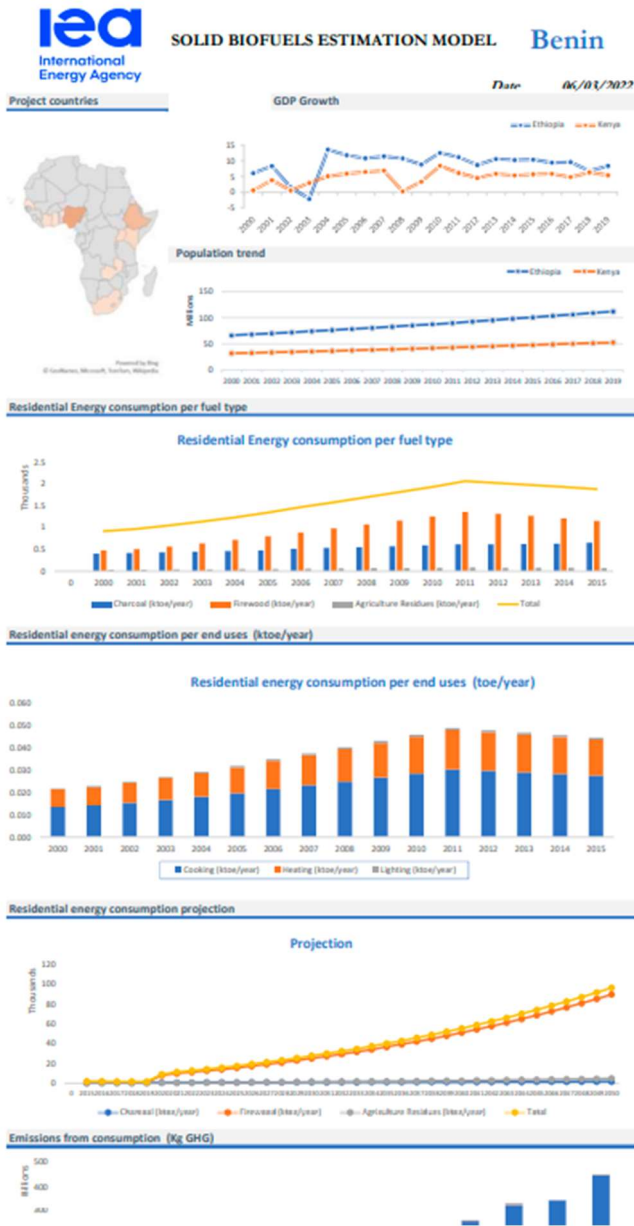

Figure 25: Dashboard screenshot

Print report

All the graphs generated as part of the different analyses are copied to the **"report" worksheet** to help the modeller export this to pdf format for different purposes.

Figure 26: Report screenshot

References

AFREC. (n.d.). AFREC | The African Energy Commission. Retrieved September 7, 2021, from https://au-afrec.org/about.php

Alinaitwe, G. (2021, June). HOUSEHOLD ENERGY DEMAND IN UGANDA: ESTIMATION AND POLICY RELEVANCE. Energy, COVID, and Climate Change,

Atteridge, A., Heneen, M., & Senyagwa, J. (2013). Transforming Household Energy Practices Among Charcoal Users in Lusaka, Zambia: a User-Centred Approach.

BREIMAN, L. (2001). Random forests. In *Random Forests*. https://doi.org/10.1201/9780429469275-8

Ekouevl, K., & Tuntivate, V. (2012). Household Energy Access for Cooking and Heating (World Bank Studies). world bank publications.

Farzaneh, H. (2019). Energy Systems Modeling. In *Energy Systems Modeling*. https://doi.org/10.1007/978-981-13-6221-7

Garba, I., & Bellingham, R. (2021). Energy poverty: Estimating the impact of solid cooking fuels on GDP per capita in developing countries - Case of sub-Saharan Africa. Energy. Published. https://doi.org/10.1016/j.energy.2021.119770

IEA. (n.d.). Mission - About. Retrieved September 7, 2021, from https://www.iea.org/about/mission

IEA. (2015). Share of population relying on different cooking fuels in selected countries, 2015 – Charts – Data & Statistics. https://www.iea.org/data-and-statistics/charts/share-of-population-relying-on-different-cooking-fuels-in-selected-countries-2015

IEA. (2019). Africa Energy Outlook 2019. https://iea.blob.core.windows.net/assets/2f7b6170-d616-4dd7-a7ca-a65a3a332fc1/Africa_Energy_Outlook_2019.pdf

IEA. (2021a). World energy balances 2021 Edition Database [Dataset].

IEA. (2021b). World energy balances 2021 Edition Database documentation. http://wds.iea.org/wds/pdf/WORLDBAL_Documentation.pdf

IRENA. (2019). SOLID BIOMASS SUPPLY FOR HEAT AND POWER TECHNOLOGY BRIEF. IRENA. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Jan/IRENA_Solid_biomass_supply_2019.pdf

Jaime Lynn Speisera, Michael E. Millerb, Janet Toozec, E. I. (2020). *A Comparison of Random Forest Variable Selection Methods for Classification*. *336*, 93–101. https://doi.org/10.1016/j.eswa.2019.05.028.A

Krajnc, N. (2015). Wood Fuels Handbook. Food and agricultural organization of the United Nations.

Kursa, M. B., & Rudnicki, W. R. (2010). Feature selection with the boruta package. *Journal of Statistical Software*, *36*(11), 1–13. https://doi.org/10.18637/jss.v036.i11

Lambe, F., Jürisoo, M., Wanjiru, H., & Senyagwa, J. (2015). Bringing clean, safe, affordable cooking energy to households across Africa: an agenda for action. Stockolm Evironment Institute.

http://newclimateeconomy.report/workingpapers/wp-content/uploads/sites/5/2016/04/NCE-SEI-2015-Transforming-household-energy-sub-Saharan-Africa.pdf

Partnership for Policy Integrity. (2011, April). Air pollution from biomass energy. https://www.pfpi.net/air-pollution-2

Satapathy, S. C., Raju, K. S., & Editors, M. N. F. (2019). *Advances in Computational and Bio-Engineering* (Vol. 1).

The International Agency for Research on Cancer. (2010). Household Use of Solid Fuels and High Temperature Frying (IARC Monographs on the Evaluation of the Carcinogenic Risks to Humans, 95) (Illustrated ed.). World Health Organization.

The World Bank. (2014, November). Clean and Improved Cooking in Sub-Saharan Africa. The World Bank. https://documents1.worldbank.org/curated/en/164241468178757464/pdf/98664-REVISED-WP-P146621-PUBLIC-Box393185B.pdf

UNEP. (2019). Review of Woodfuel Biomass Production and Utilization in Africa [E-book]. United Nations Environment Programme.

Wang, J. (2019). *An ensemble feature selection method for high-dimensional data based on sort aggregation*. 7(2), 32–39. https://doi.org/10.1080/21642583.2019.1620658

WHO, IEA, GACC, UNDP, & World Bank. (2018). POLICY BRIEF #2 ACHIEVING UNIVERSAL ACCESS TO CLEAN AND MODERN COOKING FUELS AND TECHNOLOGIES. https://sustainabledevelopment.un.org/content/documents/17465PB_2_Draft.pdf

World Urbanization Prospects - Population Division - United Nations. (1950–2050). [Dataset]. https://population.un.org/wup

Key definitions

A set of definitions have been used based on the IEA guidelines to keep the same framework used by the organisation.

- **Solid biofuels:** Solid biofuels, using the IEA conceptual framework, is defined as the sum of primary solid biofuels and charcoal. Overall, primary solid biofuels refer to any plant matter used directly as fuel or converted into other forms before combustion. (IEA, 2021)

- **Charcoal:** solid biofuels residual of distillation and pyrolysis of wood and other vegetal material (IEA, 2021). This fuel is selected instead of fuelwood as it has a higher energy density than the former one. Charcoal in Africa is produced mostly by traditional kilns whose efficiency is rated from 8-15%. (UNEP, 2019).

- **Total energy supply (TES):** the final energy flow a country can use for its demand and transformation processes.

$$TES = Total\ energy\ production - Export + Imports - International\ bunkers \pm Stock\ changes$$

- **Total final energy consumption (TFEC):** the quantity used in the different energy demand sectors, subtracting the final non-energy use in a country. For biofuels, the non-energy uses are excluded from the general balances, thus its final calculation requires exclusively the fuel demand for energy purposes at industrial, electricity and heat production, and the other uses among which it is expressed the residential flow.

- **Residential consumption:** refers to the quantity consumed at the household level, excluding transport fuels usage. The quantity also reflects the energy consumed by the home office and a diffe of productive activities made at a household level.

International
Energy Agency

Annexes

Model output

Charcoal Rural

Residuals:

Min	1Q	Median	3Q	Max
-0.0139915	-0.0044373	0.0005825	0.0041291	
0.0130937				

Coefficients :

	Estimate	Std.	Error	t value	Pr(>|t|)
(Intercept)	0.037259	0.313054	0.119	0.907407	
Access to clean fuels and technologies for cooking (% of the population)	0.021699	0.006124	3.543	0.004608	**
Energy intensity level of primary energy (MJ/$2011 PPP GDP)	0.03392	0.005757	5.892	0.000104	***
Population growth (annual %)	0.260735	0.047286	5.514	0.000182	***
Rural Average Household	-0.079152	0.121683	-0.65	0.528736	

Signif. codes: 0 '*' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1**

Residual standard error: 0.007547 on 11 degrees of freedom

Multiple R-squared: 0.9868,	Adjusted R-squared: 0.982

F-statistic: 205.2 on 4 and 11 DF, p-value: 2.989e-10

Charcoal Urban

Residuals:

Min	1Q	Median	3Q	Max
-0.0033386	-0.0020692	-0.0003354	0.0014815	0.0047662

Coefficients :

	Estimate	Std.	Error	t value	Pr(>|t|)	
(Intercept)	0.464768	0.627726	0.74	0.480221		
Access to clean fuels and technologies for cooking (% of the population)	-0.059542	0.002555	-23.305	1.22E-08	***	
Age dependency ratio (% of working-age population)	0.02042	0.005254	3.887	0.004632	**	
Arable land (%land area)	-0.047362	0.013796	-3.433	0.008914	**	
Energy intensity level of primary energy (MJ/$2011 PPP GDP)	-0.011672	0.003413	-3.419	0.009095	**	
Urban Average Household	0.401832	0.058334	6.888	0.000126	***	
GDP growth (annual %)	-0.300612	0.041637	-7.22	9.07E-05	***	
GDP per capita growth (annual %)	0.310514	0.043127	7.2	9.24E-05	***	

Signif. codes: 0 '*' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1**

Residual standard error: 0.003467 on 8 degrees of freedom

Multiple R-squared: 0.9998,   Adjusted R-squared: 0.9997

F-statistic: 7616 on 7 and 8 DF, p-value: 1.188e-14

Firewood Rural

Residuals:

Min	1Q	Median	3Q	Max
-0.0063204	-0.0015644	-0.0001158	0.0017436	0.0041330

Coefficients:

	Estimate	Std.	Error	t value	Pr(>|t|)
(Intercept)	0.144087	0.157018	0.918	0.3785	
Access to clean fuels and technologies for cooking (% of population)	0.0311	0.004119	7.55	1.13E-05	***
Life expectancy at birth, total (years)	-0.02344	0.003431	-6.831	2.84E-05	***
Population growth (annual %)	0.054189	0.01688	3.21	0.0083	**
Rural Average Household	0.867303	0.05316	16.315	4.69E-09	***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.003201 on 11 degrees of freedom

Multiple R-squared: 0.9997,   Adjusted R-squared: 0.9996

F-statistic: 9025 on 4 and 11 DF, p-value: < 2.2e-16

Firewood Urban

Residuals:

Min	1Q	Median	3Q	Max
-0.0082421	-0.0040443	-0.0009956	0.0027975	0.0174716

	Estimate	Std.	Error	t value	Pr(>|t|)	
(Intercept)	1.86963	1.63947	1.14	0.291637		
Life.expectancy.at.birth..female..years.	-10.6311	0.47705	-22.285	9.26E-08	***	
Life.expectancy.at.birth..total..years.	10.94896	0.49723	22.02	1.01E-07	***	
Arable.land....of.land.area.	-0.10078	0.03733	-2.699	0.03067	*	
Age.dependency.ratio....of.working.age.population.	0.04689	0.0161	2.913	0.022579	*	
Urban_Average_Household	1.01622	0.16249	6.254	0.000423	***	
Population.growth..annual...	1.51765	0.5142	2.951	0.021362	*	
GDP.growth..annual...	-0.90543	0.44448	-2.037	0.081062	.	
GDP.per.capita.growth..annual...	0.93547	0.46043	2.032	0.081703	.	

Signif. codes: 0 '*' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1**

Residual standard error: 0.009733 on 7 degrees of freedom

Multiple R-squared: 0.9999,   Adjusted R-squared: 0.9998

F-statistic: 1.105e+04 on 8 and 7 DF, p-value: 1.186e-13

Household specific consumption per fuel type of references countries

Table 3: Average household consumption per fuel type of references countries

Variables	Country	sd	mean	min	max	African literature Acceptable range
Rural Average household woodtec	Angola	0.15	5.43	5.12	5.57	[5.14 - 8.59]
Rural Average household woodtec	Botswana	1.81	24.46	23.58	28.92	[5.14 - 8.59]
Rural Average household woodtec	Morocco	0.87	3.13	2.34	4.85	[5.14 - 8.59]
Rural Average household woodtec	Senegal	2.31	9.22	6.66	12.70	[5.14 - 8.59]
Rural Average household woodtec	South Africa	1.92	7.91	5.85	12.89	[5.14 - 8.59]
Urban Average household woodtec	Angola	0.88	4.41	3.09	6.08	[2.6 - 5.88]
Urban Average household woodtec	Botswana	5.16	16.90	10.68	26.19	[2.6 - 5.88]
Urban Average household woodtec	Morocco	0.59	2.08	1.51	3.26	[2.6 - 5.88]
Urban Average household woodtec	Senegal	2.19	10.63	8.49	15.36	[2.6 - 5.88]
Urban Average household woodtec	South Africa	1.65	4.13	2.33	8.23	[2.6 - 5.88]
Rural Average household charcoal	Angola	0.05	1.58	1.43	1.62	[0.01 - 1.35]
Rural Average household charcoal	Botswana	0.17	1.35	1.09	1.59	[0.01 - 1.35]
Rural Average household charcoal	Morocco	0.00	0.02	0.02	0.02	[0.01 - 1.35]
Rural Average household charcoal	Senegal	0.62	1.85	0.68	2.68	[0.01 - 1.35]
Rural Average household charcoal	South Africa	0.11	0.57	0.43	0.75	[0.01 - 1.35]
Urban Average household charcoal	Angola	0.25	1.28	0.90	1.70	[0.64 - 3.14]
Urban Average household charcoal	Botswana	0.11	0.89	0.72	1.02	[0.64 - 3.14]
Urban Average household charcoal	Morocco	0.00	0.01	0.01	0.01	[0.64 - 3.14]
Urban Average household charcoal	Senegal	0.86	2.23	0.65	3.24	[0.64 - 3.14]
Urban Average household charcoal	South Africa	0.10	0.29	0.17	0.48	[0.64 - 3.14]

International
Energy Agency