



Models and Tools for Integrated Clean Cooking Planning. Case example of Rwanda.

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Acronyms

AEPC	Alternative Energy Promotion Centre
ArcGIS	General purpose GIS software system developed by ESRI
BARHAP	Benefits of action to reduce household air pollution
BAU	Business as Usual (used for the average future scenario)
BC	Black carbon
BCRM	Branded Cylinder Recirculation Model
BEST	Biomass Energy Strategy
BRD	Rwanda Development Bank
CAP	Country Action Plan
CAPEX	Capital Expenditure
CCA	Clean Cooking Alliance
CCAP	Clean Cooking for Africa Program
CCE	Clean Cooking Explorer
CCF	Clean Cooking Fund
CCDI	Clean Cooking Data for All initiative
CCPT	Clean Cooking Planning Tool
CEBGF	Cooking Energy Business Growth Fund
CFET	Cooking Fuel Energy and Technologies
CNSE	Cost of Non-Served Energy
CO ₂	Carbon Dioxide
CO _{2e}	Carbon Dioxide equivalent
DALYs	Disability-adjusted life years
DeSIRA	Development-Smart Innovation through Research in Agriculture
DFI	Development Financial Institution
DRB	Demonstrably Renewable Biomass
DSIEP	Data Standards for Integrated Energy Planning
€	Euros, European currency
EAE	Energy Access Explorer
EAP-RE	Europe-Africa Partnership for Renewable Energy program
EAQIP	Rwanda Energy Access and Quality Improvement Project
EBITDA	Earnings Before Interest, Taxes, Depreciation, and Amortisation
EDCL	Energy Development Corporation Ltd
EEP	Energy and Environment Partnership Trust Fund
EICV	Integrated Household Living Conditions Survey
ENABEL	Belgian Development Agency
EnDev	Energising Development
EPC	Electric Pressure Cooker
ESMAP	Energy Sector Management Assistance Program
ESRI	Environmental Systems Research Institute, Inc.
ESSP	Energy Sector Strategic Plan
EU	European Union
EUCL	Energy Utility Corporation Limited
FAQ	Frequently Asked Questions
FAO	Food and Agriculture Organisation
FCDO	UK's Foreign, Commonwealth, and Development Office
FISE	Energy Social Inclusion Fund (Perú)
FIX	Used to refer to fixed costs
fNRB	Fraction of non-renewable biomass
FOM	Fixed Operation and Maintenance (costs)
FRW	Rwandan Franc
GAINS	Greenhouse Gas and Air Pollution Interactions and Synergies
GCCA+	Global Climate Change Alliance Plus
GCF	Green Climate Fund
GDP	Gross Domestic Product
GEF	Global Environment Facility
GEP	Global Electrification Platform
GeoJSON	Open standard format for encoding geographic data structures, based on JSON
GeoTIFF	Geographic Tagged Image File Format
GHG	Greenhouse Gas
GIS	Geographical Information System
GIZ	German Agency for International Cooperation
GLPGP	Global LPG Partnership
GoR	Government of Rwanda

GPP	Global Petrol Prices
GWP	Global Warming Potential
ha	Hectare
HAP	Household Air Pollution
HAPIT	Household Air Pollution Intervention Tool
HH	Household(s)
HV	High Voltage
HV/MV	High Voltage to Medium Voltage (used for substations)
ICCP	Integrated Clean-Cooking Planning
ICS	Improved Cook Stove
IEA	International Energy Agency
IIASA	International Institute of Applied System Analysis
IIT	Institute for Research in Technology, ICAI School of Engineering, Comillas University
IMF	International Monetary Fund
IPCC	Intergovernmental Panel for Climate Change
IUCN	International Union for Conservation of Nature
JSON	JavaScript Object Notation
KfW	German promotional (development) bank
kg	Kilogram
kgCO ₂ Eq	Kilograms of equivalent CO ₂ , unit for emissions
km	Kilometre
KPI	Key Performance Indicator
KTH	Kungliga Tekniska Högskolan (Royal Institute of Technology in Stockholm)
kV	Kilovolt
kVAr	Kilo-Volt-Ampere, reactive power
kW	Kilowatt
kWh	Kilowatt hour
l	Litre
LCCM	Levelized Cost of Cooking a Meal
LCOC	Levelized Cost of Cooking
LCOE	Levelized Cost of Electricity (or Energy)
LNG	Liquefied Natural Gas
LMIC	Low- and Middle-Income countries
LPG	Liquefied Petroleum Gas
LREM	Little (or Local) Reference Electrification Model
LV	Low Voltage
m	Meter (distance unit)
M	Millions, or "Mega"
Matlab	Development tool and programming language, abbreviation for "matrix laboratory"
MECS	Modern Energy Cooking Services
MINECOFIN	Ministry of Finance and Economic Planning
MINICOM	Ministry of Commerce
MININFRA	Ministry of Infrastructure
MIT	Massachusetts Institute of Technology
MITMA	Spanish Ministry of Transportation, Mobility and Urban Agenda
MOE	Ministry of Environment
MT	Metric ton = 1000 kg
MTF	Multi-Tier Framework
MV	Medium Voltage
NA	Not Applicable
NDC	Nationally Determined Contributions
NDF	Nordic Development Fund
NEP	National Electrification Plan (of Rwanda)
NHRDLCP	National High-Resolution Dynamic Least Cost Options Plan
NICCP	Rwanda National Integrated Clean-Cooking Plan
NIEPT	Nigeria Integrated Energy Planning Tool
NISR	National Institute of Statistics of Rwanda
Norad	Norwegian Agency for Development Cooperation
NPV	Net Present Value
NRB	Non-Renewable Biomass
NSE	Non-Served Energy
NST1	National Strategy for Transformations
OC	Organic Carbon
OGC	Open Geospatial Consortium
OnSSET	Open-Source Spatial Electrification Tool
OPEX	Operational Expenditure

PBL	Netherlands Environmental Assessment Agency
PPP	Public Private Partnership
PV	Photovoltaic
p.u.	Per-unit or percentual magnitude
QGIS	Quantum GIS, open-source SW for GIS applications, handling raster and vectorial formats, and databases
RAB	Regulated Asset Base
RBF	Results-Based Financing
RBS	Rwanda Standards Board
RCA	Rwanda Cooperative Agency
ReCIC	Reducing Climate Impact of Cooking in Rwanda through improved cooking systems
REG	Rwanda Energy Group
REM	Reference Electrification Model
REMA	Rwanda Environment Management Authority
RF	Rockefeller Foundation
RFA	Rwanda Forestry Authority
RICCP	Rwanda Integrated Clean Cooking Plan
RLMA	Rwanda Land Administration and Use Authority
RNLGMP	Rwanda National LPG Master Plan
RNM	Reference Network Model
ROE	Return on Equity
ROI	Return on Investment
RPHC4	Fourth Rwanda Population and Housing Census
RPHC5	Fifth Rwanda Population and Housing Census
RR	Revenue Requirement
RSB	Rwanda Standards Board
RURA	Rwanda Utilities Regulatory Authority
RWF	Rwandan franc
SDG	Sustainable Development Goals
SEforALL	Sustainable Energy for All
SHEAR	Sustainable Household Energy Adoption in Rwanda
SHS	Solar Home System
SLCP	Short-Life Climate Pollutants
SNV	Netherlands Development Organisation
STIS	Socio-Technical Innovation System
SW	Software
TCO	Total Cost of Ownership
Time&Gender	Time and Gender attribute to evaluate the time spent and the inconveniences of cooking technologies
Ton	Metric ton = 1000 kg
TREPA	Transforming Eastern Province Through Adaptation
TWG	Technical Working Group
UK-Aid	Foreign aid agency of the United Kingdom
UNDP	United Nations Development Programme
UNHCR	United Nations Refugee Agency
USD	United States Dollar (\$)
UTM	Universal Transverse Mercator (projection, or coordinate system)
VAR	Used to refer to variable costs
VHV	Very High Voltage
VHV/HV	Very High Voltage to High Voltage (used for substations)
VOM	Variable Operation and Maintenance (costs)
WB	World Bank
WEM	World Energy Model
WHO	World Health Organisation
WLPGA	World LPG Association
WRI	World Resources Institute

Dictionary of terms and keywords

Access	Refers to "Fuels" , "Appliances" , and "Technologies" . It is the percentage of consumers of a given area that could use (have access to) a particular fuel, appliance, or technology. Example: for electric cooking, it would be the percentage of consumers with an electric supply compatible with the peak power and daily energy required for cooking.
Adoption	Refers to the adoption of technologies. It is the percentage of the cooking demand (or "C-Demand") satisfied by a given "Technology" . It could be applied to a single household, to an aggregated group of consumers, or to a whole country.
Appliances (set)	Category of the set of cookstoves and kitchenware used for a given cooking "Fuel" . The category is defined by its average parameters, like price, lifetime, efficiency, or emissions rate. A combination of "Fuel" and "Appliances" defines a "Technology" . In this work, a maximum of 3 appliance sets have been defined for each fuel.
Appliances (market)	The appliances market estimation is made by dividing the total annual usage of each type of appliance (country level) by the lifetime of the type of appliance, both in cooking demand units (cooks). Therefore, it represents the number of appliances "consumed" annually, which in a steady state would coincide with the number of appliances of each type to be deployed annually (sold or repaired).
Attribute	A relevant "Effect" used to evaluate plans (by the planner) or technologies (by the consumers). Here, the attributes are "Economic costs" , "Social costs" , "Health" , "Time&Gender" , "Emissions" , and "Deforestation" .
Availability	Refers to "Fuels" , "Appliances" , and "Technologies" . It is defined as a combination of two percentage parameters: "Access" and "Capacity" .
Biomass Pattern	See "Pattern" .
Blended Finance	The use of both public and private funds to finance a project.
C-Demand	Cooking demand, measured in "Cooks" .
Capacity	Refers to "Fuels" , "Appliances" , and "Technologies" . It is the percentage of the total cooking demand of a given area that could be satisfied using a particular fuel, appliance, or technology. The capacity of a technology is the minimum of the capacity of the fuel and the capacity of the appliances, since a technology is the combination of both. In the case of fuels, it depends on the total quantity that could be supplied per year (or another time unit). In the case of appliances, it depends on both the quantity supplied per time and the lifetime of the appliance. In this work, the capacities for electricity and LPG are adjusted to the actual local "Adoption" of the technologies, plus some capacity margins defined by the user.
Capital Structure	The mix of debt, equity, and other forms of financing used by an organisation or project.
Carbon Credits	Tradable certificates that represent the right to emit a certain amount of carbon dioxide or other greenhouse gases.
Concessional loans	Loans offered on more generous (lower interest) terms than market loans to support development projects, often with lower interest rates and longer repayment periods.
Cook (unit)	The cooking-demand unit defined here, so that the unit itself and the demand profile "C-Demand" are independent of the "Technology" used. The Cook is defined as "the cooking demand satisfied with 1 kWh of electricity when cooking with a hotplate, heated by Joule effect (resistor), and using non-efficient kitchenware."
Deforestation	This is a specific "Effect" selected as an "Attribute" . It is evaluated as the amount of kg of wood used, either as a raw material or as a cooking fuel.
Demand area	A territory partition defined as the set of buildings (consumers) belonging to the same "Planning area" and to the same "Supply area" for each and all the "Fuels" . Consequently, all the external conditions (like prices and "Availabilities" of cooking technologies) are homogeneous for the consumers of the demand area. In part of this work, the demand area has been aggregated to the district level (30 demand areas).
E-Demand	Electric demand excluding electric cooking, measured in kWh.
Economic costs	This is a specific "Effect" selected as an "Attribute" . From the planner's perspective, it is the cost for the State, as it is ultimately responsible for public services and welfare. From the consumer perspective, it is used as the cost of each "Technology" (a combination of price and efficiency), and the average cooking costs.
Effect	A result of the evaluation of a "Plan" subject to a given "Scenario" and using "Off-line inputs" . Some relevant effects are selected as "Attributes" , either to evaluate plans (by the planner) or technologies (by the consumers). Other effects provide additional information to analyse a plan, like the penetration of clean-cooking technologies or the average cost of cooking for the population. The results include other types of information, like the "Adoption" of different technologies over time (by groups of consumers or by "Planning Area") or sectoral cash-flows estimated from the "Economic costs" effect.
Emissions	This is a specific "Effect" selected as an "Attribute" . It is evaluated as the amount of kg of CO ₂ equivalent. Emissions include the whole supply chain, from raw materials to the kitchen.
Equity	Investments made directly by stakeholders (require confidence in the long-term viability of the projects).

Fuel	A specific fuel used for cooking, defined at the kitchen point or end of the supply chain (a different concept is the raw material at the beginning of the supply chain). In this work, 9 different fuels have been considered: “Electricity” (at the connection point), “LPG”, “Biogas” (only individual systems), “Charcoal”, “Commercial Firewood”, “Free Biomass” (collected, crops waste, forest waste, and similar fuels), “Pellets” (which includes other similar fuels, like briquettes or sawdust), “Free Firewood” (collected), and Ethanol. Note the use of capitalisation to identify the keyword. For instance, “Electricity” means the specific electric-cooking fuel, while “electricity” would be the generic and common term for the kind of energy or the economic sector.
H-Demand	Heat demand for other purposes (not for cooking), measured in “ Cooks ”.
Health	This is a specific “ Effect ” selected as an “ Attribute ”. It is evaluated as the damage to the population, especially women and children. These damages are usually calculated using the adverted Disability Adjusted Life Years (DALYs) and deaths. The values for different “ Technologies ” have been normalised with respect to the use of three-stone systems with firewood or biomass.
Interactive tool	The “what-if?” computer tool in charge of evaluating the “ Effects ” or results of a given “ Plan ” subject to a given “ Scenario ”, using “ Off-line inputs ” that have been generated with the use of “ Off-line tools ”.
Measure (of a Plan)	A specific physical action or decision, either about investments (like infrastructures to be deployed) or about pricing and regulations (like subsidies, incentives, regulated tariffs, and taxes), in specific time stages and locations, and for any cooking technology. A set of measures defines a “ Plan ”. The types of measures are called “ Policies ”; for instance, a policy could be “apply a tax on charcoal”. A measure of this type could be to apply a 20% tax to charcoal during the first “ Stage ” of the “ Plan ”.
NICCP	National Integrated Clean Cooking Plan, the clean cooking “ Plan ” proposed in this work.
Off-line inputs	Inputs to the “ Interactive tool ” that are not interactive. They are computed off-line, either because they are constant data or configuration parameters established in advance or because they require complex processes and “ Off-line tools ” that take considerable computing time.
Off-line tools	Computer tools in charge of data preparation, parameter estimation, or pre-design of infrastructures (for Electricity and LPG). They generate or assist in generating the “ Off-line inputs ” required by the “ Interactive tool ”.
Operating Margin	Measure of profitability considering operating income as a percentage of revenue.
Pattern (Biomass)	Land-use feature, or geographical environment, that affects the availability of biomass fuels, and therefore local prices and the inconveniences of gathering fuels. Three patterns are used: CITY (buildings), AGRO (agriculture), and FORE (trees). These three are combined with rural and urban features (local density of buildings).
Plan	A clean cooking plan is defined as a set of “ Measures ” – physical actions and decisions – in multiple time stages and locations and for all cooking technologies. The types of measures are called “ Policies ”.
Plan1	First period or “ Stage ” of a “ Plan ”. For instance, from 2024 to 2030.
Plan2	Second period or “ Stage ” of a “ Plan ”. For instance, from 2030 to 2035.
Planning area	Administrative territory partition (here the District, the Province of the Country) that is relevant for analysing results and applying planning decisions.
Policy	A type of “ Measure ”. For instance, a policy could be to “apply a tax to charcoal”. A measure of this type could be to “apply a 20% tax on charcoal during the first Stage of the Plan ”.
Reference years	Initial, intermediate, and final years that define the time span of a “ Plan ”. They are used to define the two “ Stages ” and the five “ States ” related to the plans. For instance, the years 2023, 2029, and 2034.
Scenario	Set of uncertain socio-economic parameters defined by the user of the “ Interactive tool ” to describe the context in which a “ Plan ” will be applied, thus affecting the “ Effects ” or results of the plan.
Social costs	This is a specific “ Effect ” selected as an “ Attribute ”. It is a weighted average of other effects (and also attributes): “ Health ”, “ Time&Gender ”, “ Emissions ”, and “ Deforestation ”.
Stacking	The use of multiple cooking technologies by a consumer, either individual or aggregate. The resulting technology mix can be described as the “ Adoption ” of technologies, as percentual shares of the total cooking demand.
Stage (of a Plan)	Each of the two planning periods, “ Plan1 ” and “ Plan2 ”, defined by the chosen “ Reference years ”. The stages could be, for instance, 2023-2029 and 2029-2034.
State (of a Plan)	Each of the five quasi-static periods (semesters) evaluated in depth by the “ Interactive planning tool ”. For instance, they could be the first and second semesters of years 2023 and 2029 and the first semester of year 2034. The first state represents the starting point or baseline, and the other four states represent the beginning and end of the two planning “ Stages ”.
Social cluster	A type of consumer, or a consumer profile, characterised by a set of behavioural parameters. For instance, two social clusters used in this work are the average rural household and the average urban household.

Supply area	A territory partition related to the supply chain of a specific fuel, defined as the set of buildings (consumers) belonging to the same supply subsystem. In the case of electricity, those buildings that would be connected to the same HV/MV substation. In the case of LPG, those buildings that would be supplied from the same local warehouse. In the initial phase of this work, the supply areas were aggregated at the district level (30 supply areas).
Tariff income	The direct revenue generated from users.
Technology	A cooking technology, defined by a combination of “ Fuel ” and “ Appliances ”. In this work, 19 technologies have been defined as combinations of 9 fuels and 13 sets of appliances.
Time&Gender	This is a specific “ Effect ” selected as an “ Attribute ”. It is evaluated as time spent and inconvenience in general (suffered mainly by women) in the preparation-cooking-cleaning process in the kitchen and the fuel-gathering process. The values for different “ Technologies ” have been normalised with respect to the use of three-stone systems with firewood or biomass.
Viability gap funds	Financial support needed to cover the shortfall between project operating costs and the revenues generated, often used in infrastructure projects.

Executive summary

This document presents the models and tools designed and implemented to develop a National Integrated Clean Cooking Plan (NICCP) for Rwanda. It is an innovative approach based on interactive computer tools, applicable to integrated clean-cooking planning for any other country or region. The methodology and the tools developed in this work are intended to become a living instrument for governments and collaborators to make and adapt decisions in a dynamic and informed way. This approach helps the planning team to estimate the future outcome of their planning decisions and to search efficiently for the combination of decisions that is likely to lead to the most desirable outcome.

A clean cooking plan is defined as a set of “measures” – physical actions and decisions – consisting of (i) investments (infrastructures to be deployed, supply chains to be established, and support to the business models necessary to implement the investments) and (ii) policy and regulatory decisions (subsidies and incentives to be applied, and regulated tariffs and taxes to be set up), in multiple time stages and locations, and for a wide range of cooking technologies. Examples of investment are the electrification of some villages by extending the grid, or the creation of the infrastructure of transport and storage of LPG canisters in a region of the country. An example of a policy decision is the taxation of certain fuels, such as charcoal.

In addition to the “measures” adopted by the planning team, the outcome of a plan is affected by the “context”, i.e., those inputs that have an impact on the outcome of the plan but that are beyond the control of the planning team. For example, the price of imported LPG or the national currency devaluation.

The presented methodology is based on an informed trial-and-error process using an interactive “what if?” approach. The tool estimates the “effects” of a “plan” subject to a given context or “scenario”. Other inputs are not interactive: they are computed off-line, either because they are constant data, configuration parameters established in advance, or because they require complex processes and tools that take a considerable computing time.

The consequences of the set of measures that define a plan are determined by the interactive planning tool developed in this work and are very diverse. For instance, the number of people that decide to switch their current cooking technology, either totally or partially, according to their preferences and the characteristics and cost of the different options, the economic costs of implementing the measures, the associated level of deforestation, and the estimated number of casualties associated with traditional cooking practices. It is impossible to achieve all the desired objectives simultaneously – for instance, a plan with the minimum economic cost will likely have undesirable consequences in other aspects.

The planning team must choose among many alternative plans due to the multiple degrees of freedom of the problem. The objective here is to find an ensemble of the “best” feasible plans, i.e., those with the best combination of desirable outcomes, leaving the final choice of the plan to be adopted by the human decision-maker.

Two successive versions of the planning tool have been developed with increasing granularity, flexibility and complexity. The first version has been tailored for Rwanda. It uses the district level to define administrative, supply, and demand areas. The external tools (Electricity, LPG, and Biomass) work at the target level of granularity, and then their results are aggregated to the district level. It is also focused on the residential demand. The country is represented by 60 aggregated consumers, accounting for 30 districts disaggregated into Rural and Urban. The second version, currently in the final stages of development, will (a) provide more granular and accurate results in geospatial and social terms and (b) be flexible enough to apply the model to other contexts, countries or regions; will handle about 800 aggregated consumers, including commercial, industrial and public demand profiles and residential consumers belonging to different socio-economic layers.

It cannot be stated that any plan is the best possible plan. First, because no such thing exists in problems with conflicting criteria, such as economic costs and different types of social costs. Second, because of aspects not included in the models, like socio-political constraints or practical problems in implementing some measures. Finally, other combinations of measures could be preferable from different points of view. However, it can be stated that a particular plan is expected to result in some positive effects as estimated by the interactive tool, that those effects are robust with respect to diverse uncertain scenarios, and that the effects are objectively better than those of other alternatives.

The main positive effects that may be used to evaluate the adequacy of a particular plan are the following:

- Penetration of clean cooking technologies in terms of percentual share, where Tier-4 and Tier-5 improved cookstoves are considered clean technologies, not transitional.

- Decrease in the relative cost of cooking for the population, considering the expected economic growth of the country.
- Reduction of health damages in absolute and/or relative terms. Health damages can be translated into premature deaths and Disability Adjusted Life Years (DALYs).
- Reduction of emissions, measured in tons of CO₂-eq per year. This is good for global and local environmental reasons, and it can be monetised in the context of a carbon economy.
- Reduction of wood consumption in tons per year. This is a proxy for deforestation reduction.
- Reduction of the here-defined Time & Gender cost, in absolute and/or relative terms. It measures the time wasted and the inconveniences in general due to fuel gathering and the cooking process, mainly suffered by women. This effect may be translated to days per year that could otherwise be devoted to work, education or leisure time.

The economic costs of the implementation of any plan are analysed and taken into consideration in two steps. First, cash flows and balances between incomes (regulated tariff incomes, taxes) and expenditures (investments and OPEX for regulated fuels, subsidies to other fuels and appliances) are found. Second, a financial model is applied to support the economic costs through grants, debt, equity, direct subsidies, and concessional loans.

The planning examples and the models and tools developed are the result of a collaboration between the Government of Rwanda, Sustainable Energy for All (SEforALL), the Institute for Research in Technology (IIT) of the ICAI School of Engineering at the Pontifical University of Comillas and the Energy Initiative of the Massachusetts Institute of Technology (MIT). This report presents the approach, the capabilities of the computer-based tools that have been developed, the results that can be obtained from their utilisation, and some implementation details. The document is designed to understand the models and the tools. However, the main goal is to provide the basic information for using the tools, prioritising the description of inputs and outputs over the internal algorithms.

1. Introduction

This document presents the models and tools for Integrated Clean-Cooking Planning (ICCP), including a financing approach, designed and implemented for developing a National Integrated Clean Cooking Plan (NICCP) for Rwanda. These models and tools define an innovative approach based on interactive computer tools that may be applied to future states of the country, as well as other contexts or countries. The tools help the planning team to estimate the future outcome of their planning decisions and to search efficiently for the combination of decisions that is likely to lead to the most desirable outcome.

The goal of clean-cooking planning is to find adequate and feasible ways to replace traditional cooking with cleaner cooking technologies. Traditional cooking uses biomass as fuel in an inefficient way. It causes environmental problems, such as deforestation and greenhouse gas emissions. It also causes health problems and consumes time (in gathering fuel and cooking), mainly affecting women. All these negative effects will be addressed as social costs.

Governments may design an integrated clean-cooking plan to mitigate these effects by supporting and promoting modern cooking technologies (electricity, gas) or transitional technologies such as improved cookstoves or the use of biomass waste from crops or livestock. A clean-cooking plan may be defined as a set of decisions:

- Some decisions are related to investments: infrastructures, supply chains, and businesses that will implement these investments.
- Other decisions may concern pricing/regulatory policies: prices, subsidies, incentives, regulated tariffs, and taxes.
- The decisions may be assigned to different locations and different time stages.

Since the tariffs and prices paid by the consumers may not cover the total cost of the plan, especially in the initial years, the plan has a cost, at least financially, for the State and the rest of the agents involved. Depending on the formulation of the economic model, they will be addressed as techno-economic or financial costs.

The methodology proposed here involves developing an assistant software (SW) tool based on the “structured multi-attribute optimisation” principles.

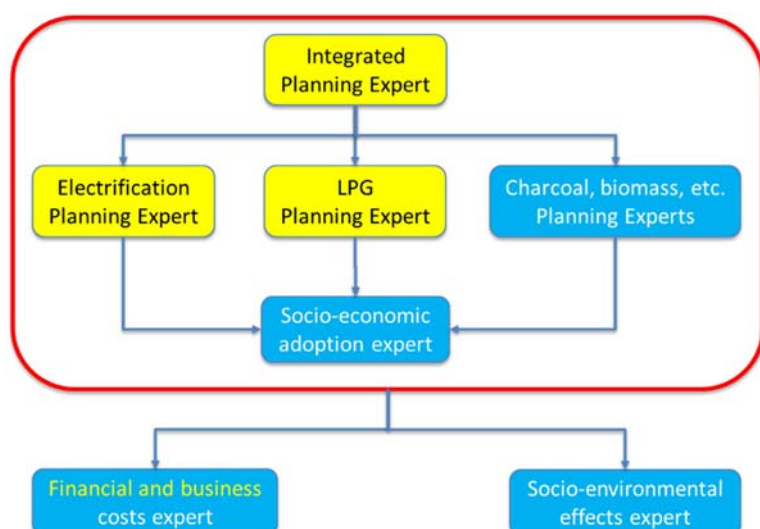
Planning is an optimisation problem because there are many alternative plans, and the goal is to find the “best” set of feasible plans. There is not a single “best” plan, because the trade-off between social costs and economic costs leads to a multi-attribute optimisation, being the final decision made by the responsible planner (the user of the optimisation tool).

The “structured” label refers to breaking the complex optimisation problem into a structure of optimisation and simulation sub-problems. It resembles human organisations where specific tasks are assigned to specialised teams of experts. Figure 1 shows an example of such a structure. Teams in charge of optimisation tasks are depicted in yellow, while teams in charge of simulation (or estimation) tasks are shown in blue.

In the figure, the roles of these specialised teams may be described as follows:

- The “Integrated planning expert” sets deployment targets and pricing policies for different technologies.
- The “Electrification and LPG planning experts” develop optimum supply chains for the given deployment targets.
- The “Charcoal and biomass planning experts” estimate the response to pricing policies of local markets for charcoal, firewood and other biomass products, as well as local markets for efficient biomass cookstoves.
- The “Socio-economic adoption expert” estimates the actual adoption of cooking technologies by different clusters of customers, given the availability and prices of those technologies.
- Finally, there are two expert teams in charge of estimating the two attributes that must be considered to evaluate a given plan: the financial cost and the socio-environmental cost.

Figure 1. Example of a breakdown of tasks and subproblems.



This complex process must deal with detailed geo-referenced data, dynamic effects along different time stages, and multiple context data (economic, technical and social parameters). This is why the data acquisition and preparation procedures are critical. On the other hand, the results will also be complex, so a significant effort must be made to display them by visualisation tools and reporting procedures.

The MIT-IIT team has solid expertise in massive electrification-planning tools/models, such as REM and RNM (Mateo Domingo, Gómez San Román, Sánchez Miralles, Peco González, & Candela Martínez, 2011), (Ciller, et al., 2019). However, the integrated clean-cooking planning problem is a qualitative leap in size and complexity. These are the main features that make the problem so challenging, with some comments about the topics related to each feature:

- Multiple technologies. This is the main source of complexity. The actual demand for each technology is unknown, and technologies compete against each other. Individual consumers may use several technologies simultaneously (stacking), and therefore, aggregate consumers will do it as well. Consumers of the same type may use different technology mixes, depending on the context, habits, or just their freedom of choice.
- Multiple types of consumers. Consumers may behave differently in similar environments by nature (residential, public, commercial, industrial) or socio-economic level. Behavioural models are required to estimate consumers' response to external factors such as access, availability and price.
- Seek universal adoption, not universal access. In electrification planning problems, demand is assumed to be certain when access is provided, maybe with some elasticity to tariffs. In clean-cooking planning, demand is already covered, although with undesired technologies. Access to cleaner technologies does not guarantee their adoption. The change of habits involves access, affordability, willingness to pay, and willingness to change.
- Multi-attribute problem. In electrification planning problems, the economic cost is the only attribute to be minimised since social effects such as “non-served energy” (due to lack of availability or reliability) are usually monetised. In clean-cooking planning, social costs are not easily monetised because they include diverse environmental, health, and social (time and gender) factors. Therefore, these factors should be kept explicit in the optimisation process so that the decision-makers can make informed choices.
- Complex financial models. Clean cooking involves multiple sectors, some regulated and others non-regulated, and even free fuels (like gathered firewood or biomass) competing against commercial ones. Moreover, the response to tariffs and pricing policies, in general, is not just elasticity but a shift to another technology mix.

All the sources of complexity mentioned above imply that more uncertain factors are involved. Not only economic and population growth, but also the evolution of costs and prices in diverse sectors, and even changes in the behaviour of consumers. This is why an interactive and dynamic tool is required, capable of providing results for multiple plans against diverse scenarios, checking robustness, and adapting plans to a changing environment.

This document is designed to understand the models and the tools. However, the main goal is to provide the basic information for using the tools, prioritising the description of inputs and outputs over the internal algorithms.

Section 2 presents the general approach and its distinctive features, with the main purpose of presenting the critical concepts of the model required to understand the following sections. Section 3 is devoted to the main tool, the Techno-economic Planner, describing the main inputs, outputs, models and sub-problems.

Once the general framework and the features of the tool are established, sections 4, 5, 6, and 7 are devoted to the off-line inputs, classified by the particular level of pre-processing required by each one. Section 8 is focused on the interactive inputs, those that will be changed most frequently by the user of the planning tool: the proposed plans and the scenarios (external uncertain factors). Section 9 describes the main outputs of the tool, including some post-processing results derived from the direct outputs.

Finally, Section 10 describes the Financial Planner, a relevant post-processing tool in charge of the financial analyses of plans. Among the plans generated by the user's interaction with the Techno-economic Planner, the user may select some candidates to be tested against one another, subject to a realistic financial analysis.

2. Description of the general approach

The approach is based on previous experiences, the specific analysis of the problem under study, the breakdown of the problem into sub-problems, and the analysis of those sub-problems. This section covers the use of semi-automatic (interactive) tools, the optimisation/simulation approach, the breakdown of the problem into sub-problems, and the application of multi-attribute criteria.

2.1. The use of semi-automated planning tools

The problem addressed in this project can be described as “large-scale and long-term clean-cooking planning”. A clean-cooking plan may be defined as a set of decisions directly related to investments (infrastructures, supply chains, businesses that will implement these investments) and another set of decisions concerning pricing/regulatory policies (subsidies, incentives, regulated tariffs, taxes), in multiple time stages and locations, and for diverse cooking technologies. It is an optimisation problem because there are many alternative plans, due to the degrees of freedom of the problem, and the goal is to find the “best” set of feasible plans.

Experience shows that semi-automated planning tools are the best way to tackle this problem. On the one hand, massive data handling and complex optimisation/simulation procedures require automation. On the other hand, the results will always depend on assumptions, scenarios, and policies that must be considered as external inputs to the problem under analysis, which should be stated explicitly by human planners.

Figure 2. Proposed architecture for the tools in Phase-II prototype.

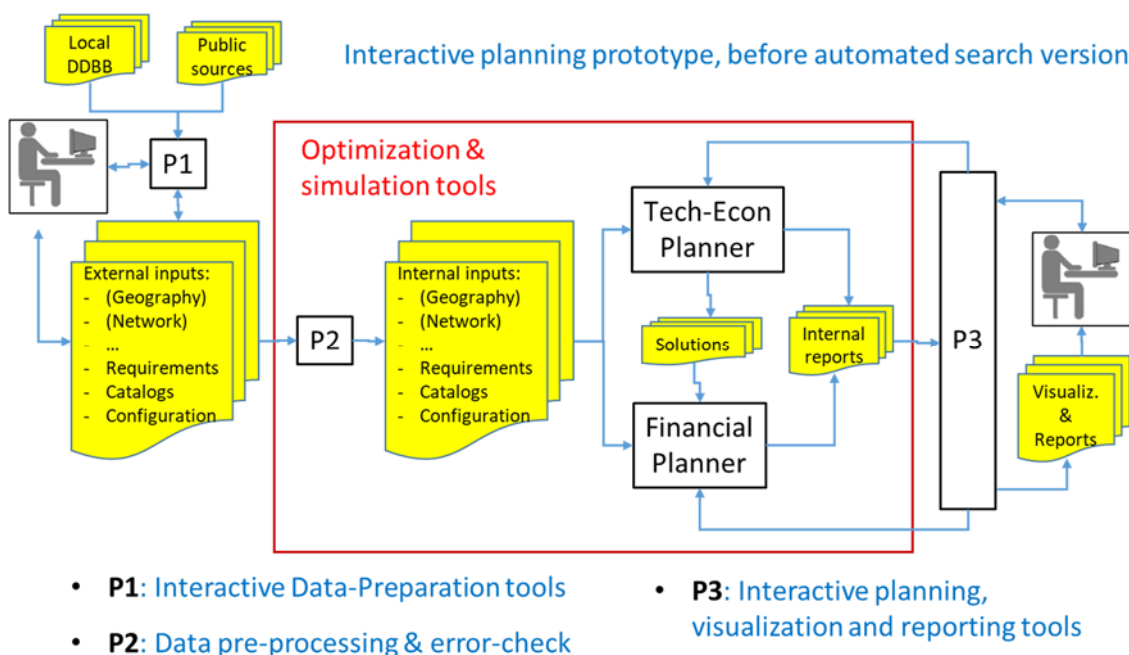


Figure 2 shows a basic architecture for a semi-automated planning tool applicable to the clean-cooking problem, in which:

- In the data-preparation phase, the human planner gathers and processes data about the country, the initial state before planning, configuration parameters, and any other stable inputs.
- In the interactive phase, the human planner tries diverse plans under different future scenarios and gets feedback from the tool.
- In the post-processing phase, some plans and their results are analysed in more detail and translated to reports, including geospatial visualisation.

A more advanced version of the tool could add the search and selection phase to the automated functionality. The reason for this intermediate prototype is that the automated search procedure may require a significant computing time, even days. Therefore, an efficient search strategy is critical, and (maybe more relevant), it would only make sense if there is blind confidence in the results. An interactive prototype allows for testing the internal modules, thinking of efficient strategies, and refining the internal models. In any case, the tool would always have some manual or interactive functions, such as the selection of configuration parameters or the definition of future scenarios.

The main processes shown in the figure are briefly described below.

- P1. Interactive Data-Preparation tools. In charge of importing data from diverse sources to fill the different data layers and interacting with the human planner to fill configuration parameters (assumptions, selection of scenarios, and so on). Extra functions include format translation, partial error-checking (partial consistency), visualisation of data layers, and data repository management.
- P2. Data pre-processing and error-check. A specific planning case will comprise multiple data layers and a set of configuration parameters. Each data layer must be partially consistent and error-free, and the set of inputs must be consistent considering all the data layers. Moreover, the inputs must often be translated and processed according to the needs of internal optimisation and simulation procedures.
- P3. Interactive reporting and visualisation tools. The internal optimisation and simulation procedures will produce solutions described using internal data structures and formats. These solutions must be post-processed to make the results understandable and accessible via visualisation tools and translated into reports with illustrative tables and figures. Other functions may be related to managing a results repository to allow sensitivity reports (comparative analyses of multiple cases). In the version with a manual search of plans, P3 must play the role of an interactive planning interface. This means allowing the cause-effect cycle of trying different planning targets, which will be different availabilities and prices for different technologies in different regions. However, since the process is already assumed to be interactive, other sensitivity analyses could also be implemented in the same trial-and-error cycle.
- Tech-econ planner. The main multi-attribute optimisation process. This is the core of the automated planning solver, which comprises a complex structure of partial-optimisation and simulation modules. It will be described in more detail in the present document.
- Financial planner. Financial optimisation/adaptation process. This is an assistant –but critical- optimisation module in charge of proposing the best (and hopefully feasible) way to finance the solutions proposed by the “Tech-econ planner” module. It must propose the most adequate blended finance from the diversity of agents and financial tools that could participate in financing any proposed plan: revenues from the tariffs, the government, development financing institutions, various donors, private corporations, commercial banks, international organisations and donations, public sector and debt/taxes/subsidies, in such a way that they are compatible with the adopted sectorial structure and choice of business models.

The need for explicit human intervention can be supported from two different points of view, one practical and the other of an ethical nature. The practical reasons involve modelling complexity and uncertainty, as well as the need for traceability. Human planners may trust the results and understand the effect of uncertainties and policies through sensitivity analyses. The ethical reasons derive from the absence of a unique optimal solution. Final solutions must balance conflicting attributes, such as “cost” versus “environment & health”. Responsible agents, i.e., human planners, must make this balance explicitly.

The proposed methodology can be characterised as “direct-search structured multi-attribute optimisation”. The following sections briefly describe the different concepts included in that definition, with examples of their intended application to the prototype development.

2.2. Optimisation approach: direct search

Figure 3 tries to illustrate the classification of optimisation techniques used to characterise the proposed one: direct search as opposed to mathematical programming, and domain-dependent problem decomposition as opposed to random search.

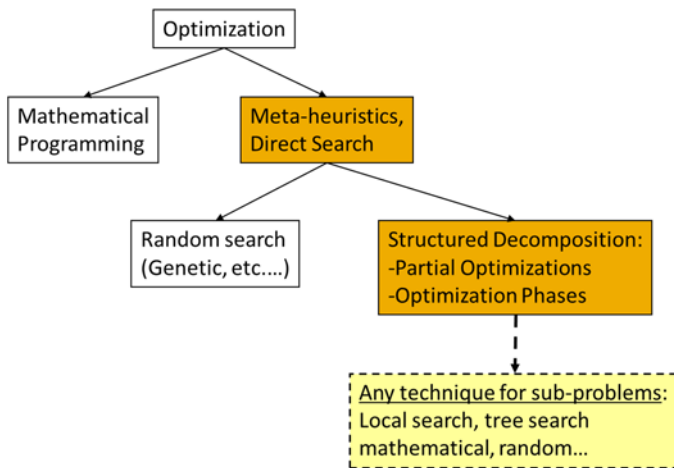
Direct search techniques (or meta-heuristics) are sometimes just a practical alternative to ill-conditioned mathematical programming models. However, in many real-life problems, they are the only feasible option because of modelling details that are hardly expressed (or hardly handled) as a closed set of equations. Some examples are:

- Dynamic/variable dimension of the space of search.
- Highly discrete variables, such as tables or catalogues of components.

- Highly discrete functions or equations.
- Non-reversible sequential procedures, like complex simulations or optimisations.

Another feature of direct search is its compatibility with multi-attribute optimisation since the selection of temporary solutions can be based on any arbitrary criterion.

Figure 3. Characterisation of the proposed optimisation technique.



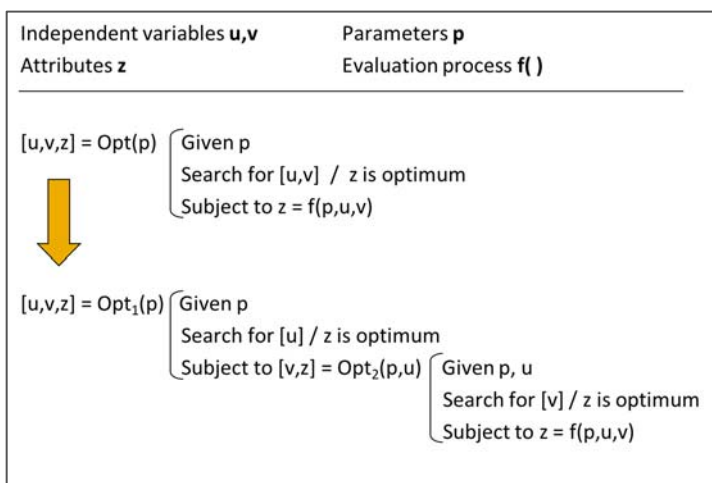
As shown in Figure 3, there is a further differentiation within the direct-search techniques: domain-dependent problem decomposition instead of random search. Both resemble a classic trial-and-error procedure (using an automated evaluation module). Random search is based on evaluating and selecting a large number of solutions in successive phases, and therefore, it requires the evaluation module to be fast enough.

In contrast, domain-dependent decomposition relies on more educated search procedures carefully tailored for the specific problem. The solutions may be approached in successive phases (using simplified models and/or simplified spaces of search), and each phase may be structured into partial optimisations.

2.3. Structured optimisation (domain-dependent decomposition)

Approaching solutions through successive optimisation phases is a practical way to save computing time and a helpful approach to avoid local optima in ill-conditioned models. However, “partial optimisations” are more relevant from a methodological point of view since they qualitatively redefine the problem. Figure 4 shows the basics of partial optimisations, which consist of generalising the multilevel optimisation concept, here applied to direct search.

Figure 4. Modelling decomposition into partial optimisations.

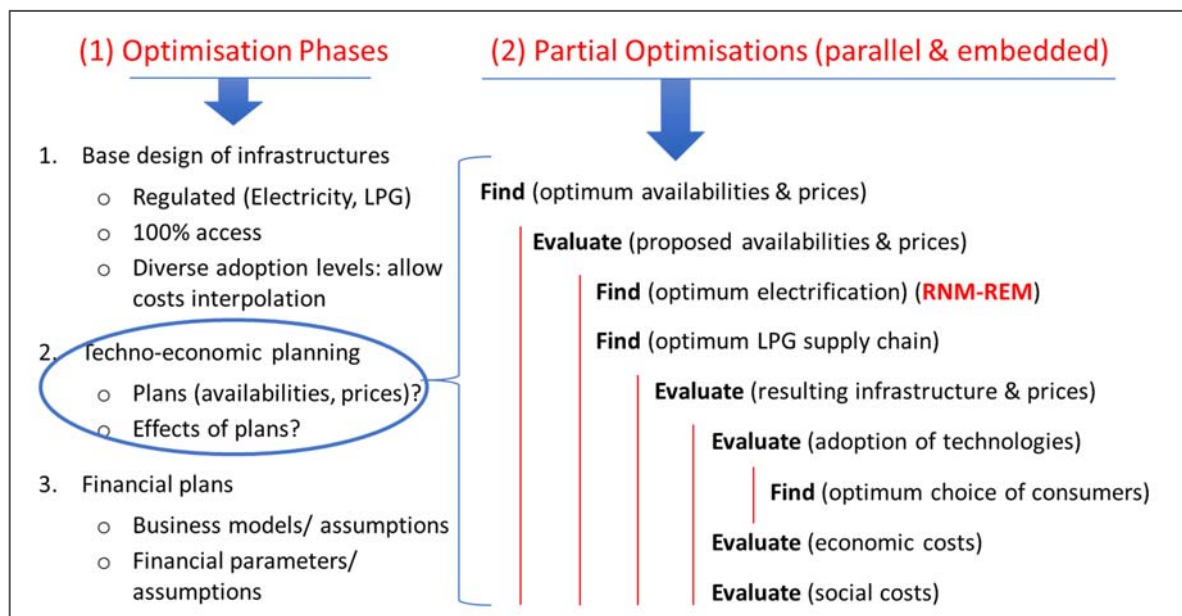


Without entering into mathematical definitions or details, the most relevant concept to be understood is that a partial optimisation can be used as the evaluation function of a higher-level search, where:

- The evaluation (or partial optimisation) links independent variables to attributes.
- The search tries and refines iteratively different values of the independent variables.

There are many potential benefits to this kind of decomposition. It allows specialised search algorithms for each sub-problem, incorporating domain-dependent knowledge and modular designs in general. Figure 5 describes how the clean-cooking planning problem is broken down into phases (left side) and how the interactive techno-economic planning phase is decomposed into partial optimisations.

Figure 5. Decomposition example in the clean-cooking planning problem.



On the left side of Figure 5, three optimisation phases are identified in sequential order (but with possible iterations depending on the user interaction):

1. Base design of infrastructures. Provide optimal layouts for fully deployed infrastructures of regulated fuels (Electricity and LPG), covering 100% of the country and identifying local supply areas. These areas are designed for different demand levels to allow cost interpolations in the interactive phase.
2. Interactive techno-economic planning. Allows the trial and error planning procedure, playing with levels of access to regulated fuels, capacity limits for all the fuels and appliances, and pricing policies for all the fuels and appliances. The previous phase provided the information to make this process quasi-optimal and fast. This phase is better explained in the “partial optimisations” sub-section below.
3. Financial plans. For any techno-economic plan of interest, the user may play with financial parameters to estimate the feasibility and adequacy of different financial options/assumptions. These include the balance between private and public capital, different stages or periods of implementation, and the impact of different financial scenarios.

The right side of Figure 5 shows the breakdown into partial optimisations of the interactive techno-economic planner:

1. At the top level, the human planner searches manually in the space of alternative plans, trying levels of global access to regulated fuels, capacity limits for all the fuels and appliances, and pricing policies for all the fuels and appliances.
2. At the second level, a complex evaluation module estimates the effects of each particular plan (a constant input here) using the rest of the processes below.
3. At the third level, specialised optimisation modules find the least cost per benefit expansion plan for each regulated fuel (local access), given the inputs from above (global access level). The least cost/benefit solutions are fast to find because of the interpolation features of the base designs of infrastructures.

4. At the fourth level, a complex evaluation module estimates the effects of the decisions coming from above using the rest of the processes below. The constant inputs at this level include pricing and capacities for all the fuels and technologies, as well as local access to regulated fuels.
5. The final evaluation block includes the estimated local adoption of technologies (which includes finding the subjective optimal decisions of the consumers) and the resulting social and economic costs. Both social and economic costs are adoption-dependent.

A critical evaluation module mentioned in the last level is the “adoption” or “penetration” model, which is in charge of estimating the response of different population clusters to availabilities and prices. It will be further described in a separate section.

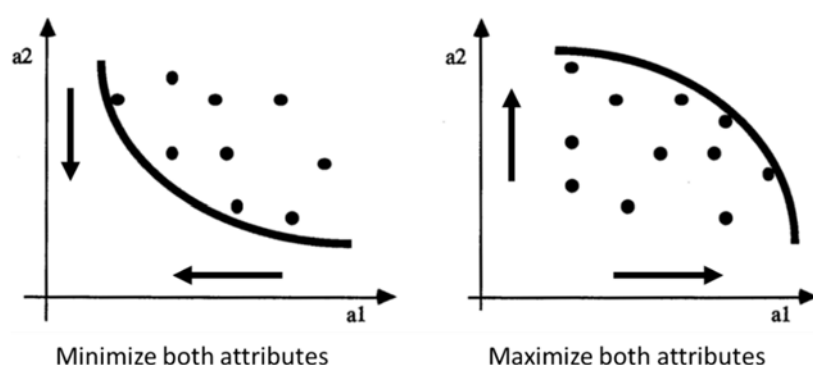
2.4. Multi-attribute optimisation

Many optimisation problems are defined as mono-attribute either because (a) there is only one optimality criterion, such as “minimise cost” or “maximise efficiency”, or (b) different optimality criteria are merged into a single objective function, usually as a weighted addition.

However, optimality criteria may be mutually conflictive and/or difficult to compare against each other, even if normalised to per-unit values. In these cases, any weighted function implies some hidden trade-off. The decision-maker (human planner) should handle this trade-off explicitly, both in practical and ethical terms.

Multi-attribute optimisation handles optimality criteria separately instead of using a single objective function. The solution is not a single point anymore but an optimal “hyper-surface” of “non-dominated” solutions (Pareto frontier –or front, or set). Figure 6 shows the Pareto concept for two attributes, either minimising or maximising both attributes – other combinations are less intuitive, although perfectly valid.

Figure 6. Examples of Pareto frontiers for two attributes.



The strategy proposed here for the clean-cooking planning problem is hybrid. In the techno-economic module, the whole set of attributes will be merged into two objective functions, and these two functions will be handled as independent attributes. In any case, the different components of these two functions are kept visible to allow detailed analyses. Multi-attribute evaluation is used in two contexts: the subjective perception of the consumers (each type with its own criteria) and the planner's viewpoint. These two functions are:

1. Cost attributes translated to a single “economic cost” function. For the planner, the annual OPEX plus the equivalent annuity of CAPEX. For consumers, the relative price of technologies (combinations of fuels and appliances) with respect to their affordability and/or willingness to pay.
2. Four social cost attributes, normalised to per-unit values and merged into a weighted “social cost” function. This function includes Health, Time&Gender, Emissions, and Deforestation.

Figure 7 (left) shows the ideal planning process from the policy-maker's point of view. The starting point is a “dirty and cheap” situation. The goal is to generate different “better” alternatives (coloured in the figure), rejecting the “worse” ones (not coloured). The choice between those non-dominated solutions depends on the investment capability and strategy. This is why the financial plan will help refine plans, choose the best feasible option, and help break investments into stages, defining a sequence of plans in successive periods.

Figure 7. Decision-making in the 2-attribute space (planner and consumer viewpoints).

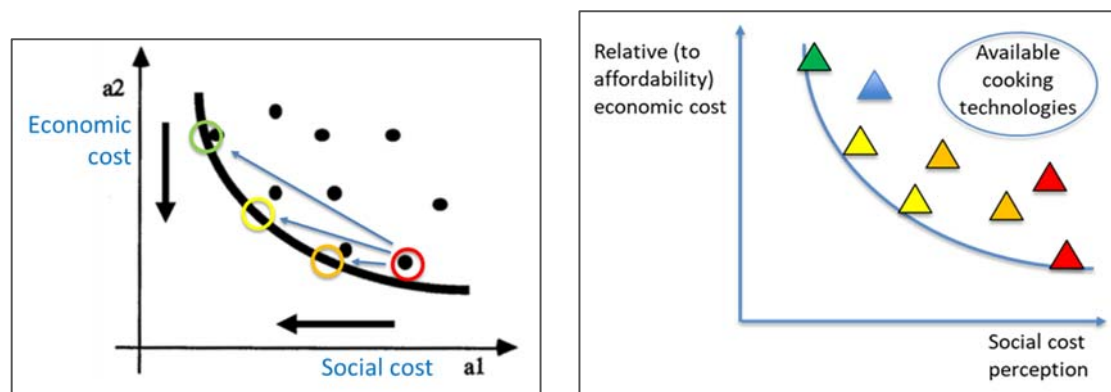


Figure 7 (right) shows how multiple technologies are evaluated by a specific type of consumer using relative (subjective) multi-attribute parameters. This decision process is at the core of the technology adoption model. Different types of consumers will make different decisions about using alternative cooking technologies, considering their price (economic cost) and their negative effects (social costs).

A final comment about handling multiple effects or attributes in a problem is the need for normalisation because the units of the different effects may be quite diverse and not comparable. For instance, “Emissions” is measured in millions of tons of CO₂ per year, while “Deforestation” is expressed as millions of tons of wood consumed yearly. In the case of technology adoption, values are normalised with respect to the previous adoption of the consumer (incremental perception). From the planner's perspective, the base magnitudes for social costs are those of the initial state; therefore, the values of the effects over time are directly understandable as percentual variations with respect to the initial state.

2.5. Distinctive features of the approach

In recent years, several models and tools have been developed for clean-cooking planning. For instance:

- Nigeria Integrated Energy Planning Tool (Federal Government of Nigeria, 2022). It was developed by SEforALL in collaboration with the Federal Government of Nigeria and sponsored by the Rockefeller Foundation. Its main features are to estimate the expansion opportunity for areas with low clean-cooking penetration, to assess the potential health, climate, and environmental co-benefits and to estimate the investment required to expand access to clean cooking technologies.
- Clean Cooking Explorer (Clean Cooking Explorer, 2022). It was developed by the Clean Cooking Alliance, World Resources Institute, KTH, Kartoza, Nepal Open University and the Alternative Energy Promotion Centre (AEPIC). The tool is based on a combination of the Energy Access Explorer and OnStove (Ramírez, et al., 2024). The tool's objectives are to identify the state of access to clean cooking and areas with high expansion potential, as well as areas where assistance is needed. It develops 4 indices: Demand, Supply, Clean-cooking Potential, and Assistance Needed. It defines high clean cooking potential where the demand and supply indices are high.
- Energy Access Explorer (Mentis, et al., 2019) and (WRI, 2022). It has been developed by the World Resources Institute (and a group of collaborators in each country). The tool's objective was initially electrification planning, but now it also addresses cooking planning, and it has been applied to six countries: Ethiopia, India, Kenya, Tanzania, Uganda, and Zambia (clean-cooking addressed only in Kenya). While energy demand is characterised by demographic parameters and social and productive uses, energy supply is characterised by energy sources and infrastructure.
- Clean Cooking Planning Tool (World Bank, 2022): It has been developed by the World Bank's Energy Sector Management Assistance Program (ESMAP). The main features are to estimate the 2020 baseline and the 2030 state of access, to test interactive transition scenarios, to test fuel-mix pathways, and to estimate the transition costs and benefits.
- Rwanda National LPG Master Plan (Global LPG Partnership, 2021) and (Čukić, Kypridemos, Evans, Pope, & Puzzolo, 2021). It has been developed by the Global LPG Partnership, with the support of the European Union through its Infrastructure Trust Fund, and the German development bank KfW, which has acted as the primary financial underwriter and funds administrator for the Clean Cooking for Africa Program. The main objective of the plan is to analyse the demand for LPG and the supply chains of LPG to achieve the national target of the displacement of biomass fuel.

- Benefits of action to reduce household air pollution (BAR-HAP) tool (Das, et al., 2021). It is a planning tool for assessing the costs and benefits of different interventions that aim to reduce cooking-related household air pollution. The tool allows users to model 16 different cleaner-cooking transitions, including both transitional options (that offer some health benefits) and clean options that meet emissions levels in the WHO Guidelines for indoor air quality. For each transition, users can also select a policy intervention that will be applied, such as a stove or fuel subsidy, financing, an intensive behaviour-change campaign, or a technology ban.
- Malawi Integrated Energy Plan (SEforALL, 2022). It has been developed by Sustainable Energy for All in collaboration with the Ministry of Energy, Malawi, with support from the Global Energy Alliance for People and Planet and The Rockefeller Foundation. The tool is an online, publicly available, interactive, and user-friendly data visualisation platform that equips Malawian policymakers and energy practitioners with data and insights to make informed decisions on strategies and operations to advance energy access in the country. The tool is powered by extensive geospatial analytics and modelling. It provides actionable intelligence for the private sector and government stakeholders to plan the expansion of least-cost access to electricity, access to clean cooking, health-facility electrification, and medical cold-chain energy assessment in the context of a national COVID-19 vaccination rollout.
- Madagascar Integrated Energy Access Planning Tool (SEforAll, 2024). It is an online, interactive platform developed by Sustainable Energy for All, with support from the Global Energy Alliance for People and Planet and the OPEC Fund for International Development, to help planners and energy practitioners make informed decisions about energy access. Utilising extensive geospatial analytics, the platform provides actionable insights for planning the expansion of least-cost electricity access, clean cooking solutions, and cold chains essential for medical, agricultural, and fisheries sectors. It integrates various supply-side solutions, including main electricity grids, mini-grids, standalone solar systems, electric cooking, biogas, briquettes, and bio-ethanol, with demand-side factors like affordability, accessibility, and population distribution. This comprehensive approach identifies pathways and opportunities to achieve universal energy access in Madagascar by 2030.

All these tools can help decision-making, but they do not cover, by design, the ambitious functional features of the present approach. The main features of the approach proposed here are summarised below, and it is left to the interested (or academic) reader to check if other existing tools and models include these features:

- Planning by detailed designs. The method presented here is based on “deep planning” or “planning by design”. In contrast with the traditional methods, it is based on the systematic search for planning solutions using detailed (and optimal) designs to evaluate each proposed plan. This alternative approach is possible by using off-line and interactive tools that perform detailed designs and simulations of alternatives.
- Granularity down to the “building” level. This is used in the off-line pre-design of infrastructures, specifically for Electricity and LPG. Multiple types of buildings and demand profiles are considered, together with detailed street maps, roads, and other geographical data. This is relevant to estimate the supply costs accurately, although consumers may be aggregated to estimate the demand response.
- Interactive planning. Multiple plans can be tested and systematically improved. Each plan can be tested against uncertain factors to check its sensitivity and robustness.
- Combination of off-line tools that provide accurate and incremental (sensitivity) results with interactive tools that apply weighted averages, interpolation, extrapolation, and aggregation. This feature makes detailed designs compatible with real-time interaction.
- Explicit technology adoption model. Matching supply and demand by adjustable models for the consumers’ behaviour and considering multiple consumer profiles.
- Stacking model. Combine a mix of energy sources/appliances that includes traditional, transitional, and modern technologies in the overall solution.
- Definition of a standard cooking-demand unit, the “Cook”. This contribution is more practical than theoretical, simplifying the definition of parameters, models and calculations.
- Multi-stage model. Successive planning stages can be defined.
- Multi-effect model. Handle separately (and jointly when needed) multiple effects in the evaluation of plans, such as economic costs and the different components of social costs.
- Financial planner. Refine cost models with the financial assessment of diverse agents, such as the State, economic sectors, or companies. This feature includes implementing three major components: a techno-economic planning model, a financial model, and a search procedure to iterate between both models to propose a final set of “better” solutions.
- Normalisation and unit-handling. Intensive use of base/reference magnitudes to define relative (per-unit or percentual) reasoning and processing.

- Use of general catalogues and standard patterns of elements that may be adapted by multipliers and/or weighted averages to achieve specific/local features. This feature adds flexibility to modelling and implementation in different contexts.

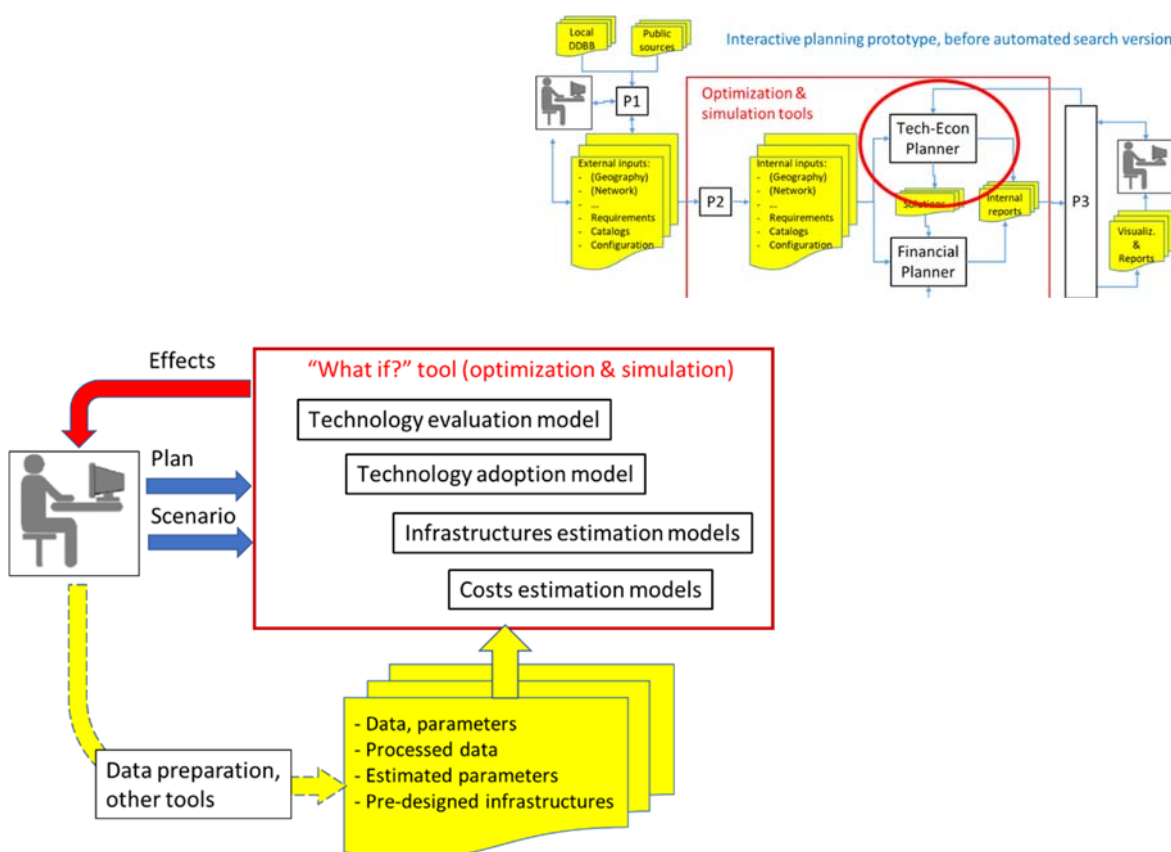
The approach presents some conceptual limitations, meaning that some aspects of the real-world problem have not been modelled yet (and maybe not modelled ever), like forest management or the geo-referenced commercial flows of Charcoal and Firewood. Other limitations are due to the version of the set of tools used in elaborating the plans, a partial implementation or prototype (Version 1).

3. The interactive techno-economic planner

The bottom of Figure 8 shows an expanded representation of the techno-economic planner, already introduced as part of the general structure of tools (top of Figure 8). The tool estimates the “effects” of a “plan” subject to a given “scenario”, and the user or planner may try different plans until some targets or combination of desired “effects” are met.

There are other inputs, coloured in yellow at the bottom of Figure 8, that are not interactive. They are computed off-line, either because they are constant data or configuration parameters established in advance or because they require processes and tools that take a considerable computing time.

Figure 8. The interactive planning tool.



In the terminology used here, a “plan” is defined as a set of political and strategic “measures”, and the different types of measures are called “policies”. For instance:

- Two policies could be (a) Apply taxes to charcoal and (b) Subsidise high-efficiency charcoal cookstoves.
- A simple plan could consist of two specific measures, like (a1) Apply 20% of taxes to charcoal and (b1) Subsidise 50% of the price of high-efficiency charcoal cookstoves.
- Some expected effects of this plan could be (i) High income for the State due to taxes, (ii) Moderate expenditure of the State due to subsidies, (iii) Reduction of the overall consumption of charcoal for cooking by the population, because of taxes and because of more efficient appliances, (iv) Decrease of negative effects of cooking with charcoal, like deforestation, emissions, or health problems, and (v) Less cooking expenditure of the population, since the savings in the fuel quantities purchased overcompensate the increment of price.

This analysis of qualitative effects looks fine and simple enough, but this is far from reality. First, it is insufficient to handle statements like “high” or “moderate”; we need to quantify all those expected increments. Second, other

combinations of measures (including other policies) could provide better results. Third, there are side effects to consider, like people partially replacing charcoal with firewood, which could alter the expected results. This is why a complex “What if?” tool is required to evaluate every possible effect quantitatively.

Inside the “What if?” tool, Figure 8 shows several internal modules in charge of the accurate estimation of effects so that the complexity of the tool can be appreciated:

- The “Technology evaluation model” calculates the standard effects of the different cooking technologies, considering the whole supply chain of each fuel and the particularities of each type of appliance. Part of the results are already calculated off-line, but those related to costs and prices must be updated in the interactive loop since they depend on the Scenario and the Plan.
- The “Technology adoption model” estimates the population's response to prices, habits (response is incremental), and availability of the different technologies. This response is assumed to be optimal from the subjective perspective of each type of consumer.
- The “Infrastructure estimation models” apply to Electricity and LPG supply chains. The mission of these modules is the processing of pre-designed infrastructures (part of the off-line inputs in Figure 8) to adapt them to particular plans, including partial deployment of access and sizing of components according to the required capacity (which depends on the level of penetration of the technologies, plus some capacity margins defined as design parameters). These processes involve the minimisation of local cost/benefit ratios from the perspective of the utilities, which is consistent with the perspective of the State (being regulated businesses).
- The “Costs estimation models” evaluate the economic and social costs (the “effects”) using the results of the other modules.

During the planning process, different plans may be tested against the same scenario to select good plans according to the desired effects and, eventually, to select the best plan (the definition of “best” is subjective since the effects comprise diverse factors related to economic costs and social costs). The planning process may also include testing the same plan subject to different scenarios to assess its robustness against uncertainty.

3.1. Main inputs and outputs of the tool

The main inputs of the interactive planning tool are the “plan” and the “scenario”, and the main outputs are the “effects”. To understand their contents, particular modelling aspects must be clarified in advance.

The difference between regulated and non-regulated businesses is critical both for the planning strategy and for the evaluation of costs. In the regulated businesses, the Government centrally plans their supply chains (infrastructures) and fixes their prices (or tariffs). Therefore, the State must cover eventual deficits in terms of remuneration for public service. In contrast, the rest of the fuels and all the appliances are modelled as non-regulated, distributed, and private businesses; their prices and supply chains are assumed to be fixed by competition and viability (enough returns of investments).

In the case example of Rwanda, Electricity and LPG are modelled as regulated fuels and, therefore, regulated businesses. Other countries may require adding more regulated businesses to the model, like NG (Natural Gas) or even Ethanol. This is conceptually easy to do, but requires the development of tailored off-line modules to design in detail their supply chains and estimate their deployment costs.

The scenarios define the (uncertain) evolution of different socio-economic parameters, including the base prices for fuels and appliances. On top of those base prices, the plans may impose price variations as specific measures, modelled as price multipliers:

- In the case of regulated fuels, the price multiplier may increase or decrease the tariff. The tariff will result in some deficit or benefit in the business, which will be translated into costs for the State because of the required remuneration to the utilities.
- For non-regulated fuels and all appliances, a price multiplier means a tax (price multiplier > 1) or a subsidy (price multiplier < 1). Taxes are income for the State, while subsidies are costs for the State.

Since the effects include components of quite diverse nature measured in different units, such as economic or social costs (deforestation, health, emissions, etc.), comparing them using absolute figures is not practical. Instead, the effects of a plan subject to a given scenario are evaluated in per-unit (or percentual) reductions with respect to the initial state. For instance, when comparing two alternative plans A and B, we may state that Plan A reduces 10% of the cost, 15% of deforestation and 20% of health damages, while Plan B reduces 5% of the cost, 20% of deforestation

and 25% of health damages. It is up to the planner (the user of the tool) to decide which plan is better, but at least the features of each plan are easier to understand.

The differences between regulated and non-regulated fuels and the use of price multipliers allow the description of the possible policies included in plans as follows (all of them applicable in different “stages” or planning periods):

- Deployment targets (infrastructures) for regulated fuels.
- Tariff variations for regulated fuels.
- Subsidies/taxes for non-regulated fuels and all appliances.
- Bans on certain fuels or appliances, especially in urban environments.
- Education/awareness campaigns that could bias the habits and preferences of the population towards cleaner technologies.

To better understand the “deployment targets” for Electricity and LPG, it is important to note that the availability of these fuels, as perceived by the consumers, has two different features: “access” and “capacity”. Access is the percentage of consumers in a given area that could use a fuel, while capacity is the percentage of total demand that could be supplied with that fuel. For electricity, access is limited by the percentage of consumers connected and with enough peak power for electric cooking, while capacity is limited by the simultaneous peak power at upstream transformers, substations, and lines (or maybe by the maximum energy at the generation level). In the case of LPG, access is limited by the proximity to retail shops or delivery services, while capacity is limited by the total quantity of LPG that could be delivered per week or month to the area.

In the present model, “deployment targets” mean “access”, i.e., the percentage of the population that could adopt electricity or LPG as cooking technology. Capacity is adjusted to the local adoption of the technologies, plus some capacity margin defined by the planner (for example, around 5% for electricity and LPG).

The scenarios are defined to model uncertain macroeconomic and behavioural factors expressed as annual percentual variations. The economic figures in the model are deflated (in constant currency) and expressed in USD to avoid inflation and exchange rate effects. The scenario factors selected in the elaboration of the NICCP are the following:

- Base prices of fuels/appliances/imports and costs of the components of infrastructures (Electricity and LPG).
- Consumer behaviour/awareness related to the education and social development of the population.
- Economic growth of the country. This factor affects energy demand and average income levels.
- Population growth, including the unbalances due to rural-to-urban migrations.

Scenarios used in the elaboration of the NICCP are labelled as pessimistic, optimistic, or neutral (or BAU, Business As Usual). This is because the uncertain macroeconomic and behavioural factors may favour -or accelerate- the transition to clean-cooking technologies by themselves, without specific plans or measures, or could prevent -or slow down- that transition.

The main output, the “effects” of applying a plan subject to a given scenario, is related to the different types of damages related to cooking with traditional (dirty) technologies, the so-called “social costs”. However, this reduction should be achieved with a minimum burden of economic costs, and therefore, economic parameters are included in the effects to be evaluated. The effects that a plan should try to minimise include:

- Economic cost for the State, as the ultimate responsible party for public services and welfare. The technoeconomic planner evaluates the costs as annual cash flows or equivalent annuities. The financial planner analyses in detail the financial health of the State and the sectors involved.
- Health cost. Damages to the population, especially women and children. These damages are usually calculated using the adverted Disability Adjusted Life Years (DALYs) and deaths. However, the use of percentual reductions with respect to the initial state allows any kind of unit, and the values for different technologies have been normalised with respect to the use of three-stone systems with firewood or biomass.
- Time&Gender cost. Time spent and inconvenience in general (suffered mainly by women) in the kitchen-preparation-cleaning and fuel-gathering processes. The values for different technologies have been normalised with respect to the use of three-stone systems with firewood or biomass.
- Emissions. Measured in kg of CO₂ equivalent. They include the emissions of the whole supply chain, from raw materials to the kitchen.

- Deforestation. Measured in total kg of wood used, either as a raw material or as a cooking fuel.

Other components of the effects are used as additional evaluation criteria (or KPIs) to compare alternative plans:

- The fraction of cooking demand covered with clean technologies (to be maximised). This is the addition of the percentual adoptions of Electricity, LPG, Biogas, Pellets (including similar fuels, like briquettes or sawdust), Ethanol, and top-level improved cookstoves for Charcoal, Firewood, and Biomass.
- Cooking costs for consumers (minimised if possible, or at least to keep it reasonable). Average costs are expressed as per-unit figures (\$/unit) and annual average expenditure on fuels and appliances. This evaluation criterion is also relevant in relative terms, comparing the increments in cooking costs with respect to the initial state and the country's economic growth.

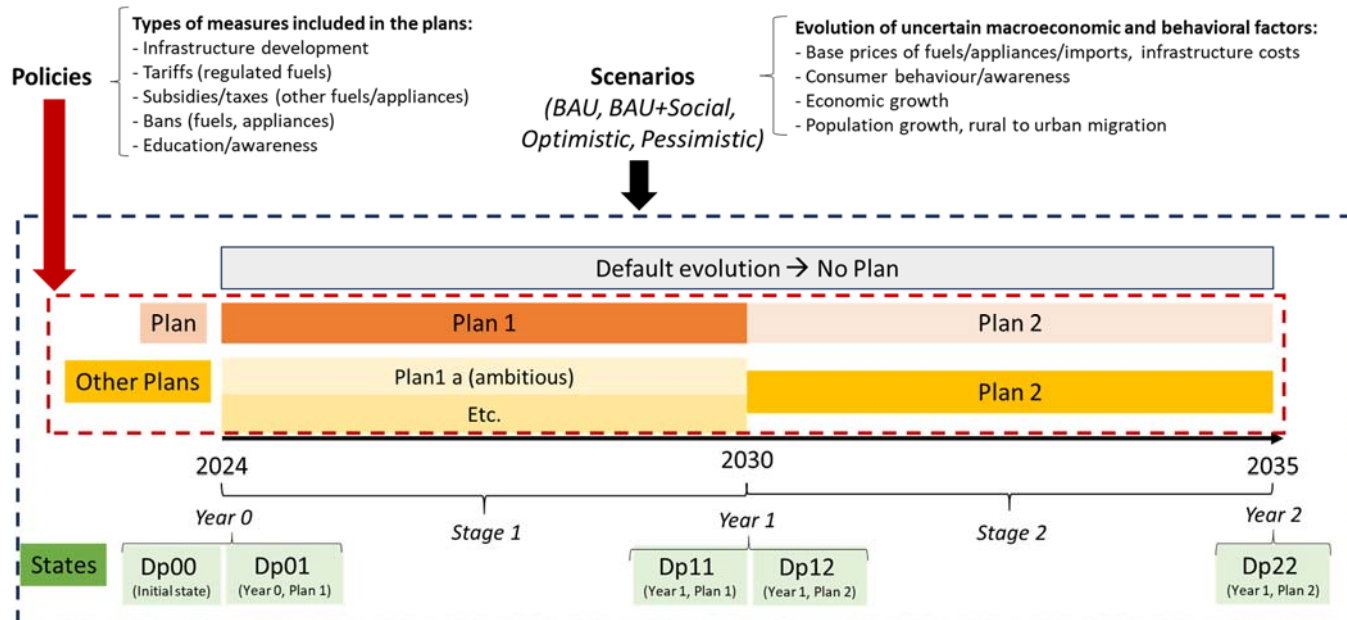
3.2. Time-related concepts in the ICCP

The natural time unit is the year. Magnitudes such as demand, incomes, or costs are usually defined in units/year, seeking meaningful orders of magnitude: GWh/year for global electric demand, M\$/year for global costs or incomes, and so on. Hourly profiles are only relevant in the design of the electric infrastructures, especially in the case of off-grid electrification modes like mini-grids or individual solar systems.

Figure 9 summarises the specific application of plans and scenarios to the ICCP problem, introducing the “time” model in terms of reference years, “stages”, and “states”. It also summarises the components of the plans and scenarios presented in the previous sub-section. Note that the limitation to two stages applies to Version 1 of the tool; in Version 2, the user may define any number of stages; however, the concepts of stage, state, and reference year fully apply to both versions.

The tool allows the definition of scenarios with socio-economic parameters that vary in a given percentage every year. The policies are applied in two successive “stages”, each defined separately by its measures, referred to as “Plan 1” and “Plan 2”. The user may arbitrarily define three reference years, namely “Year 0”, “Year 1”, and “Year 2”.

Figure 9. Explanation of scenarios, policies, plans, stages, and states.



The semester is used to model the change of measures in the middle of the reference years (those in which the measures change), and for calculating annual cash flows and delays. Let us assume that the reference years 2024, 2030, and 2035 have been selected, and therefore, Plan 1 goes from the second semester of 2024 to the first semester of 2030, while Plan 2 extends from the second semester of 2030 to the first semester of 2035. The modelling assumption is that the changes of measures happen in the middle of the transitional years, so that:

- The first semester of 2024 is represented by state Dp00 (Year 0, initial state, no plan yet).

- The second semester of 2024 is represented by state Dp01 (Year 0, Plan 1).
- The first semester of 2030 is represented by state Dp11 (Year 1, Plan 1).
- The second semester of 2030 is represented by state Dp12 (Year 1, Plan 2).
- The first semester of 2035 is represented by state Dp22 (Year 2, Plan 2).

In all these states, the economic magnitudes, such as subsidies, incomes, taxes, and costs (CAPEX and OPEX), are expressed as equivalent annuities (perpetual equivalent quantities) in millions of dollars per year (M\$/year). The annuities of these states are also translated to total investments, annual investments, and annual cash flows.

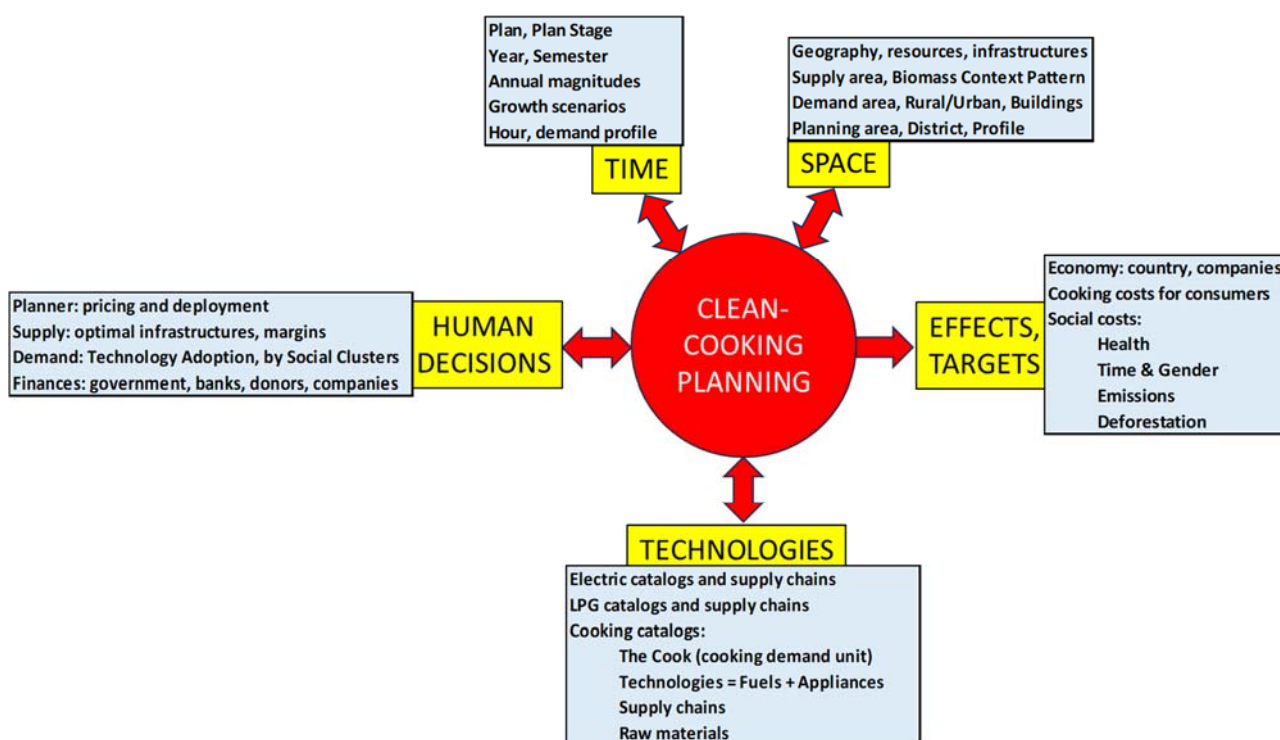
Another critical assumption related to plans, semesters, and states is that pricing policies of a plan stage are applied almost immediately (some short delay is imposed on the consumers' reaction), while infrastructures are developed gradually along the plan stage. For instance, state Dp01 includes the pricing of Plan1 but not its new infrastructures, while state Dp11 includes both measures.

Figure 9 also shows a full-span default plan called "No-Plan" or "Default evolution", with no specific measures and following already established infrastructure deployment criteria. This is used to evaluate the actual influence of a given plan by comparing its effects against the effects of the absence of measures, both being subject to the same scenario. The figure also shows that other plans (like Plan1a) can be evaluated against each other, containing different measures for the first stage, the second, or both.

3.3. Other modelling concepts and terms

Any planning activity involves making decisions in a temporal and spatial context to obtain the desired effects or planning targets. In addition to the planner, other agents make decisions that must be included in estimating the effects, thus conditioning the planning decisions. Specific technologies and resources are part of the problem as well, and they are related to the characteristics of the planning area.

Figure 10. Elements of the clean-cooking planning problem.



The modelling concepts are classified here into five groups: Time, Space, Technologies, Human Decisions, and Effects. Figure 10 represents the elements of the clean cooking planning problem. These elements appear in the model as inputs, outputs, intermediate parameters, and procedures.

Concepts related to “Time” have already been introduced in sections 3.1 (scenarios) and 3.2 (stages, years, etc.). The “Effects” group has been covered in Section 3.1. Section 3.1 also presents the “Human Decisions” topics related to the planner’s point of view in terms of policies, measures, and plans. The modelling aspects that deserve special attention and have not been explained yet are the following:

- In the “Human Decisions” group:
 - The design decisions from the supply experts materialised in the optimum pre-design of infrastructures (off-line inputs in Figure 8), and
 - The decisions of the consumers about cooking technologies, which are implemented in the “Technology adoption model” shown in Figure 9. They are based on the definition of types of consumers, named here “Social Clusters”, each with its behavioural parameters to be adjusted.
- In the “Space” group, the multi-level territory partitions. They include the planning level, the supply levels (different for different fuels), and the demand level.
- In the “Technologies” group:
 - The overall model used to handle cooking technologies.
 - The definition of a new unit to measure cooking demand, independent of technologies: the Cook. This unit has been critical in analysing the technology supply chains, from raw materials to the kitchen.

The off-line optimisation tools used for electricity and LPG are responsible for optimum infrastructure designs, with incremental information to allow interpolation. These decisions are embedded in the base plans for electricity and LPG, and this topic will be briefly presented in Section 7. The classification of types of customers into “Social Clusters” is mentioned in the technology-adoption model and the territory-partition logic (both in Section 3), as well as in the description of estimated parameters (Section 6), because their behavioural parameters are adjusted off-line.

3.4. Geo-spatial features and territory partitions

Geo-referenced data are critical elements in the analysis. Some data represent natural characteristics, like mountains, rivers, lakes, and natural resources (such as solar irradiance). They also include administrative data, such as province, district, or municipality borders, represented as polygons (see Figure 11).

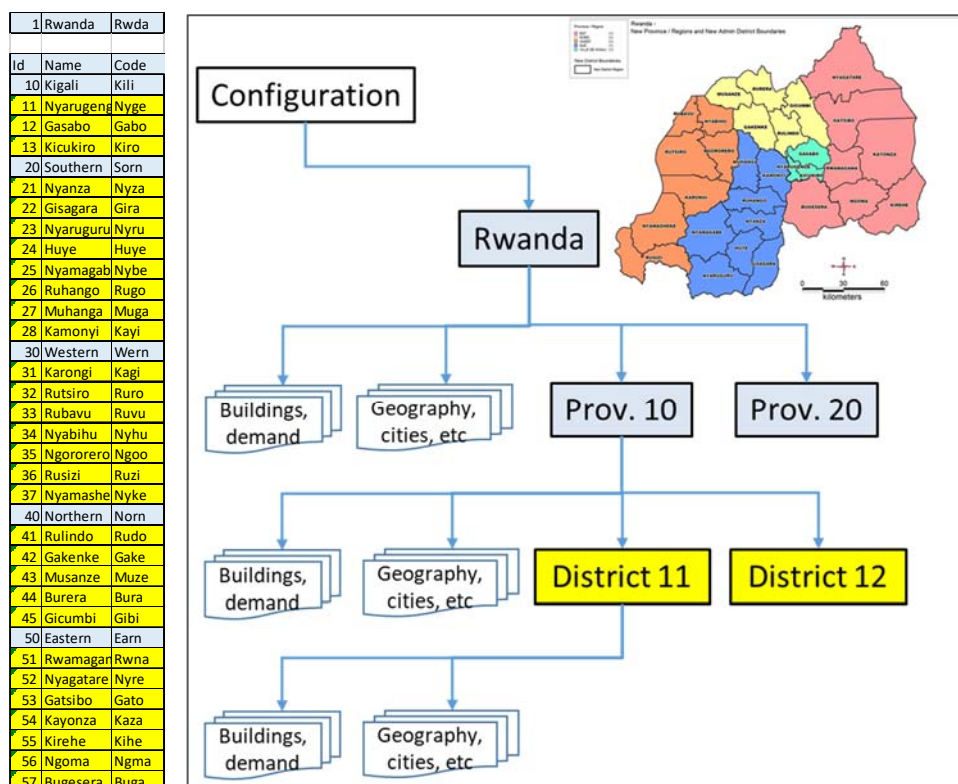
The existing infrastructures, like roads, streets, electric grids (including substations or generation plants), or LPG infrastructures, and the buildings themselves are quite relevant. All this information is considered but handled externally by the electric and LPG design tools, which are run off-line, and their outputs are used as inputs by the interactive tool. Something similar happens with the description of land use and biomass patterns; the information is processed off-line and used as inputs (processed data, as shown in Figure 8).

In the general model devised to solve the clean-cooking planning problem, the base plans generated by the electric and LPG design tools, and the biomass data, define supply areas as follows:

- In the case of electricity, a supply area is defined by all the consumers that would be connected to the same HV/MV substation if every customer were connected to the grid. This does not mean that they will be actually connected; it is just a territory-partition (or clustering) criterion based on the electric supply.
- For LPG, a supply area is defined by all the consumers that would be supplied by the same local warehouse that provides canisters to retail dealers.
- Finally, areas with homogeneous availabilities and pricing of biomass fuels (charcoal, firewood, crop waste, other biomass fuels, and biogas) define another territory partition related to supply. In the modelling terms used here, these homogeneous areas are identified as “Biomass Patterns” related to land-use standards like the ESRI categories “Built”, “Trees”, “Crops”, “Rangeland”, and so on (ESRI, 2023).

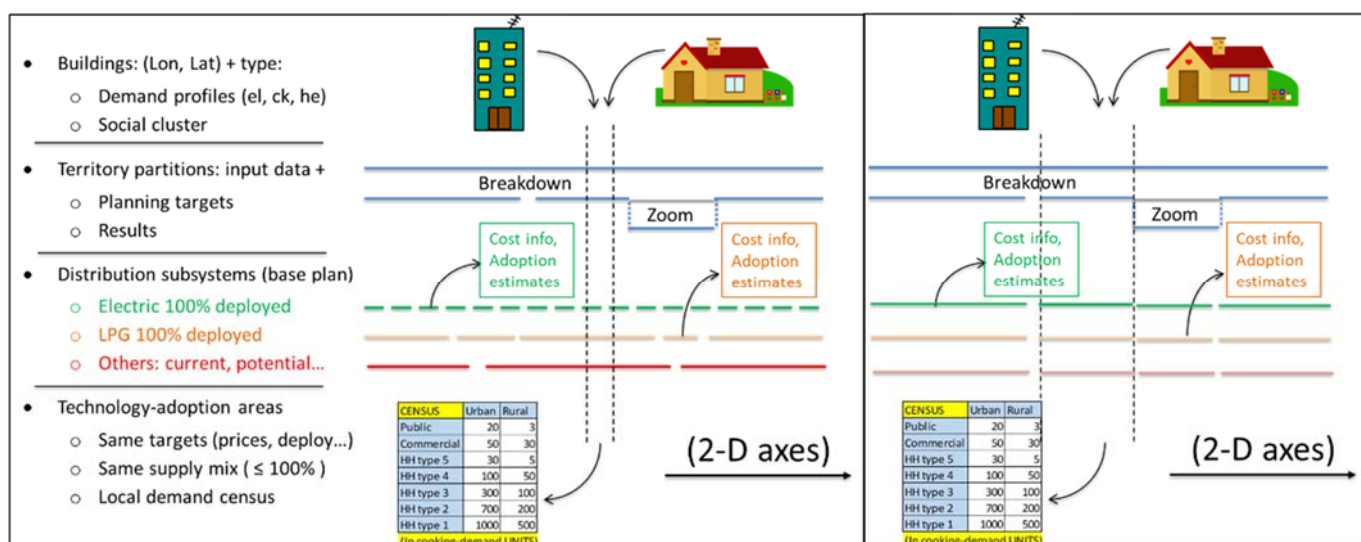
The intersections between administrative partitions, electric areas, LPG areas, and biomass patterns areas define the “demand areas” or “technology-adoption areas”. These are regions defined by a list of buildings (consumers) in which the planning targets (identified with administrative partitions) and the supply availabilities are homogeneous. Thus, the behaviour of the consumers belonging to the same demand area may be aggregated into just two social clusters: the Rural and the Urban local consumers.

Figure 11. Organisation of Rwanda: provinces and districts.



However, Version 1 of the tool uses a simplified version of the administrative, supply, and demand areas, which are identified with districts. The external tools (electric, LPG, and Biomass) work at the target level of granularity, but their results are aggregated to the district level. Therefore, the whole country is represented here by 60 social clusters, one Rural and one Urban in each of the 30 districts. Figure 12 shows the general concept of territory partitions, from administrative to supply and demand areas; the right side represents the simplification made, adapting the partitions to the district level.

Figure 12. Territory partitions (administrative, supply, demand) and the simplified version.



Another simplification implemented is the planning granularity. A single pricing policy is applied to the whole country, and the availability targets for electricity and LPG are defined as "Adoption+Margin", being the "margins" specific user-defined inputs, different for electricity and LPG. Version 2 of the tool implements this simplification as well in its current interface, but it is internally prepared for the definition of local pricing policies.

3.5. Technologies and the “Cook” unit

Cooking technologies are a central part of the models and tools designed for the ICCP. The data sources used and the bases to adjust the technology parameters are described in Section 6.4, but the fundamentals are briefly presented here.

A schematic view of the cooking-technologies model is shown in Figure 13. In this application of the ICCP, a total of 19 cooking technologies have been defined by combining 9 fuels with 13 sets of appliances. The appliance sets related to a particular fuel are defined in increasing order of average efficiency and average price:

- The “Electricity” fuel allows 3 alternative sets of appliances, and thus 3 technologies: “EI-0”, “EI-1”, “EI-2”.
- The “LPG” fuel is assumed to be used only with one level of appliances, a single technology: “LPG”.
- The “Biogas” fuel with a unique level of appliances, and thus a single technology: “Biogas”.
- The “Charcoal” fuel with 3 sets of appliances, and thus 3 technologies: “Charc-0”, “Charc-1”, “Charc-2”.
- The “Commercial Firewood” fuel with 3 sets of appliances, and therefore 3 technologies: “CFirw-0”, “CFirw-1”, “CFirw-2”.
- The “Free Biomass” fuel with 3 sets of appliances, so 3 technologies: “FrBio-0”, “FrBio-1”, “FrBio-2”.
- The “Pellets” fuel (which includes other similar fuels, like briquettes or sawdust) with a unique level of appliances, and thus a single technology: “Pellets”.
- The “Free Firewood” fuel with 3 sets of appliances, so 3 technologies: “FFirw-0”, “FFirw-1”, “FFirw-2”.
- The “Ethanol” fuel is assumed to be used only with one level of appliances, a single technology: “Ethanol”.

The three sets of appliances allowed for “Commercial Firewood”, “Free Biomass”, and “Free Firewood” are assumed to be similar in price and efficiency. This is why there are only 13 types of appliances instead of 19 to be characterised by their parameters (price, efficiency, lifetime, and so on). In general, those parameters have been adjusted by grouping diverse combinations or types of appliances into three categories to simplify the problem and the interpretation of the results.

Figure 13. Cooking technology = fuel + appliances set.

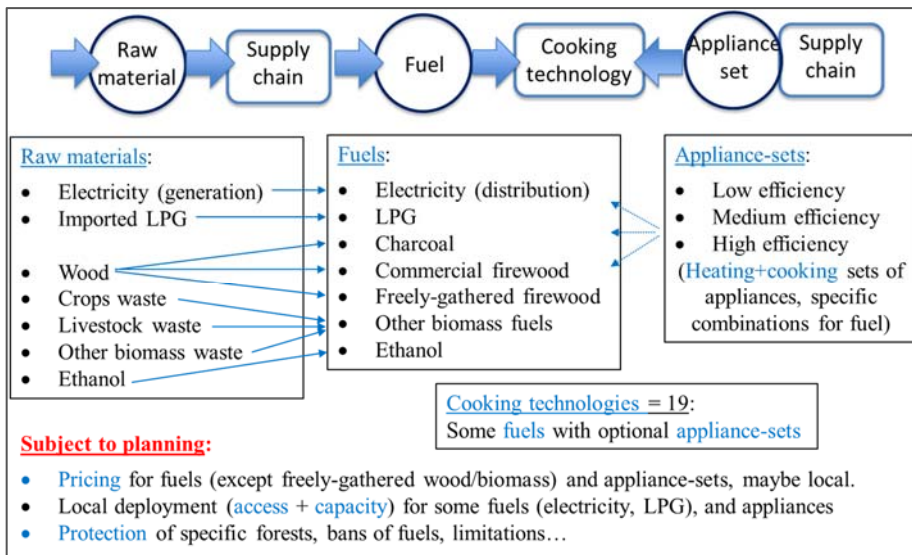


Figure 13 shows how a fuel and an appliance set define a technology. Moreover, there are supply chains for fuels and appliances, as well as raw materials at the origin of the supply chain. The model used in this approach considers different effects (see sections 2.4 and 3.1), mainly Economic, Health, and Time&Gender costs, Emissions, and Deforestation, and these are assigned to technologies considering all their components:

- “Economic costs” for the State include the costs of the deployed infrastructures (Electricity and LPG), and the balance between all the incomes (tariffs), subsidies and taxes. They are a consequence of the plan applied.
- “Economic costs” for the consumer include the price of fuels (tariffs, subsidies, taxes) and the equivalent price of appliances, combining purchase price (maybe subsidised) and lifetime. A partial monetisation of time is also included here.
- “Health costs” are a direct consequence of the technology used, considering only the effects in the kitchen because of the cooking process. Therefore, this effect is the closest connection to the usual definition of “clean cooking”.
- “Time&Gender costs” includes both the cooking-process inconveniences (storage of fuels, preparation, cooking time, cleaning) and the fuel-gathering inconveniences (time to gather the fuel and transportation). Therefore, some of the effects are related to the technology, and some to the fuel.
- “Emissions” are considered along the whole supply chain, from raw materials to cooking. Some emissions are linked to the raw material (pre-import processes of LPG and Ethanol, or generation emissions of Electricity), some are related to the transformation processes (like the production of Charcoal from Wood), and some to transportation (LPG, Charcoal, Commercial Firewood, Ethanol). Other emissions are generated during cooking (with any technology except those using Electricity).
- “Deforestation” effects are directly related to the raw material “Wood”, so they are applied to Charcoal, Firewood (free or commercial), and Pellets.

To some extent, the cooking-technologies model, the whole tool, and the resulting plans rely on the definition of an absolute, standard, and objective unit for the cooking demand: the “Cook”. This is an original contribution of the present approach. The need for such a demand unit comes from different factors:

- Cooking involves diverse activities, such as boiling, frying, grilling, heating, or roasting. Moreover, any of these activities may be performed with various fuels and appliances with different efficiencies. The Cook unit attempts to handle cooking demand uniformly.
- Measures of effective heat or effective energy are not good enough. In fact, the cooking effects are not only linked to the effective heat produced by stoves. A hot plate, a microwave oven, or a kettle can produce heat, but the cooking effects on food are hardly comparable. Incorporating “pressure cookstoves” into the problem makes the effective heat even less meaningful.
- As in the case of LCOE (Levelized Cost of Electricity, or Energy), a definition of LCOC (Levelized Cost of Cooking) is required to compare different technologies in objective terms, as shown in Figure 14. For instance, (Fuso Nerini, Ray, & Boulkaid, 2017) offers the concept of ‘levelized cost of cooking a meal’ (LCCM)- While LCOE can be measured in \$/kWh units, here it is proposed to measure the LCOC in \$/Cook.

The requirement for the demand unit is that demand must be independent of the cooking technology used and only dependent on the types of food and cooking tasks of a given culture, country, or population segment. To define this absolute unit, the solution is to make it relative to a very specific technology. The Cook is defined here based on the most straightforward, understandable, and replicable technology (labelled as “EI-0” in the model):

“1 Cook is the cooking demand satisfied with 1 kWh of electricity when cooking with a hotplate, heated by Joule effect (resistor), and using non-efficient kitchenware.”

This is why the “efficiency” parameter of technology “EI-0” equals 1 Cook/kWh. Combining the efficiency with the calorific value of each fuel (for instance, in kWh/kg), the fuel usage in terms of kg/Cook is calculated. Similarly, any parameter related to a particular technology will be expressed in “units/Cook” (Costs, Emissions, Deforestation, Health, etc.), as in Figure 14.

Figure 14. Socio-economic unit costs, at standard prices, for cooking technologies.

TECHNOLOGIES	Fuel	Dis-Electric			LPG	Biogas	Charcoal			Com. Firew.			Free Biom.			Pellets	Free. Firew.			Ethanol
	Appliances	EI 0	EI 1	EI 2	LPG	Biogas	Charc 0	Charc 1	Charc 2	FW-B 0	FW-B 1	FW-B 2	FW-B 0	FW-B 1	FW-B 2	Pellets	FW-B 0	FW-B 1	FW-B 2	Ethanol
PRICE/COST RESULTS		EI 0	EI 1	EI 2	LPG	Biogas	Charc 0	Charc 1	Charc 2	C Firw 0	C Firw 1	C Firw 2	Fr Bio 0	Fr Bio 1	Fr Bio 2	Pellets	F Firw 0	F Firw 1	F Firw 2	Ethanol
Fuel Price	\$/Cook	0.199	0.142	0.105	0.074	0.170	0.151	0.088	0.063	0.166	0.083	0.055				0.066				0.111
Appl. Price	\$/Cook	0.004	0.008	0.012	0.012	0.012		0.014	0.014		0.011	0.011		0.011	0.011	0.013		0.011	0.011	0.007
Health	Units/Cook				0.119	0.563	0.762	0.716	0.443	1.000	0.925	0.849	1.000	0.925	0.849	0.661	1.000	0.925	0.849	0.390
Fuel TimeGen	Units/Cook				0.001	0.039	0.023	0.013	0.010	0.115	0.058	0.038	2.696	1.348	0.899	0.010	1.923	0.962	0.641	0.004
Appl TimeGen	Units/Cook	0.017	0.017	0.017	0.050	0.050	1.000	0.833	0.667	1.000	0.833	0.667	1.000	0.833	0.667	0.333	1.000	0.833	0.667	0.050
Emissions	KgCO2e/Coo	0.222	0.159	0.117	0.274	0.317	3.374	2.128	1.532	5.670	2.814	1.826	4.588	2.272	1.465	0.397	4.632	2.295	1.480	0.465
Deforestation	Units/Cook						4.009	2.339	1.684	2.024	1.012	0.675				0.253	1.962	0.981	0.654	

As a practical example of the analysis of surveys using the Cook unit, the cooking (and extra heating) demand of the average household in Rwanda has been adjusted to 5 Cooks/day, or 1.25 Cooks/day/person. The process behind this estimation is explained at the beginning of Section 6.1, and it is based on the analysis of households using a single fuel for cooking. For instance, in the case of using a single fuel for cooking, the daily fuel consumption for the average household would be:

- Electricity: from 2.5 to 5.0 kWh, depending on the appliance set (only cooking and heating).
- LPG: 0.9 kg.
- Charcoal: from 1.2 to 2.8 kg, depending on the appliance set.
- Firewood: from 3.2 to 9.1 kg, depending on the appliance set.

Note that these figures for cooking demand include some extra-heating demand for other purposes (like domestic hot water) since the mix of fuels would be similar. The extra heating demand is added to the cooking demand in the inputs to the interactive tool.

3.6. Human decisions: the technology adoption model

The “Technology Adoption Model” simulates or predicts the behaviour of different types of customers when choosing combinations of alternative cooking technologies according to perceived (subjective) economic and social costs. The procedure may be applied to each socio-economic cluster of an area (for a detailed explanation of results) or to an equivalent rural/urban aggregated consumer (for planning optimisation). In any case, it will be applied to an already aggregated consumer: the Social Cluster or just the CONSUMER.

Figure 15. Aggregated Urban/Rural consumers in a Technology-Adoption (or Demand) Area.

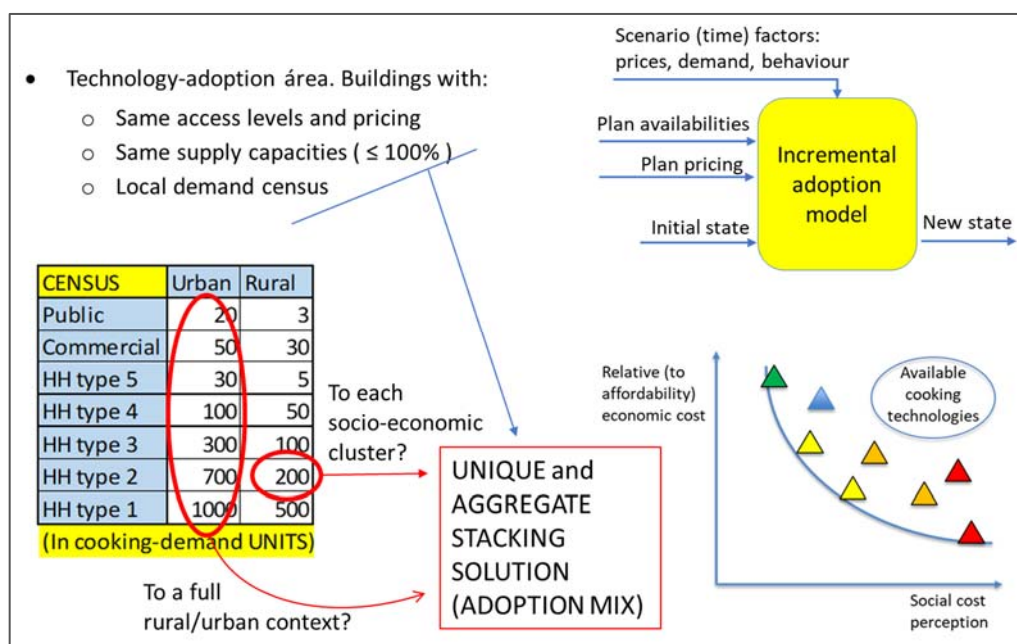
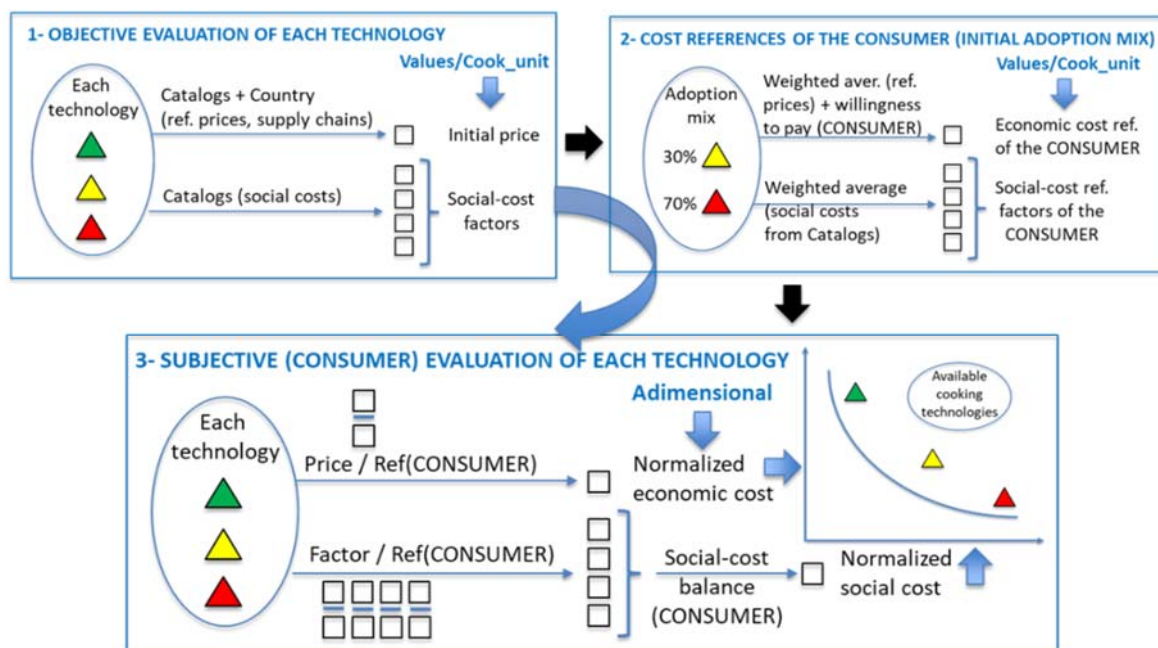


Figure 15 illustrates several concepts: the aggregation of local consumers into Rural and Urban equivalents, the adoption of technologies as a black-box process, and the multi-attribute nature of the choice of technologies from the consumer's perspective. Note the black-box representation of the process (top-right of Figure 15): consumers were already cooking with some adoption mix (initial state), but time brings changes (scenarios), and plans may modify the prices and availabilities of technologies. The result is a new state of adoption mix.

The successive steps of the procedure are described here to understand the logic and the influence of each input parameter (to be adjusted), defining the behaviour of each type of consumer or each Rural or Urban aggregated consumer. Steps are grouped into two blocks: (a) the normalisation of objective economic and social costs to the

subjective perception of the consumer, and (b) the application of the adoption criteria to estimate the new adoption mix of the consumer.

Figure 16. Normalisation steps in the adoption model.



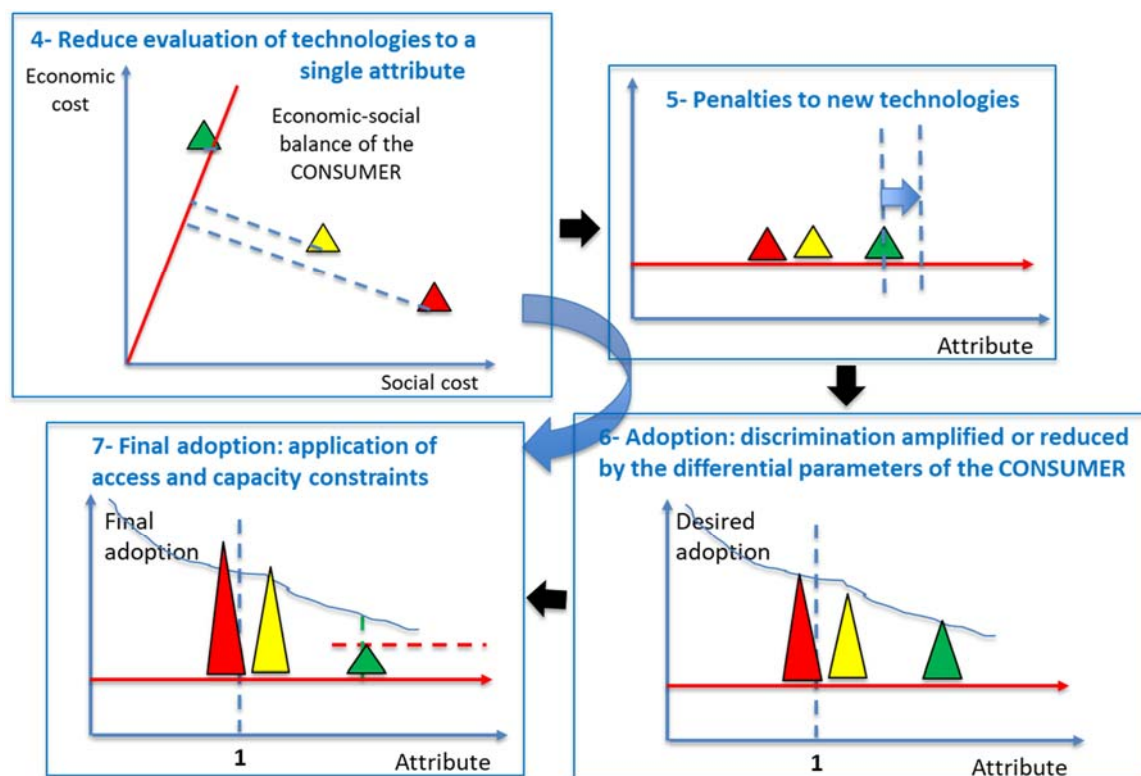
Steps towards the normalisation of economic and social costs (see Figure 16):

1. Compute the objective evaluation of each technology (separated values for fuels and appliances because their prices may be altered by the plan independently). These include absolute local prices for fuels and appliances and actual social costs (health, time & gender, emissions, deforestation).
2. (Economic costs) Compute the economic-cost reference of the CONSUMER (the local overcost is included). This calculation considers what the consumer was already paying for cooking and his willingness to pay.
2. (Social costs) Compute the four reference social factors of the CONSUMER (the local overcost is included). These reference factors are those of the initial adoption of the consumer because these are the social costs to which the consumer is accustomed.
3. (Social costs) Normalisation of the social costs of the technologies with respect to the references of the CONSUMER:
3. (Economic costs) Normalisation of the economic costs of technologies with respect to the reference of the CONSUMER:

Steps to estimate the new adoption mix of the consumer (see Figure 17):

4. Reduction of the technologies' evaluation to a single "attribute" (a single equivalent effect). This step applies the relative importance given by the consumer to social costs with respect to economic costs.
5. Penalties to new technologies, those not present in the initial status of the adoption mix, and penalties to relatively expensive appliances (depending on the expenditure capacity of the CONSUMER).
6. Preliminary assignment of the desired adoption mix (or stacking). This step applies a function of the family "1/x", meaning that technologies with lower costs (aggregated and normalised) are assigned a greater adoption share. The function has two parameters that tailor the assignment to each type of consumer: a sensitivity to adopt better options and a sensitivity to reject worse options (both with respect to the initial state reference). This step also includes the relative importance of the fuel versus the appliance in the decision (see comments at the end of this section).
7. Final assignment of the estimated adoption mix (or stacking). The previous steps define the CONSUMER's preferences in case of full availability of options. This final step includes limitations of access or capacity (iterative redistribution of the excess of adoption for saturated technologies):

Figure 17. Criteria-application steps in the adoption model.



As said before, these steps are mentioned here to better understand the behavioural parameters that should be adjusted for every type of consumer. Some steps depend on the initial adoption of technologies (the model is incremental, and consumers tend to maintain their habits). Some depend on subjective costs, which are related to the socio-economic status and the initial expenditure. Other steps reflect resistance to change, which are cultural characteristics related to progress and education. Finally, the relative balance between different effects (Cost, Health, Time&Gender, Emissions, and Deforestation) depends on education and social awareness.

A topic of interest was mentioned in step (6) of the procedure: the relative importance of the fuel versus the appliance in the decision. Let us use an example to explain this modelling dilemma: Electricity, with three types of appliances, results in three technologies; however, LPG has a single type of cookstove or burner in the model, resulting in a single technology. Assuming that these are the only technologies available to the consumer, there are two extreme solutions to this problem:

1. They should be modelled as four independent options for the consumer in open competition. This solution favours the fuels with more available appliance sets.
2. They should be modelled only as two options for the consumer, Electricity or LPG. Once the adoption share is decided between them, a second decision would be to distribute the Electricity share among its different types of appliances. This solution focuses 100% on the fuel.

The best solution lies somewhere in between. The choice of fuel is relevant, no matter the appliance used; however, the diversity of available appliances provides marketing advantages, making the fuel option more visible (and attractive) and reaching more consumer niches.

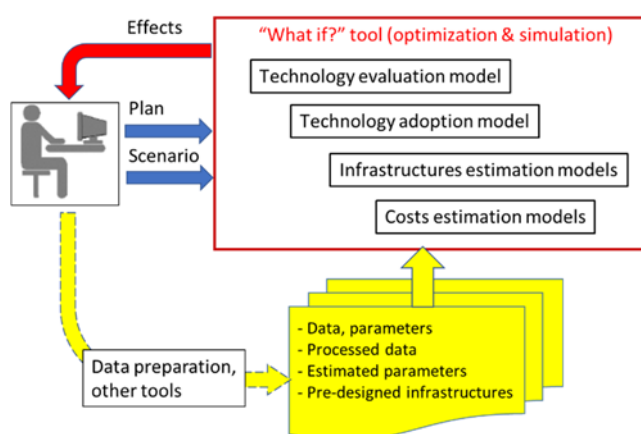
4. Off-line inputs: non-processed data

The plans, the conclusions and the recommendations resulting from the ICCP application generally depend on the quality of the input data and the underlying assumptions. The following sections briefly describe the off-line inputs, their sources, assumptions, and simplifications. They are structured according to the four types of off-line inputs depicted in Figure 18: data and parameters (direct inputs, without processing), processed data, estimated parameters, and finally, the pre-designed infrastructures for Electricity and LPG. Inputs should be reviewed and validated by local stakeholders so that their feedback can be added to the subsequent planning revisions.

In the general approach, the tools allow a high level of parameterisation of the problem. However, the current versions are partially defined for a particular model of Rwanda, so some options are rigidly established, like the administrative regions or the cooking technologies considered in Version 1. Version 2 is more flexible but not fully adaptable to other countries or contexts.

Note that the examples of inputs and outputs of the tool presented in this document are taken from Version 1, which is the one that is fully operative at the moment. However, the modelling concepts apply to both versions.

Figure 18. The interactive planning tool.



Part of the inputs are configuration parameters or objective data that do not require pre-processing tasks but are defined directly by the user. Some examples are:

- The emissions rate of the country's grid-generation mix. Rwanda's example has been set to 0.2 kg of CO₂eq per kWh based on the current generation mix; however, this parameter can be easily updated anytime.
- The FIX costs of the grid-generation mix of the country. It should be consistent with the fraction estimated to design the tariff (in \$/kWh). It has been set to 0.06 \$/kWh in this application for Rwanda.
- The VARIABLE costs of the grid-generation mix. It should be consistent with the fraction estimated to design the tariff (in \$/kWh). It has been set to 0.03 \$/kWh in this application.
- The average diesel generator consumption (used in mini-grids) is set here at 0.4 litres/kWh.

The inputs shown in Figure 19 are design options that the planner may adjust freely. In these initial versions of the tool, the capacity of infrastructures (Electricity and LPG) is adjusted to the expected adoption plus some capacity "margin" in the expectation of adoption growth in the short-medium term.

Figure 19. Extra capacity margins for electricity and LPG (design options).

DESIGN AND EVALUATION CRITERIA: FOR ALL PLANS		
List of Deployed Fuels	Dis-Elec	LPG
Design: extra capacity margin	5%	6%

The planner may also fix the balance weights to translate the five effects used in evaluating states and plans into two main attributes and then into a single value (although disaggregated information is always available). Figure 20 shows how these weights are introduced in the tool.

Figure 20. Choice of relative weights for attributes (planner perspective).

PLANNER: Social Costs Weights						
1-(Social W)	0<= SW <=1	Social factors balance: weights, add to 1				
Econ W	Social W	Health	Time & Gender	Emissions	Deforestation	
0.50	0.50	0.25	0.25	0.25	0.25	1.00

Remember that in a future state estimate for the application of a plan, the social cost factors (Health, Time & Gender, Emissions and Deforestation) are individually normalised with respect to the initial state. Therefore, they are always handled as per-unit values and may be added to a weighted average, with the weights being a choice of the planner. In the case shown in Figure 20 (right side), the weights are balanced (all equal to 0.25) so that the planner gives the same importance to the variation of any of them when evaluating the overall variation of social costs.

Similarly, on the left side of Figure 20, the planner has given the same importance to the variation in economic and social costs (both equal to 0.5) when evaluating the overall fitness of the state estimate. In summary, these particular inputs aid the decision-making process and reflect the decision criteria of the user (the planner).

5. Off-line inputs: processed data

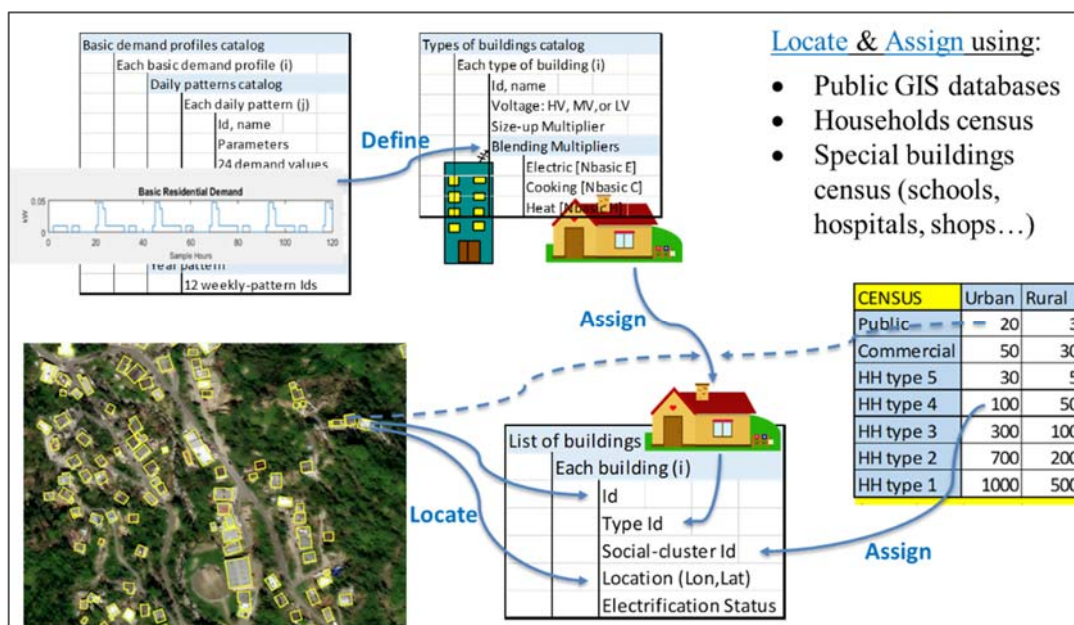
These are off-line inputs that can be extracted from public sources but require some processing to adapt their contents and/or their formats. This section includes two types of processed data: buildings and land-use features (related to biomass patterns). Other types of processed data are not described here because they are inputs to the off-line tools for electric and LPG infrastructure design, like solar irradiance, roads, topography, and “forbidden” areas (such as natural reserves).

5.1. Building identification and labelling

This section describes the data sources and processing steps used to develop inputs about buildings for the ICCP tools and, in particular, for the case of Rwanda. The information was prepared using Google Open Buildings, OpenStreetMap, Census data and geo-political or administrative boundaries.

Note that in Version 1 of the tool, only two types of buildings have been used: the average urban household and the average rural household. The non-domestic electric demand has been emulated via a non-residential demand factor, to be explained later, to estimate the actual size of the infrastructures, costs, and incomes. The general approach (and Version 2 of the tool) includes identifying multiple types of buildings and demand profiles, as has already been done for electrification planning problems. Figure 21 summarises the full process of identification and labelling of buildings, with multiple types of buildings and with multiple profiles (social clusters) and sizes of consumers.

Figure 21. Building information, demand profiles, and census.



The Google Open Buildings dataset provides building footprints across Africa and Southeast Asia and was created using high-resolution satellite imagery, convolutional neural networks, and polygonization models. Google reports 80% and 90% precision levels for their building detections. The OpenStreetMap dataset is comprised of manually annotated building shapes.

Google Open Buildings has been combined with OpenStreetMap, prioritising OpenStreetMap where the two data sources show overlapping buildings. Building density attributes were computed, defined as the number of buildings within a radius of 1 km, to assign urban or rural labels to the buildings. Buildings with more than 2000 neighbours within a 1 km radius were designated as urban, and those with fewer were designated rural.

The buildings' data was then geographically clipped by district and ultimately saved as 30 separate GeoJSON files, one for each district. These files contain each building as an object in the GeoJSON file, defined as a polygon of the shape of the building and including additional parameters such as the estimation of being rural or urban, as described above. However, the number of buildings initially obtained and the category rural/urban did not match current census data, so it was necessary to perform some post-processing of the data to increase the accuracy.

Systematic procedures were applied to match the census information. Small structures were discarded as buildings; these could be auxiliary buildings such as storage, sheds, or garages. Local incongruences in rural/urban labels were filtered. The results used in Version 1 of the tool are shown in Figure 22, in the format used by the interactive tool as an off-line input (the number of buildings shown in the columns at the right of the table). The figure also shows the proportions of biomass patterns, explained in Section 5.2.

Figure 22. Biomass patterns proportions and rural/urban buildings assigned to districts

Id	Name	Code	Type balance (add = 1)				#Buildings	
			CITY	AGRO	FORE		Rural	Urban
10	Kigali	Kili	CITY	AGRO	FORE	1.00	15802	94013
11	Nyarugenge	Nyge	0.50	0.36	0.13	1.00	42409	208105
12	Gasabo	Gabo	0.49	0.41	0.10	1.00	1256	135536
13	Kicukiro	Kiro	0.61	0.24	0.15	1.00		
20	Southern	Sorn	CITY	AGRO	FORE		Rural	Urban
21	Nyanza	Nyza	0.17	0.63	0.19	1.00	85113	5772
22	Gisagara	Gira	0.13	0.67	0.20	1.00	98351	4137
23	Nyaruguru	Nyru	0.04	0.47	0.49	1.00	72217	2636
24	Huye	Huye	0.20	0.59	0.21	1.00	79521	21029
25	Nyamagabe	Nybe	0.04	0.43	0.54	1.00	82716	10970
26	Ruhango	Rugo	0.11	0.67	0.22	1.00	84243	9480
27	Muhanga	Muga	0.09	0.59	0.32	1.00	71374	22007
28	Kamonyi	Kayi	0.22	0.60	0.18	1.00	79108	37192
30	Western	Wern	CITY	AGRO	FORE		Rural	Urban
31	Karongi	Kagi	0.10	0.59	0.30	1.00	83016	8174
32	Rutsiro	Ruro	0.04	0.59	0.37	1.00	82977	4711
33	Rubavu	Ruvu	0.24	0.66	0.09	1.00	57325	67581
34	Nyabihu	Nyhu	0.11	0.62	0.27	1.00	57396	19609
35	Ngororero	Ngoo	0.04	0.63	0.33	1.00	87457	4168
36	Rusizi	Ruzi	0.12	0.23	0.65	1.00	70294	32960
37	Nyamashek	Nyke	0.16	0.24	0.61	1.00	87148	8581
40	Northern	Norn	CITY	AGRO	FORE		Rural	Urban
41	Rulindo	Rudo	0.26	0.53	0.21	1.00	82568	10785
42	Gakenke	Gake	0.15	0.50	0.35	1.00	89875	3527
43	Musanze	Muze	0.34	0.45	0.21	1.00	60542	62187
44	Burera	Bura	0.29	0.53	0.18	1.00	83154	9673
45	Gicumbi	Gibi	0.26	0.51	0.24	1.00	102611	2742
50	Eastern	Earn	CITY	AGRO	FORE		Rural	Urban
51	Rwamagana	Rwna	0.32	0.58	0.10	1.00	80231	46317
52	Nyagatare	Nyre	0.08	0.79	0.13	1.00	120984	37298
53	Gatsibo	Gato	0.11	0.58	0.30	1.00	120933	16617
54	Kayanza	Kaza	0.09	0.64	0.27	1.00	98015	17495
55	Kirehe	Kihe	0.11	0.62	0.27	1.00	105328	10817
56	Ngoma	Ngma	0.18	0.63	0.19	1.00	94054	9276
57	Bugesera	Buga	0.18	0.56	0.25	1.00	82532	59604

5.2. Distribution of biomass patterns

The ultimate purpose of this procedure is to link biomass patterns to actual districts and consumers. These patterns are closely related to local biomass resources and, therefore, to the local prices (multipliers) of commercial biomass and the local Time&Gender cost multipliers for the free-gathered biomass (like firewood, crop waste, and manure).

Three patterns are defined in Version 1 of the tool: "CITY" (areas dominated by buildings or by low biomass availability), "AGRO" (areas dominated by agriculture and livestock), and "FORE" (areas dominated by trees). The central columns of the table shown in Figure 22 are the results of this process: each district is assigned a certain proportion of the patterns to be combined with the urban/rural proportions. In Version 2 of the tool, a fourth pattern is handled separately (Rangeland), and the biomass patterns are assigned not only to regions but also to individual buildings.

The distribution of biomass patterns was obtained at the district level after the analysis of satellite images that cover the whole country of Rwanda. The goal was to determine the land use at a pixel resolution of 10x10 meters. Then the percentage of each land use was aggregated at the district level.

The most suitable data source for this task is the satellite imagery provided by the ESRI Sentinel-2 satellite, called Sentinel-2 Land Cover Explorer. This dataset is publicly available as raster images from ArcGIS (ESRI, 2022). Files come in GeoTIFF format (OGC, 2023), a normalised image georeferenced in UTM (Universal Transverse Mercator coordinate system), and they refer to 2022. Each pixel is assigned a value between 1 and 11, described in Table 1.

Table 1. Types of land identified by Sentinel-2 Land Cover Explorer.

Type	Name	Description
1	Water	Water was predominantly present throughout the year; may not cover areas with sporadic or ephemeral water; contains little to no sparse vegetation, no rock outcrop nor built up features like docks; examples: rivers, ponds, lakes, oceans, flooded salt plains.
2	Trees	Any significant clustering of tall (~15-m or higher) dense vegetation, typically with a closed or dense canopy; examples: wooded vegetation, clusters of dense tall vegetation within savannas, plantations, swamp or mangroves (dense/tall vegetation with ephemeral water or canopy too thick to detect water underneath).
4	Flooded	Areas of any type of vegetation with obvious intermixing of water throughout a majority of the year; seasonally flooded area that is a mix of grass/shrub/trees/bare ground; examples: flooded mangroves, emergent vegetation, rice paddies and other heavily irrigated and inundated agriculture.
5	Crops	Human planted/plotted cereals, grasses, and crops not at tree height; examples: corn, wheat, soy, fallow plots of structured land.
7	Built	Human-made structures; major road and rail networks; large homogeneous impervious surfaces including parking structures, office buildings and residential housing; examples: houses, dense villages / towns / cities, paved roads, asphalt.
8	Bare ground	Areas of rock or soil with very sparse to no vegetation for the entire year; large areas of sand and deserts with no to little vegetation; examples: exposed rock or soil, desert and sand dunes, dry salt flats/pans, dried lake beds, mines.
9	Snow/Ice	Large homogeneous areas of permanent snow or ice, typically only in mountain areas or highest latitudes; examples: glaciers, permanent snowpack, snow fields.
10	Clouds	No land cover information due to persistent cloud cover.
11	Rangeland	Merged from previous categories: 3. Grass. Open areas covered in homogeneous grasses with little to no taller vegetation; wild cereals and grasses with no obvious human plotting (i.e., not a plotted field); examples: natural meadows and fields with sparse to no tree cover, open savanna with few to no trees, parks/golf courses/lawns, pastures. 6. Scrub/shrub: Mix of small clusters of plants or single plants dispersed on a landscape that shows exposed soil or rock; scrub-filled clearings within dense forests that are clearly not taller than trees; examples: moderate to sparse cover of bushes, shrubs and tufts of grass, savannas with very sparse grasses, trees, or other plants.

The images contain colour values that correspond to the different types of land. Two images were needed to cover the area of Rwanda, the one corresponding to UTM zone 35M and the one corresponding to zone 36M, as shown in Figure 23. Then, any GIS software (such as QGIS) can be used to clip the images according to the polygon that defines the contour of Rwanda and then each of the districts (as shown in Figure 24).

The total number of pixels associated with each district was computed and converted into square kilometres to compare with the official areas of each district. This was done just to ensure the accuracy of the process. Then, each type of land was described with a number of pixels, an area in km², and a percentage of the district area. As a result, the dominant types of land in Rwanda were found to be the following:

- Type 5: Crops. 32% Minimum 9% at Nyamasheke, Maximum 65% at Nyagatare.
- Type 11 Rangeland. 28% Minimum 4% at Rubavu, Maximum 57% at Ruhango.
- Type 2 Trees. 18% Minimum 4% at Rwamagana, Maximum 59% at Rusizi.
- Type 7 Built. 14% Minimum 2% at Rutsiro, Maximum 60% at Kicukiro.

Figure 23. Sentinel-2 images for UTM zones 35M (left rectangle) and 36M (right).

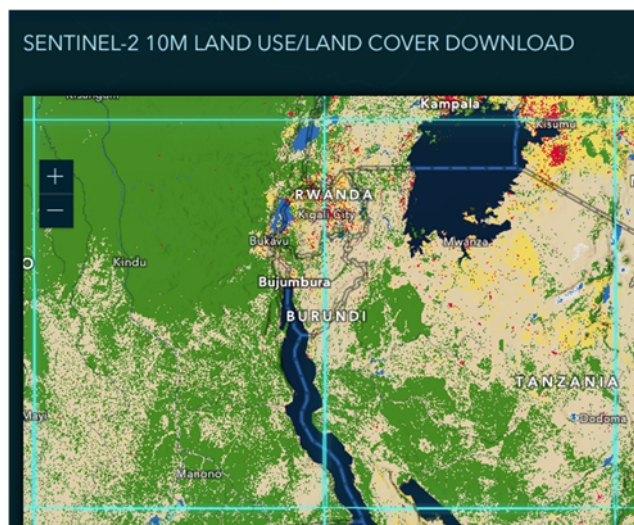
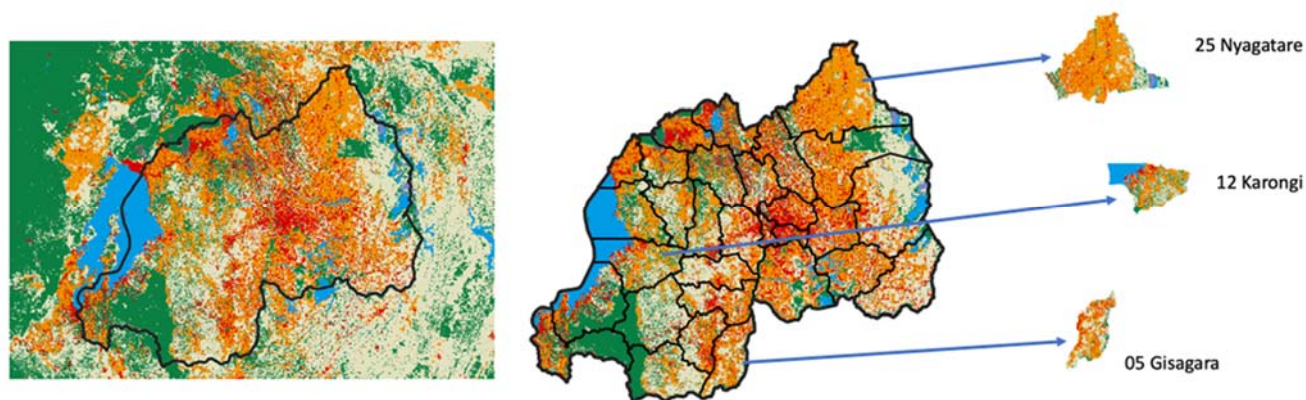


Figure 24. Clipping process to obtain the relevant pixels of the satellite images.



These are also the types of land where people live and the types of land relevant for biomass availability and pricing. Thus, once the area of each land-use type per district was obtained, we discarded the areas where people cannot live or where no information is available (water, flooded, snow/ice, bare ground, and clouds) and normalised the proportions to the usable land area. In Version 1, the correspondence between land types and biomass patterns has been applied as follows:

- Type 5: Crops. Assigned to pattern AGRO.
- Type 11 Rangeland. Split among AGRO (70%) and FORE (30%).
- Type 2 Trees. Assigned to pattern FORE.
- Type 7 Built. Assigned to pattern CITY.

The proportions used in the split of “Rangeland” were decided according to the expected availability of biomass; this is a compromise required for this version of the tool, but in the general approach (and in Version 2), “Rangeland” is considered explicitly as a biomass pattern. The result is that every district, concerning its biomass characteristics, is expressed as a linear combination of biomass patterns with weights adding up to 1 (see Figure 22). As said before, in Version 2 of the tool, the “Rangeland” pattern is handled separately, and the biomass patterns are assigned not only to regions but also to individual buildings.

6. Off-line inputs: estimated parameters

This section is devoted to off-line inputs that have required specific estimation assumptions and procedures, using data published or provided by the institutions of Rwanda. Therefore, this section is relevant for future validation, feedback, and improvement. Some of the procedures and even some of the results could be useful in applying the model to other countries, but in general, the specific procedures will require some adaptation to the information available in each case.

In the case of Rwanda, the primary source is the Biomass Survey on Cooking Fuel Energy and Technologies (MININFRA, 2021). It has been processed using the raw data, and the first part of this section describes this process. Results could be improved using a more recent survey version, not only because of the updated information but mainly due to the incremental evolution.

6.1. Processing the Biomass Survey on Cooking Technologies

(MININFRA, 2021) indicates that as of 2021, a substantial 80.37% of households in Rwanda relied on firewood for cooking, predominantly using traditional three-stone stoves. Charcoal and agricultural waste also constitute significant portions of the cooking fuel mix. Liquefied Petroleum Gas (LPG) is the most prevalent among cleaner fuel options, as detailed in Table 2.

Table 2. Distribution of household cooking fuel types based on energy source (MININFRA, 2021). Totals in columns exceed 100% because one household may use multiple types of fuels.

	Fuel type	Urban	Rural	Nationwide
Biomass	Firewood	39.42%	91.14%	80.37%
	Charcoal	59.34%	7.17%	18.03%
	Pellets	0.10%	0.12%	0.11%
	Biogas	0.25%	0.20%	0.21%
	Cow dung	0.10%	0.10%	0.10%
	Crop residues	5.05%	10.71%	9.54%
	Papyrus	0.00%	0.07%	0.06%
	Sawdust	0.16%	0.39%	0.34%
Fossil energy	Kerosene	0.00%	0.03%	0.02%
	LPG	25.62%	0.40%	5.65%
Electricity	Electricity	0.92%	0.03%	0.21%

The raw data from (MININFRA, 2021) with more than 5000 households has been carefully processed to adjust critical parameters of the planning problem. The steps, purposes, and results are summarised as follows:

1. Isolate households using a single type of fuel. Adjust demand and efficiencies.

The purpose of the step is twofold: (a) estimate the average “cooking+heating” demand in Cooks, and (b) adjust the efficiency and the emissions of the technologies considering their actual usage, not just laboratory results.

The survey provided 1986 samples for 100% Commercial Firewood, 282 samples for 100% Free Firewood, 551 samples for 100% Charcoal, and 113 samples for 100% LPG. The rest of the fuels did not present significant results. For the numeric results provided below, only households of sizes between 3 and 6 people were used (with an average size close to 4.4 people).

Electricity and LPG are reliable, controllable, replicable, and widespread technologies. Therefore, the laboratory results that estimate their effective heat and efficiency can be used safely. LPG was used to estimate the average demand, rounded to 5 Cooks/day for the average household, or 1.25 Cooks/day/person. The model will use an average of 4 people per house, consistent with the buildings identified and the census.

To estimate the percentages of each type of stove, they are grouped by efficiency levels into three groups and the average efficiency and relative percentage of each group of stoves are calculated: around 10%, 20% and 30% efficiency for Firewood, and 15%, 25% and 35% for Charcoal.

The efficiency of Firewood, Charcoal, and other technologies could be adjusted using the average demand value and the proportions of appliance types (also included in the survey). For Electricity and Biogas, laboratory results were used. The efficiency of the Pellets technology was slightly reduced to 95%, Charcoal reduced by a factor of 82%, and Firewood and Free Biomass by a factor of 60%.

2. Translate fuel usage to Cooks. Adjust the initial adoption of technologies.

The survey was now revisited, translating the quantities of different fuels to Cooks for each household and applying the declared proportions of appliances. This produced percentual adoption results for each household and for each rural/urban subset of each district. From these results and the proportions of biomass patterns in each district (see Section 5.2 and Figure 22), the initial adoption of technologies was assigned to the six profiles used in the ICCP for Rwanda (Version 1), the three biomass patterns with their respective rural/urban types.

3. Process local prices for Commercial Firewood and Charcoal. Adjust local price multipliers for profiles.

After selecting those households that declared that 100% of the firewood used was purchased and those using charcoal, the declared expenditures were divided by the quantities. This process proved unreliable, consistent with how the data was gathered (the local prices were used a priori in the survey to relate expenditures and quantities). The local prices were estimated and assigned to profiles, but they were just an initial value to be further adjusted to match adoptions.

4. Final adjustment. Behavioural parameters and local multipliers.

The final processing phase combined the adjustment of the behavioural parameters (consumers) and the profile parameters (local price and Time&Gender multipliers) so that the model could predict the already known initial adoption using the same initial adoption and the actual prices. This self-referenced process would be more straightforward and accurate if (a) reliable local prices were used and (b) the two most recent surveys were available to provide incremental information.

6.2. Demand profiles

Three independent demand profiles have been included in the model: electric demand (or E-Demand), measured in kWh; cooking demand, measured in Cooks; and other heating demands (like domestic hot water), also measured in Cooks because heating can be supplied by any of the fuels used for cooking.

It is important to know the hourly demand profiles for the electrical design. Hourly details are irrelevant for other fuels that can be stored and managed; however, since cooking and heating may be supplied by electricity, hourly profiles are defined for the three types of demand. The peaks of demand for cooking are obviously concentrated in the hours of preparation of breakfast, lunch, and dinner.

This subsection explains the simplified demand models used in Version 1 of the tool. Version 2 uses more than 20 types of buildings of different sizes, and the demand profiles have been adjusted more realistically according to type and size. Both versions have been adjusted to meet the country's actual energy statistics.

Using the Cooking Diary study of Rwanda (Energy 4 Impact, 2022), the demand for cooking and heating water was initially estimated at 3 Cooks/day for the average household. However, the analysis of the national survey described in the previous section proved that 5 Cooks/day was much more accurate. It is assumed that 4.6 Cooks/day are used for cooking and 0.4 Cooks/day for heating water. These proportions may vary in diverse households and may even be wrong, but this is not relevant since what matters is the total sum of the “cooking+heating” demand, which is based on the survey.

The demand for other uses of electricity (neither cooking nor heating), referred to as E-Demand in the document and the tool, has been estimated as Tier 3 of the Multi-Tier Framework (Bhatia & Angelou, 2015). It is established as 1 kWh/day in rural households and 1.5 kWh/day in urban households, resulting in a weighted average of approximately 1.2 kWh/day. It is important to note that this level of purely electric demand is much higher than the current one, and this fact has been considered in the estimation of the factor for non-residential customers, explained below (for Version 1 of the tool). The hourly distribution was made using the profiles used in the design of the National Electrification Plan (NEP) in Rwanda (REG, 2019).

The reason for using Tier 3 demand is that in the ICCP context, “Electricity deployment” means “access to Electricity compatible with e-cooking”. This is why the initial deployment of electricity is set to 60%; it includes all the grid-connected customers, 55% currently, plus a fraction of the off-grid customers. Low-power electrification, below 1.5 kW peak, is ignored or considered a different problem with separate business results that are assumed to be self-sustainable, or at least negligible in terms of overall results (incomes minus costs). Concerning the over-demand resulting in the non-cooking electric energy, it is completely corrected and compensated by the factor for non-residential customers (this is required in Version 1 of the tool because only residential buildings are handled).

Factor for E-Demand of non-residential consumers.

The influence of non-residential consumers has been included in the problem through a factor that has been estimated considering the statistics in the electricity sub-sector as of September of the year 2022 (RURA, 2022). The factor has been adjusted to a value of “1.65”. This factor affects both the costs of the electric system deployment (due to the actual capacity required and the economies of scale) and the income due to the electric tariff. The way to estimate this factor is shown in Figure 25 and explained below.

(RURA, 2022) provides the total electric demand per year (1200 GWh/year) and the fraction corresponding to residential consumers (20.21%). Since the connection rate of these consumers to the grid is 55%, we can calculate that the average demand of a household is 0.361 kWh/day, considerably lower than the Tier 3 level assumed in the model. This is why the initial value of the factor, assuming the 1.2 kWh/day average, is 1.49 instead of 5 (suggested by the 20.21% figure). See the left part of Figure 25 for these calculations.

The problem is estimating the value of the factor in the future, for instance, in 2035. The right part of Figure 25 is devoted to this projection. The assumptions use a standard scenario of 2.3% annual population growth, 6% annual economic growth, 100% electrification, and the rise of the household average E-Demand to 1.5 kWh/day (without e-cooking or e-heating, just other electricity uses). Being so, we can estimate the households' accumulated E-Demand as 2405 GWh/year. The total demand per year is calculated as indicated at the bottom of Figure 25: the non-residential demand grows at the same rate as the economy, and the residential demand is added on top. This produces 55% of the residential fraction of demand and thus a value for the factor of 1.8. The final choice is 1.65, the average between the initial value (1.49) and the final value (1.8).

Figure 25. Estimation of the non-residential consumers' FACTOR.

	End of 2023		Growth	End of 2035	
Total	1200.000	GWh grid	Calculated:	4331.759	GWh all
Residential	20.21%	Fraction %		55.52%	Fraction %
Residential	242.520	GWh		2405.121	GWh
Conectivity	55%	To grid	Up to:	100%	Electrified
Households	3.342	Million	2.30%	4.390	Million
Daily dem.	0.361	kWh/day	Up to:	1.500	kWh/day
FACTOR assuming 1.2 kWh/day:				FACTOR:	
	1.49			1.80	
		Economy:	6.00%		
GWh all = Non_residential(2023) X Economy_growth + Residential(2035)					

As a final remark, note that the accuracy of this estimation is relevant but not so critical as to alter the conclusions of the model presented here. The marginal costs and incomes due to electric cooking are not that strongly dependent on the economic balance of the electrification process itself.

6.3. Initial technology adoptions and availabilities

First, the concepts of “adoption” and “adoption mix” (or stacking) should be clarified. The “Cook” has been defined as an absolute unit for cooking and heating demand, and an average demand profile of 5 Cooks/day for the average household has been estimated. A statement such as “50% of LPG adoption” means that half of the demand in Cooks

is satisfied using LPG. This applies to a particular household, aggregated consumers of a certain type and location, or the whole country. The corresponding Cooks covered by a particular technology can be easily translated to fuel consumption, costs, health, emissions, or any other relevant effect since all these effects are expressed in units/Cook (remember Figure 14 in Section 3.5).

Second, the concept of “availability” can be recalled from Section 3.1 as a combination of “access” and “capacity”. Access is the percentage of consumers in a given area that could use a fuel, while capacity is the percentage of the total demand of the area that could be supplied with the fuel.

The estimation of initial adoptions is based on the processing of the raw data from the National Survey on Cooking Fuel Energy and Technologies in Households (MININFRA, 2021), as described in Section 6.1. Figure 26 shows the process results, as presented in the tool inputs.

Figure 26. Initial technology adoptions based on the National Survey.

Initial Adoptions	El 0	El 1	El 2	LPG	Biogas	Charc 0	Charc 1	Charc 2	C Firw 0	C Firw 1	C Firw 2	Fr Bio 0	Fr Bio 1	Fr Bio 2	Pellets	F Firw 0	F Firw 1	F Firw 2	Ethanol
100.0% CITY-Rural	0.20%	0.01%	0.01%	2.00%	0.02%	2.00%	5.00%	0.40%	31.00%	22.60%	2.70%	3.00%	2.90%	1.40%	0.30%	15.00%	10.00%	1.46%	0.00%
100.0% CITY-Urban	1.50%	0.20%	0.10%	32.00%	0.00%	8.00%	33.00%	2.70%	8.00%	5.00%	1.50%	0.80%	0.50%	0.30%	0.10%	3.00%	1.50%	1.80%	0.00%
100.0% AGRO-Rural	0.10%	0.02%	0.01%	1.50%	0.10%	1.00%	3.35%	0.30%	31.00%	21.00%	3.00%	3.30%	3.00%	1.00%	0.40%	17.00%	12.70%	1.22%	0.00%
100.0% AGRO-Urban	1.00%	0.10%	0.10%	22.00%	0.05%	4.00%	28.00%	2.30%	19.00%	8.10%	1.10%	1.60%	1.40%	0.60%	0.20%	5.00%	3.00%	2.45%	0.00%
100.0% FORE-Rural	0.10%	0.02%	0.01%	1.50%	0.05%	0.60%	3.00%	0.50%	31.00%	19.00%	3.50%	2.60%	2.00%	0.90%	0.30%	19.00%	14.00%	1.92%	0.00%
100.0% FORE-Urban	1.00%	0.10%	0.10%	22.00%	0.02%	4.00%	25.00%	0.90%	21.00%	8.00%	1.10%	1.50%	1.30%	0.50%	0.20%	6.00%	4.30%	2.98%	0.00%

The initial status of electrification (60% of access) has been estimated from (REG, 2023), considering that not all the off-grid systems installed are compatible with e-cooking because of a lack of peak power and/or daily energy capacity. The initial status of LPG deployment (25% of access) has been estimated from the scenarios described in (Global LPG Partnership, 2021). The maximum capacities of electricity and LPG have been adapted to the urban and rural environments.

Using actual data on deployment for the different districts is not practical in this version of the NICCP, and it would be useless for future states. Instead, there is an internal simulation of partial deployments for electricity and LPG. It is based on the Electricity and LPG pre-design of infrastructures. The logic consists of assuming that the most deployed areas are those with the lowest cost/benefit ratios. Comparing the results with the electricity deployment levels per district (75% average for the country) described in (REG, 2023), these are more than acceptable, with an average error of 14%. In general, our algorithm is more radical than actual policymakers; it amplifies the differences between low-cost and high-cost districts.

The maximum initial capacities of fuels and appliances have been estimated considering the current adoption of technologies and the adaptability of these local markets to actual demand. This means that the supply of appliances will be adapted easily to the demand increments.

Figure 27. Initial maximum availabilities of fuels and appliances.

State 00	2024																					
Initial ELECTRIF:	60%	25%	LPG	MAX Initial availabilities of FUELS					MAX Initial availabilities of APPLIANCES													
Pattern	Dis-Elect	LPG	Biogas	Charcoa	Com. Fir	Free Bio	Pellets	Free. Fir	Pattern	El 0	El 1	El 2	LPG	Biogas	Charc 0	Charc 1	Charc 2	FW-B 0	FW-B 1	FW-B 2	Pellets	
CIT-Rur	50.0%	10.0%	5.0%	10.0%	65.0%	10.0%	0.5%	32.0%	CIT-Rur	3.0%	2.0%	1.0%	10.0%	5.0%	100.0%	5.0%	2.0%	100.0%	40.0%	10.0%	0.5%	
CIT-Urb	75.0%	30.0%	1.0%	70.0%	25.0%	5.0%	0.2%	10.0%	CIT-Urb	5.0%	2.0%	1.0%	30.0%	1.0%	100.0%	45.0%	10.0%	100.0%	40.0%	10.0%	0.5%	
AGR-Rur	50.0%	10.0%	5.0%	10.0%	65.0%	20.0%	0.5%	34.0%	AGR-Rur	3.0%	2.0%	1.0%	10.0%	5.0%	100.0%	4.0%	2.0%	100.0%	40.0%	10.0%	0.5%	
AGR-Urb	75.0%	30.0%	5.0%	60.0%	35.0%	15.0%	0.2%	15.0%	AGR-Urb	4.0%	2.0%	1.0%	30.0%	5.0%	100.0%	40.0%	7.0%	100.0%	40.0%	10.0%	0.5%	
FOR-Rur	50.0%	10.0%	5.0%	10.0%	65.0%	15.0%	0.5%	36.0%	FOR-Rur	3.0%	2.0%	1.0%	10.0%	5.0%	100.0%	4.0%	2.0%	100.0%	40.0%	10.0%	0.5%	
FOR-Urb	75.0%	30.0%	2.0%	60.0%	45.0%	10.0%	0.2%	20.0%	FOR-Urb	4.0%	2.0%	1.0%	30.0%	2.0%	100.0%	40.0%	7.0%	100.0%	40.0%	10.0%	0.5%	

Initial availabilities (in fact, maximum capacities) must be consistent with the initial adoptions, and they may show that some of those adoptions are constrained by the actual availability and not by the consumer's choice. These inputs play an informative role. However, the maximum capacities in further states, defined in the plans, play a relevant role in the results. They may model industrial targets or limitations, bans (like forbidding charcoal sales in urban environments), or restrictions (like controlling the exploitation of protected forests).

6.4. Technology parameters

The model applied to cooking technologies has already been presented in Section 3.5. This section is devoted to the sources for the different types of parameters, and it is included in the group of “estimated parameters” because of the variations of practical efficiencies and emissions applied in the processing of the raw data from (MININFRA, 2021).

The “Fuels” parameters include the standard per-unit purchasing price, the calorific value, and the standard per-unit Time&Gender effects of gathering (or acquiring) the fuel, mostly suffered by women and children. The “Supply Chains” parameters model the emissions, efficiencies and costs of the transportation and processing tasks. Finally, the “Raw Materials” parameters include costs and emissions parameters (for instance, the imported LPG has its own emissions track before its arrival at the import site). In the case of electricity, the raw material is electricity at the generation point, while the fuel is electricity at the consumer’s connection point. The “Deforestation” attribute is directly related to the raw material “Wood”.

For the parameters describing Fuels, (MININFRA, 2021) has been used for firewood and charcoal. The rates established by RURA have been used for LPG and Electricity (considering a consumption for general use and cooking of 75 kWh/month), the information from (HomeBiogas, 2021) for Biogas, and the data provided by (Energy 4 Impact, 2021) for Pellets. The calorific values were taken from (MININFRA, 2021), and the Time&Gender effects have been estimated considering the time and difficulties of getting the fuel, plus the final adjustment process.

In the parameters for supply chains, the “raw material to fuel” productivity ratio was calculated using losses of 10% for Electricity and 2% for LPG. For Biogas, the reference is the biogas manual from (FAO, 2011), and for Charcoal, it has been considered that 7 kg of firewood is used to obtain 1 kg of charcoal. Unusable waste has been subtracted from the rest of the fuels derived from wood.

Concerning the parameters describing the Appliances, for EI-0, it has been considered a hotplate, and its price has been obtained from the websites of providers. For EI-1, it has been considered induction and infra-red stoves, and for EI-2, efficient modern appliances (rice cooker, insulated electric frying pan, electric pressure cooker), and the prices have been obtained from the publication Electric Cooking in Rwanda (Byrne, et al., 2021). The prices for gas burners come from the Rwanda National LPG Master Plan (Global LPG Partnership, 2021). SNV provided the prices for Firewood and Charcoal appliances. For Pellets, the Mimi Moto stove has been used as a reference.

Figure 28. Base prices for fuels and appliances.

FUELS		Dis-Elec	LPG	Biogas	Charcoal	Com. Fir	Free Bio	Pellets	Free. Fir	Ethanol
Price-Cost pu	\$/kg-kWh	0.199	1.016	1.096	0.263	0.086	0.000	0.275	0.000	0.824

APPLIANCES SETS		EI 0	EI 1	EI 2	LPG	Biogas	Charc 0	Charc 1	Charc 2	FW-B 0	FW-B 1	FW-B 2	Pellets	Ethanol
Price	\$	30.00	57.25	87.00	68.00	68.00	0	25.00	50.00	0	20.00	40.00	72.00	40.00

The base prices adopted for fuels and appliances are shown in Figure 28 in the format used in the tool for the technology parameters. Units are \$/kg, or \$/kWh for electricity (named Dis-Elec because it is the price at the distribution level), and some fuels and appliances are free (zero price). The lifetime of Appliances considered is 5 years for electric appliances, 4 years for gas burners, 1 year for biomass stoves level 1, 1.5 years for biomass stoves level 2, and 3 years for pellet stoves. These lifetimes have been translated to Cooks (using average usage) to express their costs in homogeneous magnitudes, and because their lifetime depends on actual hours of cooking in practice.

In terms of effective heat (ratio between the actual heat applied to the food and the energy of the fuel consumed), the efficiencies considered for electric appliances are 50%, 65 and 80% for EI-0, 1 and 2, respectively, 52% for gas burners based on the Rwanda National LPG Master Plan, 40% for pellets stoves based on the Mimi Moto model, and 45% for Ethanol burners. For firewood or biomass stoves, 10%, 20% and 30% have been considered for levels 0, 1 and 2, respectively. For charcoal stoves, 15%, 25% and 35% have been considered for levels 0, 1 and 2, respectively. In terms of Cooks/kWh, these values were adjusted as explained above, using the raw data of (MININFRA, 2021).

Health effects are calculated through the averted Disability Adjusted Life Years (DALYs) and deaths, comparing the initial situation for each appliance against an ideal situation without health risks. The Household Air Pollution Intervention Tool – HAPIT III (Pillarisetti, Mehta, & Smith, 2016) has been used to estimate the deaths and DALYs, and the values have been integrated with a ponderation of one death equivalent to 1000 DALYs. The values have been normalised, giving the value 1 unit/Cook to the worst situation corresponding to using three-stone systems (the 0 level of appliances) with Firewood or Biomass.

Time and Gender effects are a combination of the time required to prepare the appliance, time for cooking (estimated in minutes per day) and the inconveniences of cleaning and storage. In the same way as health effects, the values have been normalised, giving the value 1 unit/Cook to the worst situation that corresponds to using three-stone systems with firewood or biomass.

Emissions refer to greenhouse gases measured as kilograms of CO₂ equivalent. The CO₂ equivalent is calculated based on the emissions factors and the Global Warming Potential using data from (IPCC, 2007), the Intergovernmental Panel on Climate Change.

6.5. Social clusters parameters

Table 3 explains the influence of each parameter in the adoption model described in Section 3.6. The first group of parameters, labelled as “Demand and economic level,” characterise the electrical demand (not for cooking) and its elasticity relative to the tariff, affordability, and willingness to pay (both for cooking in general and for buying appliances). The second group, labelled “Elasticity and willingness to change”, models the resistance against new technologies and the level of discrimination between better and worse options. Finally, the “Social costs evaluation” group includes the weights or subjective criteria used to balance the different social costs and the economic costs in the decision-making process.

Table 3. Description of parameters for the Rural and Urban consumers (Social Clusters).

Type	Parameter	Units	Step	Comments
Demand and economic level	E-Dem M	p.u.	NA	Electric demand multiplier. It is applied to the standard E-Demand profile. Allows differentiation between Rural/Urban habits or variations of the standard profile.
	Elast. E-Dem	p.u.	NA	Elasticity of E-Demand with respect to tariff variations. The reference used is the standard price of electricity in the catalogs. It should be negative. For instance, Elasticity = -0.5 means that if the tariff increases by 10%, the electricity consumption decreases by 5%.
	Will. pay	\$/Cook	2	Willingness to pay. Alters the price reference of the consumer = average between the current cooking expenditure and the willingness to pay.
	InvestCap	\$	5	Investment capacity. It affects the willingness or capacity to buy appliances by penalising technologies with more expensive appliances.
Elasticity: willingness to change	New tech.	p.u.	5	Penalty for new technologies. The parameter is the maximum adoption reduction (multiplier) of new technologies. This maximum reduction is applied to 0% previous adoption, and it is linearly tending to 1 as the previous adoption is closer to 5%.
	Better	p.u.	6	Amplification (multiplier) of adoptions for technologies better than the reference technology. For instance, a value of 5 means that a technology perceived as 10% better than the reference is adopted 50% more than the reference.
	Worse	p.u.	6	Same as “Better” but applied to technologies perceived as worse than the reference.
Social costs evaluation	Social Weight	p.u.	4	Relative weight of social costs in the overall evaluation of technologies as a single attribute. The relative weight of economic costs is = 1 - Social Weight.
	Health	p.u.	4	Relative weight of Health costs in the overall evaluation of social costs as a single attribute. The four weights must add = 1 (Health + Ti-Gender + Emissions + Deforest = 1)
	Ti_Gender	p.u.	4	Same as Health, but for the Time&Gender attribute.
	Emissions	p.u.	4	Same as Health, but for the Emissions attribute.
	Deforest	p.u.	4	Same as Health, but for the Deforestation attribute.

Figure 29. Parameters of the aggregated Rural and Urban consumers (social clusters).

Social Clusters	Mult p.u.	p.u/p.u.	\$/Cook	\$		Pen <= 1	>1 (5,10,..)	>1 (5,10,..)		0<= SW <=1					
	E-Dem M	Elast. E-D	Will. pay	InvestCap		New tech	Better	Worse		1-(Econ W)	Health	Ti_Gend	Emission	Deforest	
Aggregate Rural	1.00	-0.60	0.07	20.00	Rural	0.20	4.00	6.00	Rural	0.35	0.20	0.70	0.05	0.05	1.00
Aggregate Urban	1.50	-0.40	0.10	25.00	Urban	0.30	4.00	6.00	Urban	0.35	0.20	0.70	0.05	0.05	1.00
	Dem & Economic level					Elasticity: change				Social Weight	Social factors balance: weights, add to 1				

Figure 29 shows the current parameters as they appear in the inputs of the interactive tool, with their adjusted values. Only two types of consumers have been modelled in Version 1 of the ICCP tool: the average rural and urban households.

6.6. Biomass patterns parameters

As already mentioned, Version 1 of the tool defined three Biomass Context Patterns to characterise the local prices and social costs for biomass fuels related to the environment in which the consumers live. In addition to the three patterns, rural and urban consumers must be treated separately.

Figure 30. Parameters adjusted for Biomass Patterns.

Biomass areas param	Local price mult		Free biomass TimGen mult			
	Charc	Firew	Firew	Biogas	Other	
CITY-Rural	1.00	0.80	1.75	5.00	3.00	
CITY-Urban	1.00	1.30	5.00	10.00	8.00	
AGRO-Rural	1.00	0.65	1.25	3.00	1.50	
AGRO-Urban	1.20	0.80	1.25	7.00	1.60	
FORE-Rural	0.80	0.60	1.00	3.00	3.00	
FORE-Urban	0.85	0.65	2.00	8.00	4.00	

The result is the definition of six different contexts, shown in Figure 30, with the parameters assigned to local prices and local Time&Gender costs (all expressed as multipliers over the standard values provided in the parameters of the technologies). Local prices affect charcoal and commercial firewood, while local Time&Gender multipliers are applied to free biomass, free firewood, and biogas (livestock manure in this model). In Version 2 of the tool, there are four biomass patterns, and all the fuels have been included in the corresponding table to model local distribution overcosts, both economic and social (inconvenience).

The assignment of specific parameters to the different Biomass Patterns is part of the “Final Adjustment” process mentioned in Section 6.1. The behavioural parameters (consumers) and the Biomass Patterns parameters (local price and Time&Gender multipliers) are adapted so that the model predicts the already known initial adoption. This self-referenced process would be more straightforward and more accurate if (a) reliable local prices were used and (b) the two most recent surveys were used to apply incremental information. However, the critical result is the combined adjustment of behaviour and patterns, not each of them separately.

7. Off-line pre-designed infrastructures

The off-line optimal design of infrastructures for Electricity and LPG allows the following features of the approach:

- Planning by detailed designs. Planning by design is based on the systematic search for planning solutions using detailed (and optimal) designs to evaluate each plan proposed.
- Granularity down to the “building” level. Multiple types of buildings and demand profiles are considered, as well as detailed street maps, roads, and other geographical data. This is relevant to accurately estimating supply costs, although consumers may be aggregated to estimate the demand response.
- Combination of off-line tools that provide accurate and incremental (sensitivity) results with interactive tools that apply weighted averages, interpolation, extrapolation, and aggregation. This feature makes detailed designs compatible with real-time interaction.

Version 1 of the ICCP tool is subject to some limitations of the interactive model. However, the off-line tools are designed and implemented in full functionality, and then their results are adapted to the needs of the interactive tool.

In both the Electricity and LPG designs, the general principles are the same: (a) design for 100% access and a high level of capacity, (b) break the infrastructures into local supply areas, (c) design the local supply areas for different levels of capacity to allow further interpolation for cost variations, with the differentiation of rural and urban consumers, and (d) design the upstream network that feeds the different local supply areas with incremental information to estimate costs variations. By doing so, the interactive tools may estimate costs without running the off-line tools again.

7.1. Electric infrastructures

As previously mentioned, “Electricity deployment” means, in this context, “access to Electricity compatible with e-cooking”. Here, the buildings (consumers) are assigned a Tier-3 demand level. Low-power electrification, below 1.5 kW peak, is ignored or considered a different problem. Concerning the over-demand resulting in the non-cooking electric energy, it is completely corrected and compensated by the factor for non-residential customers (see the demand profiles descriptions in Section 6.2).

The systematic approach to generating the off-line pre-designed infrastructure comprises four key steps:

1. Comprehensive data processing. This includes utilising geospatial information about buildings, streets, and existing substations (transmission and high-to-medium-voltage) for each district. Service drops—electrical points of connection—are assigned to every individual building, defining active power [kW], reactive power [kVAr], voltage level [kV], and the number of phases. Additionally, this phase involves planning the potential locations of poles along roads and streets and locating existing power substations.
2. Building supply areas. The data from the initial phase are used as inputs to the Reference Network Model (RNM) (Mateo Domingo, Gómez San Román, Sánchez Miralles, Peco González, & Candela Martínez, 2011), assuming high e-cooking penetration. For each district, supply areas are identified (see Figure 31), each encompassing a high-to-medium-voltage substation and catering to a mix of urban and rural consumers. This clustering stage assumes that all consumers are connected to the main grid, but this assumption is just for clustering; the optimal electrification mode (grid, mini-grid, or stand-alone) is decided in step (3).
3. Obtaining low- and medium-voltage service costs with incremental information. This involves using REM (Ciller, et al., 2019) to classify consumers as either connected to the main grid or off-grid (mini-grids or stand-alone), estimating individual low- and medium-voltage costs, and calculating the load for each high-voltage to medium-voltage substation (see Figure 32). The process is applied to each designed supply area, and it is repeated four times for extreme cases of rural or urban levels of penetration to allow further interpolation in the interactive tool (see Figure 33).
4. Calculating VHV (Very High Voltage) transmission and HV (High-Voltage) distribution service costs. This estimation uses RNM to ensure accuracy and efficiency in cost allocation. This step involves recalculating the power load for each high-to-medium-voltage substation, excluding off-grid consumers, as identified in the previous step. It incorporates an altitude map, restricted construction areas, and the locations of existing high-voltage substations and generation plants. Based on this data, the plan estimates locations and sizes of extra-high- and high-voltage substations (Figure 34) and calculates the associated upstream costs for each connected consumer under the full-load scenario, but also with local incremental information to estimate cost

savings in cases with different loads (four alternative designs to interpolate, as in Figure 33). Figure 35 shows an estimated layout of the current VHV and HV networks, with the information retrieved from (EUCL, 2021). Note that although existing generation sites and substations are used in the network design, the layout is not meant to resemble the real one; what is important is to estimate costs. Differences are due to (a) different load levels and (b) design from scratch instead of incremental.

Figure 31. Clustering by substation areas.

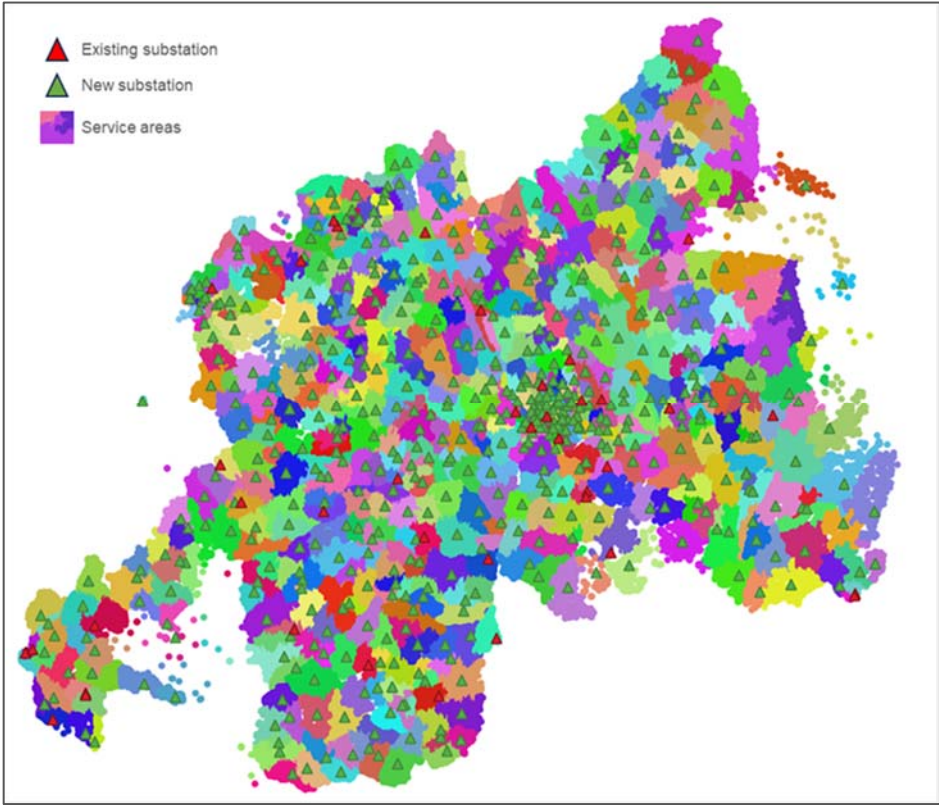


Figure 32. Detailed design of the distribution networks.

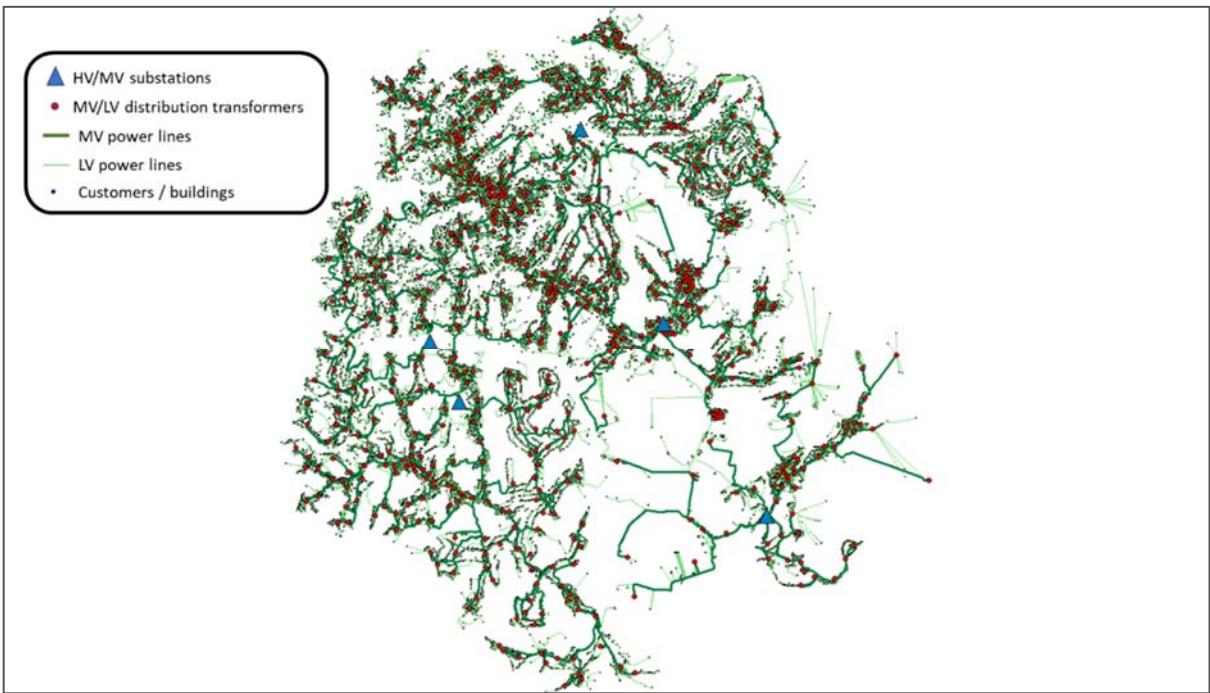


Figure 33. Four extreme designs for each area (data for interpolation), example for the Gasabo district.

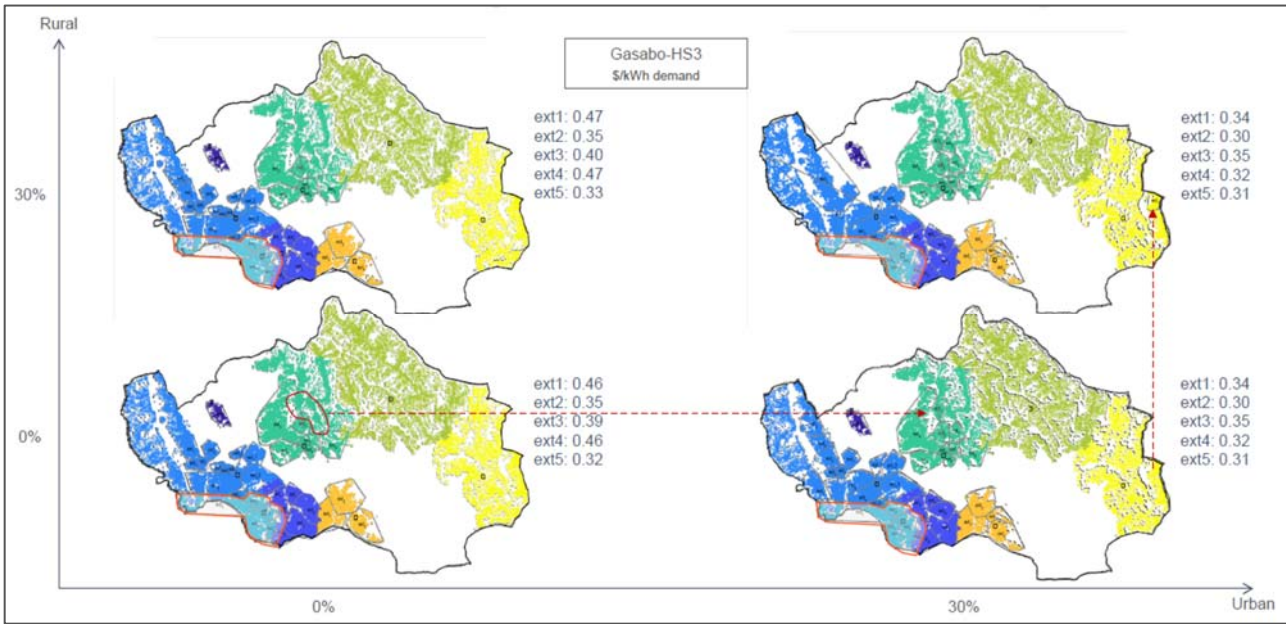


Figure 34. Design of synthetic "upstream" grids: HV distribution and VHV transmission for 100% high-power access.

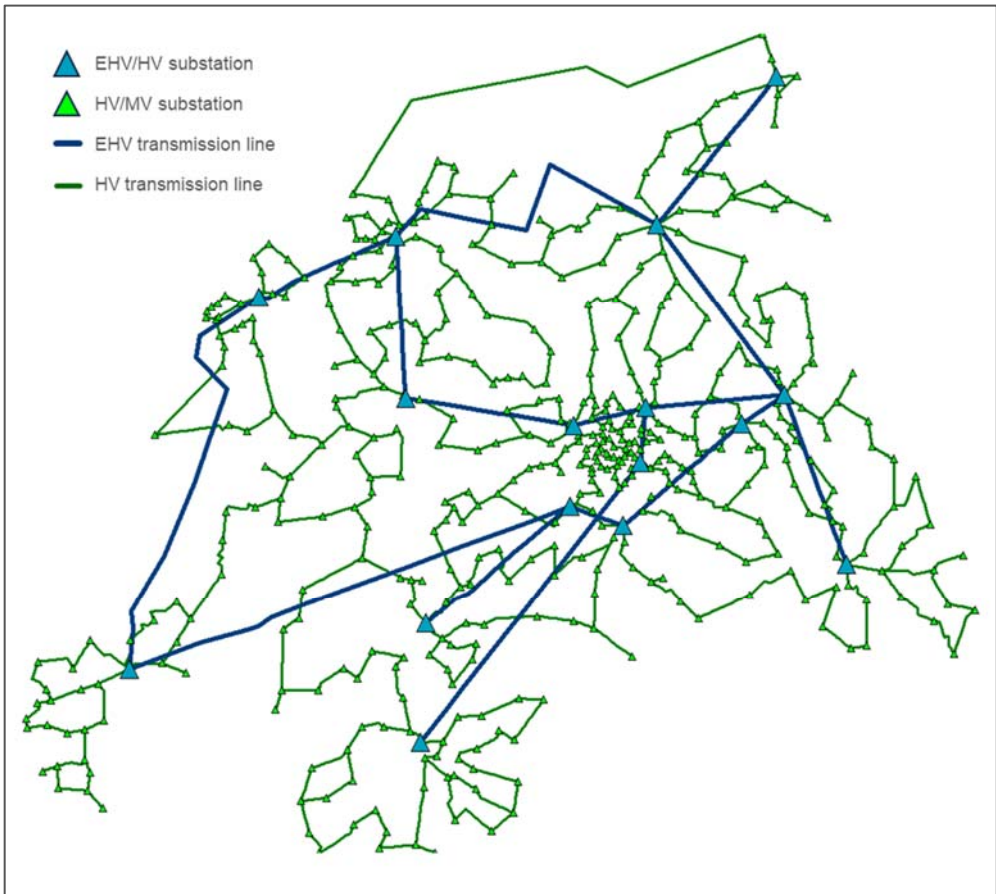
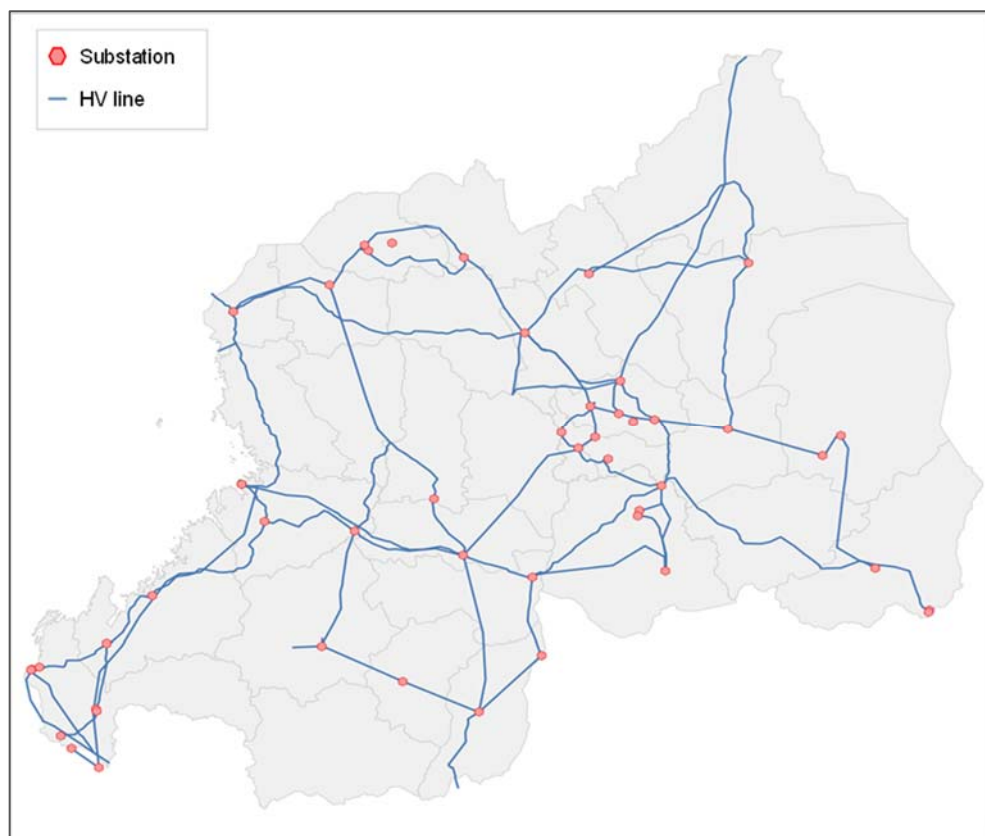


Figure 35. Approximate layout of the actual HV distribution and VHV transmission.



This process requires considerable time and external software¹, adequate input data and expert assumptions, especially in cases where data are not readily available or synthetic data is required. Most of this data is derived from the National Electrification Plan, supplemented with recent updates from newer sources. This foundation ensures the plans are grounded in current realities and informed projections.

A relevant topic is the design of “catalogues” of components. These include types of lines, substations, transformers, diesel generators, solar panels, and batteries, together with many other ancillary elements. Some of these components must be adapted to equivalent elements. For instance, medium voltage lines are assumed to work at a single voltage level (30 kV), so lines defined for other voltages are adapted, keeping their power capacity and cost invariant.

Notwithstanding the effort already made, the adequate definition of these catalogues and other technical inputs leaves room for expert feedback and further improvement of the plans.

In addition to the granular data obtained from planning the electrification mode for each building, other key metrics for different demand levels are generated. These metrics include (1) annualised fixed costs of the local subsystem, including contribution to the upstream substation, but excluding grid generation costs; (2) variable costs of off-grid (mini-grid and standalone) generation in \$/kWh; (3) percentage of off-grid generation from diesel; (4) proportion of district-level demand connected to the main grid; and (5) urban demand percentage with respect to the ones connected to the main grid. These off-line results are presented to the interactive tool in a standard format to allow interpolations and estimations of costs, emissions, priority deployment areas, etc.

7.2. LPG infrastructures

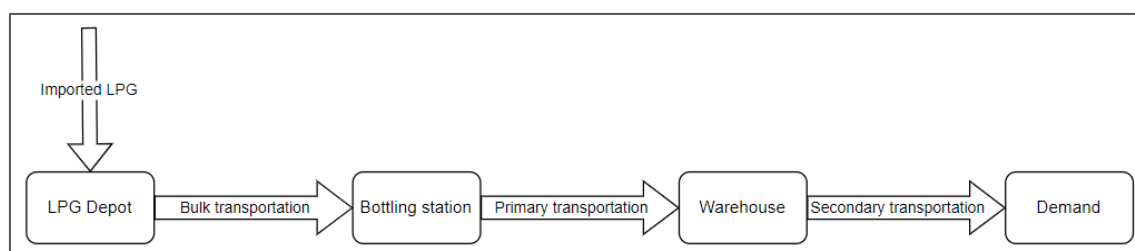
Following the same approach as for Electricity, the pre-design of infrastructures for LPG looks for a least-cost layout designed for the implementation and expansion of LPG as a primary cooking fuel. The goal is to establish a reliable and accessible supply chain for LPG, ensuring its affordability. This requires a thorough breakdown of the country into supply areas, along with the design of upstream supply chains for diverse LPG penetration scenarios for interpolation

¹ This study employs the Reference Electrification Model (REM), a sophisticated tool designed to optimize and streamline the electrification planning process (Ciller, et al., 2019).

and planning within each supply area. Due to the lack of consolidated LPG models, such as the ones previously used (REM and RNM for electricity infrastructure), this off-line tool has been developed independently, tailoring it specifically to the unique requirements and conditions of Rwanda.

The tool model estimates LPG expansion costs of the entire supply chain from importation to end consumers. While simple, this model effectively estimates delivery costs for cylinders to specific locations. It examines each part of the LPG logistics chain, offering detailed capital (CAPEX) and operational (OPEX) expenditure estimates. Data has been diligently gathered to populate the model to enhance accuracy and robustness, ensuring reliable cost projections. The model analyses how different supply chain decisions influence the overall cost of establishing a distribution network for LPG, an essential aspect of clean cooking adoption.

Figure 36. LPG linear supply chain.



The logical structure of the simplified LPG supply chain is depicted in Figure 36. This figure illustrates the sequential flow of LPG from its importation into Rwanda to the retailer, highlighting the key infrastructure components and transportation routes involved.

A bottom-up approach calculates all the costs within the supply chain. This methodology is chosen primarily because it accounts for losses that may occur at various stages of the supply chain. The total annual costs associated with this simplified scenario include:

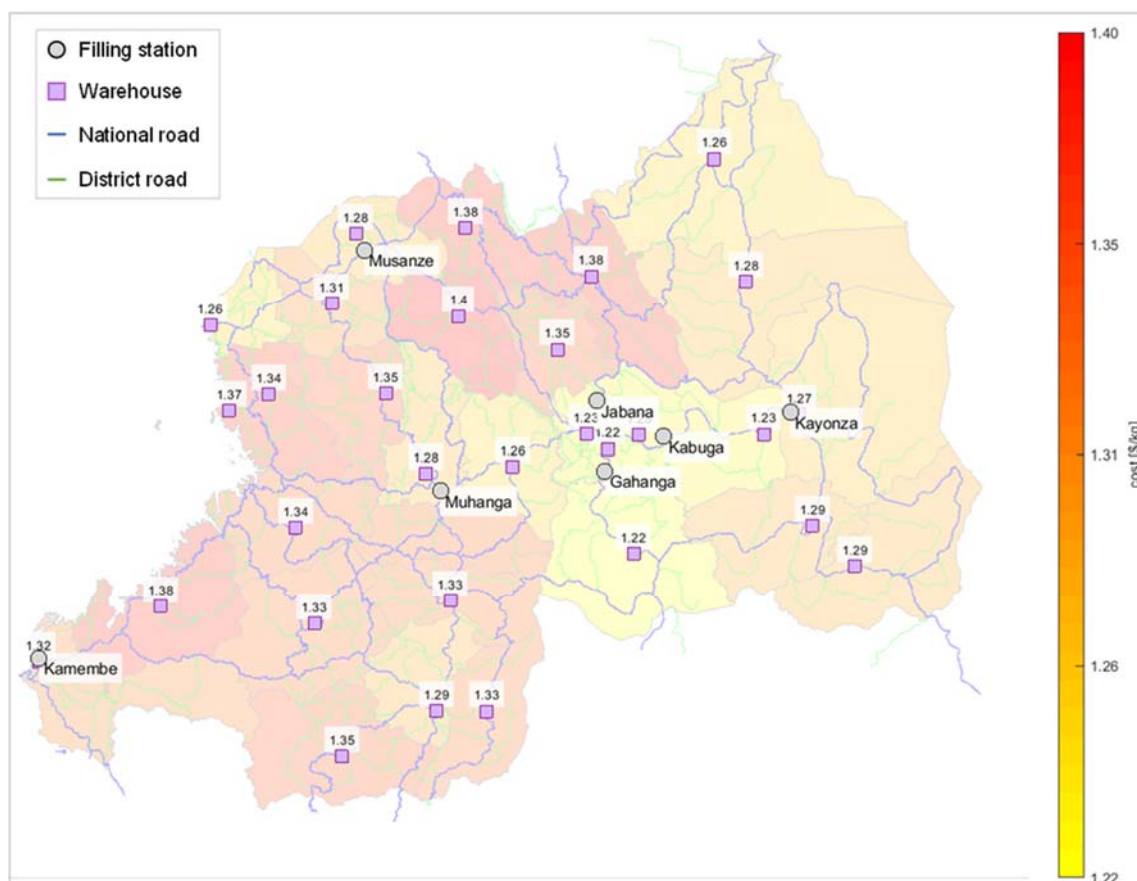
- Cylinders: acquisition, lifetime and replacement, and a variety of sizes.
- Transportation (secondary, primary, and bulk): investment cost for the vehicle fleet, the cost of operating licenses, fuel (or diesel) consumption, Fixed Operation and Maintenance (FOM) costs, as well as variable operation and maintenance (VOM) costs.
- Infrastructure: expenses for warehouses, bottling stations, and LPG depots, including the overnight cost, the operating license cost, “fixed operation and maintenance” (FOM) costs, and “variable operation and maintenance” (VOM) costs.
- Finally, the cost of importing LPG is calculated as the product of the import price and the total quantity imported.

The layout of the supply chain has been adapted to the granularity used in the interactive tool: (a) a single LPG terminal assumed to have unlimited storage capacity, (b) the potential installation of six bottling stations, (c) one warehouse per district, for managing cylinder inventories and supplying retailers, and (d) retailers defined by the proximity to settlements and consumer accessibility, with at least one retailer per settlement, up to 14,837 sites. The model assesses import needs and storage, bottling, and transportation capacities along the whole supply chain. Figure 37 shows the designed layout, in which colour intensity is proportional to the magnitude of supply costs.

In economic terms, finding the least-cost solution involves balancing storage and transportation capacities. A larger warehouse can reduce the frequency of trips, saving on diesel and vehicle costs. This model seeks this balance, optimising vehicle fleet size for various transportation stages (bulk, primary, and secondary). Distances between bottling stations and warehouses were determined using the Google Maps API.

A systematic method for data gathering has been followed, although expert feedback and updated data could improve the results. The first sources were Rwandan reports and institutions, such as the Rwanda Institute of Statistics of Rwanda (NISR) on census data, Rwanda Energy Group, the Ministry of Infrastructure, the Rwanda National LPG Master Plan (by the GLPGP), and the Rwanda Utilities Regulatory Agency (RURA, 2018). When required, the next sources were reports focused on Africa from international institutions, such as the World LPG Association (WLPGA), the World Bank, or the Global Petrol Prices website. Finally, the gaps were filled with data from Europe or the US, such as reports by the Spanish Ministry of Transportation and Sustainable Mobility (MITMA).

Figure 37. Design of the LPG supply chain (layout), with local-costs heat map.



The exhaustive list of input data includes:

- The import price for LPG is set at \$786/ton, derived as an average from Tanzania's \$807/ton and Kenya's \$765/ton (Global LPG Partnership, 2021). The CO₂ emission rate for LPG is calculated at 3 kg per kg of LPG. Additionally, the licensing cost for LPG operations is noted as \$550/year (RURA, 2018). The diesel price in Rwanda is set at \$1.25 per litre, according to (Global Petrol Prices, 2023).
- The LPG cylinder types considered are 6kg, 12kg, and 35kg (Global LPG Partnership, 2021). These cylinders require requalification every 10 years, with associated costs ranging from \$1 to \$7 per cylinder (WLPGA, 2016, September). The estimated lifespan of these cylinders is 20 years (Global LPG Partnership, 2021).
- Key data for bulk, primary, and secondary transportation are consolidated in Table 4.
- For each LPG depot or bottling station, the installation license incurs a one-time fee of \$850 (RURA, 2018), while the annual storage license is priced at \$1450 (RURA, 2018).
- Each bottling station has a lifespan of 15 years, with a filling capacity ranging from 7,000 to 35,000 tons per year. The initial cost of an equivalent 35 kton station, or overnight cost, is \$7 million. It incurs fixed operation and maintenance costs of \$348,400 annually, while the variable cost per ton of LPG processed varies between \$35 and \$77 (Global LPG Partnership, 2021).
- The annual license cost for each warehouse is \$1850 (RURA, 2018). These warehouses have an estimated lifespan of 15 years (Global LPG Partnership, 2021). A typical warehouse, with a capacity of 1,300 m², incurs a cost of \$27,300 (Raballand & Teravaninthorn, 2009, October). Additionally, the fixed operation and maintenance costs for these warehouses amount to \$154,800 annually (Global LPG Partnership, 2021).

A crucial assumption relates to the distance travelled in secondary transportation. Expert consultation suggests that the average delivery distance per day in urban areas is 50 km, while it extends to about 300 km in rural areas. Concerning labour intensity, particularly for drivers in the industry, 246 working days per year are considered, accounting for holidays and minimum vacation periods in Rwanda. This results in 1,968 working hours annually for driving. The annual salary, based on Internet sources, is set at \$2,604 and increased by 18% to cover taxes and other legal fees.

Table 4. Main input data on bulk, primary, and secondary transportation.

	Bulk	Primary	Secondary	Source
License	\$100 per year	\$100 per year	\$100 per year	(RURA, 2018)
Vehicle cost	\$200,000	\$170,200	\$58,500	(Global LPG Partnership, 2021) (MITMA, 2023, January)
Vehicle lifetime	15 years	15 years	10 years	(MITMA, 2023, January)
Variable O&M	\$0.20 per kilometre	\$0.20 per kilometre	\$0.20 per kilometre	(MITMA, 2023, January))
Fixed O&M	1.27xVOM	1.27xVOM	1.27xVOM	(Raballand & Teravaninthorn, 2009, October)
Fuel consumption	35 litres per 100 km	27 litres per 100 km	19 litres per 100 km	(MITMA, 2023, January)
Capacity	24 ton	10 ton	3.2 ton	(Global LPG Partnership, 2021)

The optimisation model is designed to efficiently manage the vehicle fleet, aiming to minimise delivery costs and achieve 100% LPG access in both rural and urban areas. Analysis of the input data and assumptions indicates that urban deliveries are generally cheaper than rural ones. Additional metrics calculated include the LPG molecule's cost contribution at 69%, with the remaining 31% attributed to logistics in a maximum access scenario. Furthermore, it's estimated that 92% of the total costs are operational expenditures (OPEX), like LPG import and diesel fuel, with only 8% being capital expenditures (CAPEX), highlighting the sensitivity of LPG costs to potential fluctuations in oil prices.

Key metrics for diverse levels of demand have been developed to estimate the costs of LPG solution adoption, such as (1) the annualised fixed and variable costs of the local subsystem up to the warehouse level and (2) the annualised fixed and variable costs from the LPG depot to, but not including the warehouse. These and other off-line results are presented to the interactive tool in a standard format to allow interpolations and estimations of costs, emissions, priority deployment areas, etc.

8. Interactive planning inputs

Recalling the main concepts related to the interactive tool used for Integrated Clean-Cooking Planning is convenient. It is also important to remember that the examples of inputs and outputs presented here are taken from Version 1 of the tool because it is fully operational and has been used to develop the proposed plans and cases.

Figure 38 shows how the interactive tool evaluates the “Effects” of applying a “Plan” subject to a certain “Scenario” using off-line inputs, like pre-designed infrastructures or adjusted parameters.

Figure 38. The interactive planning tool.

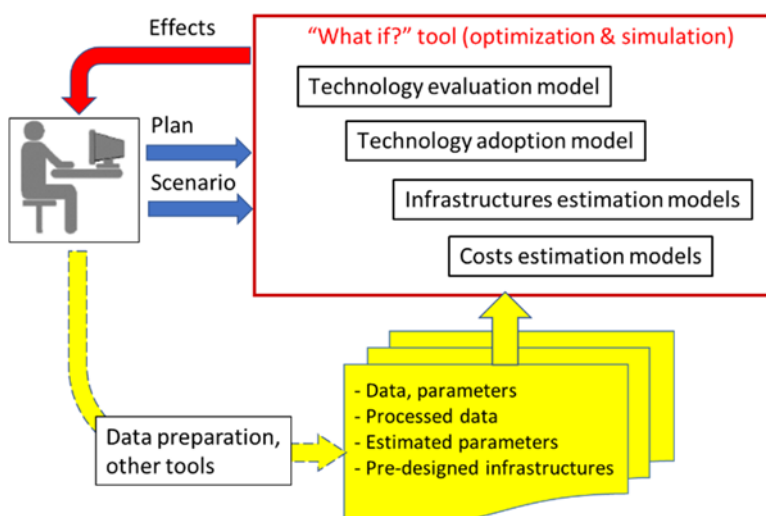


Figure 39. Explanation of scenarios, policies, plans, stages, and states.

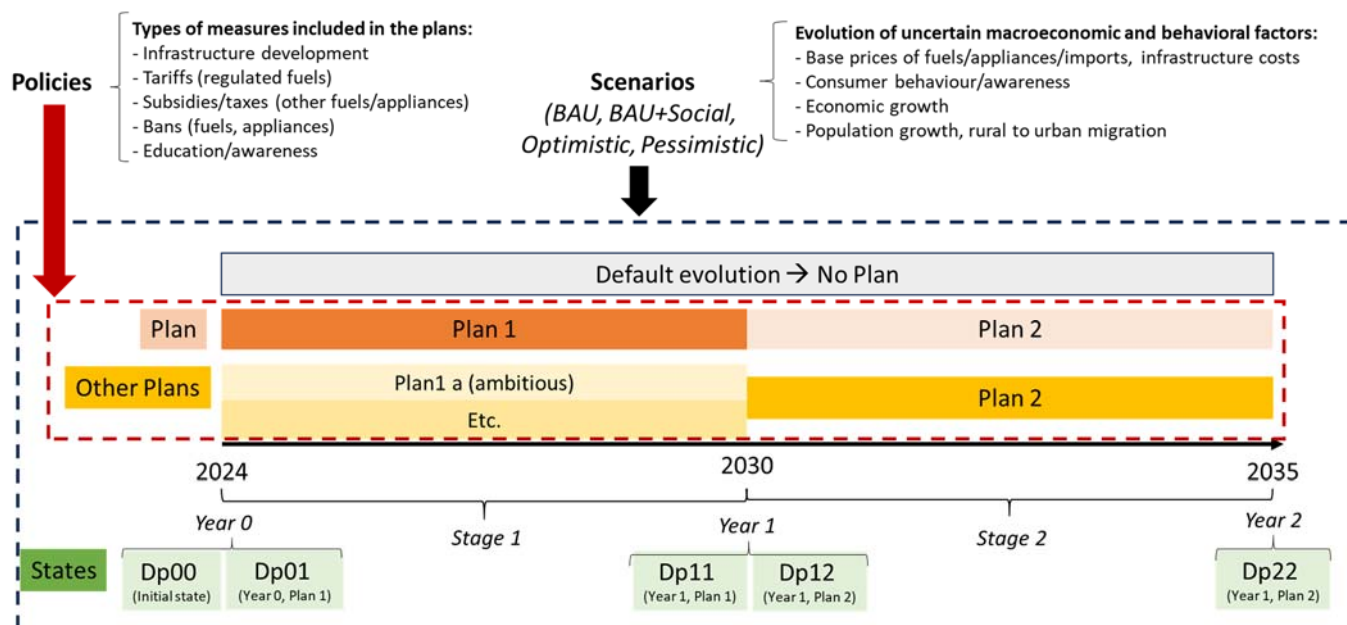


Figure 39 explains the types of “Measures” (types of measures are called “Policies”) that may be included in a “Plan” and the uncertainty factors that define a particular “Scenario” (like population or economic growth or cost evolution) that vary in a given percentage every year.

The measures of the plans are applied in two successive “Stages”, each defined separately by its particular measures, referred to as Plan 1 and Plan 2. The user may arbitrarily define three reference years, namely Year 0, Year 1, and Year 2 (2024, 2030, and 2035 in the figure). Finally, quasi-static states are defined at the beginning and the end of the reference years, and they are used to deploy cash flows and other effects in annual terms.

In the following sections, the inputs and outputs will be taken from a particular plan that was presented as an exercise or example, labelled as “Clean Step”. The reference years in this example are 2023, 2029, and 2034. The plan is designed to seek a high penetration of clean cooking by 2029 while focusing on the economic recovery in the second period (2029-34), ensuring that the absolute social costs are kept stable during this second period despite the expected population growth.

8.1. Measures applied: the Plan

In this example, the following measures have been applied to the periods 2023-29 and 2030-34, respectively:

Plan1. From the second semester of 2023 to the first semester of 2029:

- 100% deployment of electricity (75% with access to e-cooking) and 100% deployment of LPG infrastructures.
- Subsidising the upfront cost of the least efficient e-cooking appliances by 60% and the most efficient e-cooking appliances by 80%.
- Subsidising by 80% the stoves for LPG, biogas, ethanol, pellets, and Tier3+ stoves for charcoal and firewood.
- Increased taxation on charcoal and commercial firewood by 20%.

Plan2. From the second semester of 2029 to the first semester of 2034:

- Subsidising the most efficient e-cooking appliances by 40%.
- Subsidising stoves: LPG by 35%, biogas by 50%, ethanol by 30%, pellets by 40%.
- Increased taxation on charcoal and commercial firewood by 35%.

Figure 40. Inputs of the measures applied to the Plan.

Plan 1	2023 -2029															
Target ELECTRIF:	75%	100%	LPG	MAX target availabilities of FUELS						MAX target availabilities of APPLIANCES						
Pattern	Dis-Elect	LPG	Biogas	Charcoa	Com. Fir	Free Bio	Pellets	Free. Fir	Ethanol	Pattern	El 0	El 1	El 2	LPG	Biogas	Cha
CIT-Rur	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	CIT-Rur	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
CIT-Urb	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	CIT-Urb	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
AGR-Rur	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	AGR-Rur	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
AGR-Urb	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	AGR-Urb	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
FOR-Rur	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	FOR-Rur	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
FOR-Urb	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	FOR-Urb	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Plan 1 Price multipliers																
Fuels prices mul.	Dis-Elec	LPG	Biogas	Charcoa	Com. Fir	Free Bio	Pellets	Free. Fir	Ethanol							
Relat. to Base 0	1.00	0.80	0.80	1.20	1.20	1.00	0.80	1.00	0.80							
Appliances mult.	El 0	El 1	El 2	LPG	Biogas	Charc 0	Charc 1	Charc 2	FW-B 0	FW-B 1	FW-B 2	Pellets	Ethanol			
Relat. to Base 0	0.40	0.20	0.20	0.20	0.20	1.00	1.00	0.20	1.00	1.00	0.20	0.20	0.20			
Plan 2	2029 -2034															
Target ELECTRIF:	75%	100%	LPG	MAX target availabilities of FUELS						MAX Initial availabilities of APPLIANCES						
Pattern	Dis-Elect	LPG	Biogas	Charcoa	Com. Fir	Free Bio	Pellets	Free. Fir	Ethanol	Pattern	El 0	El 1	El 2	LPG	Biogas	Cha
CIT-Rur	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	CIT-Rur	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
CIT-Urb	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	CIT-Urb	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
AGR-Rur	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	AGR-Rur	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
AGR-Urb	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	AGR-Urb	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
FOR-Rur	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	FOR-Rur	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
FOR-Urb	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	FOR-Urb	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Plan 2 Price multipliers																
Fuels prices mul.	Dis-Elec	LPG	Biogas	Charcoa	Com. Fir	Free Bio	Pellets	Free. Fir	Ethanol							
Relat. to Base 0	1.00	1.00	1.00	1.35	1.35	1.00	1.00	1.00	1.00							
Appliances mult.	El 0	El 1	El 2	LPG	Biogas	Charc 0	Charc 1	Charc 2	FW-B 0	FW-B 1	FW-B 2	Pellets	Ethanol			
Relat. to Base 0	1.00	0.60	0.60	0.65	0.50	1.00	1.00	1.00	1.00	1.00	1.00	0.60	0.70			

Figure 40 shows a partial snapshot (part of the right side has been cut) of the inputs that define the measures of this plan. Note how the price multipliers are used to define tariff variations, taxes and subsidies. Note also that in both stages, the capacity limits for all the fuels and appliances have been set to 100%, meaning there are no limits. The idea is to obtain the size of the expected markets, assuming that the different sectors will adapt swiftly to the demand, provided their confidence in this stable framework and the support of the State.

In other examples, as said before, the maximum capacities defined in the plans may play a relevant role in the results. They may model industrial targets or limitations, bans (like forbidding charcoal sales in urban environments), restrictions (like controlling the exploitation of protected forests), or realistic limits of the resources, like the maximum livestock waste available to produce biogas.

8.2. Scenario applied to evaluate the Plan

Figure 39 explains the uncertainty factors that define a particular “Scenario” (like population or economic growth or cost evolution) that vary in a given percentage every year. Figure 41 shows the inputs of the tool that define the scenario used to evaluate this Plan. It is considered a neutral scenario, neither optimistic nor pessimistic, with:

- Moderate annual variations of reference prices for fuels and appliances, considering economies of scale according to the expected growth of technologies.
- Moderate variations in infrastructure costs, considering economies of scale and efficiencies.
- Stable prices in international markets, including the import price of LPG.
- Realistic population growth, including the rural-to-urban migration.
- Realistic economic growth, reflected in moderate increases in affordability and willingness to pay, and increases in electric demand (not related to cooking).
- A moderate level of improvement in education and awareness of the population, reflected in the positive evolution of behavioural parameters (increase of social costs awareness).

[illegible]

Note that all the economic figures in the model are deflated (in constant currency) and expressed in USD to avoid inflation and exchange rate effects.

9. Outputs of the tool

As stated before, the input and output examples included here are taken from Version 1 of the tool. This section includes only some of the outputs of this version of the tool in approximate order of appearance.

9.1. Effects and KPIs

The initial sheet of results includes explanations about the contents and some navigation features, as well as the main results along the different states of the Plan. Figure 42 shows a partial view of this initial sheet, including:

- From top to bottom, the base magnitudes used to normalise the attributes, and the results of the successive states are shown. Note that the base magnitude for economic cost is (arbitrarily) defined as 20% of the electrification cost of the full country, but only considering the electric demand without cooking. The rest of the base magnitudes are just the values of the social cost components in the initial state.
- From left to right, the results for each state, displaying (a) the global fitness function of the state, (b) the relative values of economic costs and social costs, (c) the relative values of the different components of the social costs, (d) the penetration of clean technologies in rural and urban environments, and (e) the cost of cooking for the population in rural and urban environments in per unit values, annual expenditure, and their relative increments with respect to the previous state.

Figure 42. Summary of results of the Plan.

RESULTS: SUMMARY													
Econ:	154	Base	Health	Ti_Gende	Emission	Deforest	Econ.Base= 20% of full electrification (E-Demand)						
	M\$/year	Magnit.	5321	10135	21.610	9.297	INITIAL STATE						
			MUnits/Year		MTon/y	MTon/y							
					CO2Eq	wood							
RESULTS: Relat. values			Relative social parameters				Clean techn. %		Cost of cooking for population				
Econ:	0.753		Health	Ti_Gende	Emission	Deforest	Rural	6.68%	Rur/Urb	\$/Cook	\$/Year	Incr %	2023
	0.876	1.000											
Balance:		Social:	1.00	1.00	1.00	1.00	Urban	25.34%	Urban	0.099	180.94		Year 0
Econ:	0.407	APPLICATION OF PLAN 1: PRICES											2023
	0.692	0.978	Health	Ti_Gende	Emission	Deforest	Rural	10.91%	Rural	0.066	119.61	13.6%	Plan1
Balance:		Social:	0.99	0.99	0.97	0.97	Urban	28.46%	Urban	0.107	195.79	8.2%	
Econ:	1.271	APPLICATION OF PLAN 1: PRICES + INFRASTRUCTURES + GROWTH											2029
	0.892	0.513	Health	Ti_Gende	Emission	Deforest	Rural	81.35%	Rural	0.057	103.02	-13.9%	Year 1
Balance:		Social:	0.72	0.53	0.42	0.38	Urban	90.62%	Urban	0.083	151.62	-22.6%	
Econ:	0.533	APPLICATION OF PLAN 2: PRICES											2029
	0.522	0.511	Health	Ti_Gende	Emission	Deforest	Rural	80.30%	Rural	0.072	130.83	27.0%	Plan2
Balance:		Social:	0.72	0.53	0.42	0.38	Urban	90.59%	Urban	0.101	183.64	21.1%	
Econ:	-0.365	APPLICATION OF PLAN 2: PRICES + INFRASTRUCTURES + GROWTH											2034
	0.071	0.507	Health	Ti_Gende	Emission	Deforest	Rural	73.59%	Rural	0.083	151.91	16.1%	Year 2
Balance:		Social:	0.73	0.51	0.44	0.36	Urban	92.65%	Urban	0.109	198.40	8.0%	

These basic results are extended in other sheets of the tool. For instance, the evolution of the different attributes is graphically displayed in Figure 43, with separate representations for rural and urban environments. The evolution of the penetration of clean technologies is described in terms of demand share (percentage of demand) and equivalent number of households in Figure 44. There are also detailed outputs from the results of the representative states, describing each type of social cost generated at each district and province by each cooking technology and rural or urban consumers.

Figure 43. Graphical display of the evolution of the attributes.

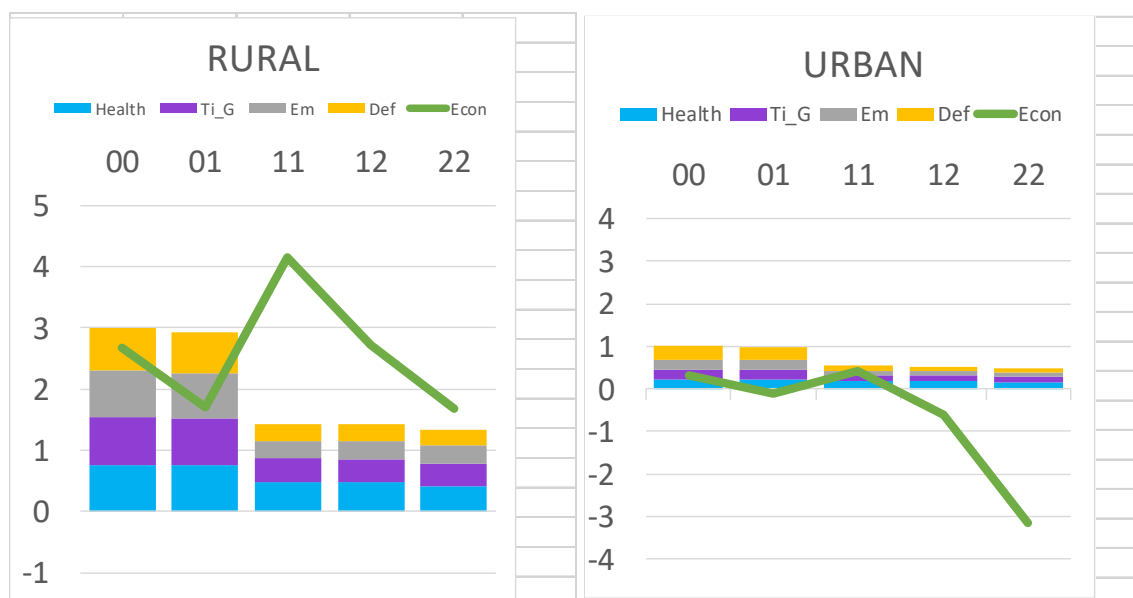


Figure 44. Statistics on the penetration of clean technologies.

CleanTech	Rural %	Urban %	TOTAL %	CleanTech
2023	6.68%	25.34%	12.17%	2023
2029	81.35%	90.62%	84.98%	2029
2034	73.59%	92.65%	82.73%	2034

ADOPTION OF CLEAN-COOKING BY BUILDINGS: total, rural and urban by Tier level											
Rwanda				Rural				Urban			
Tier 4-5	Tier 3	Rest		Tier 4-5	Tier 3	Rest		Tier 4-5	Tier 3	Rest	
2023	195727	210878	2934944	2023	14950	142540	2201060	2023	180777	68338	733883
2024	547303	365928	2547345	2024	201558	264535	1910971	2024	345745	101393	636374
2025	898879	520978	2159746	2025	388166	386530	1620883	2025	510713	134448	538864
2026	1250454	676027	1772148	2026	574774	508525	1330794	2026	675680	167503	441354
2027	1602030	831077	1384549	2027	761382	630520	1040705	2027	840648	200558	343844
2028	1953605	986127	996951	2028	947990	752514	750616	2028	1005616	233612	246334
2029	2305181	1141177	609352	2029	1134598	874509	460527	2029	1170583	266667	148825
2030	2564518	1008162	657729	2030	1208921	776074	503950	2030	1355596	232088	153779
2031	2823854	875147	706106	2031	1283245	677639	547373	2031	1540609	197508	158733
2032	3083191	742132	754484	2032	1357569	579203	590796	2032	1725622	162928	163687
2033	3342527	609117	802861	2033	1431892	480768	634219	2033	1910635	128349	168642
2034	3601864	476102	851238	2034	1506216	382333	677642	2034	2095648	93769	173596

9.2. Adoption of technologies (and fuels)

The evolution of the adoption of technologies is described in several detail and formats, from the whole country (rural and urban) to the district level and from representative states to annual evolution. Figure 45 shows partial views of such results. There are also detailed outputs from the results of the representative states, describing the adoption of each technology in each district and province and rural or urban consumers.

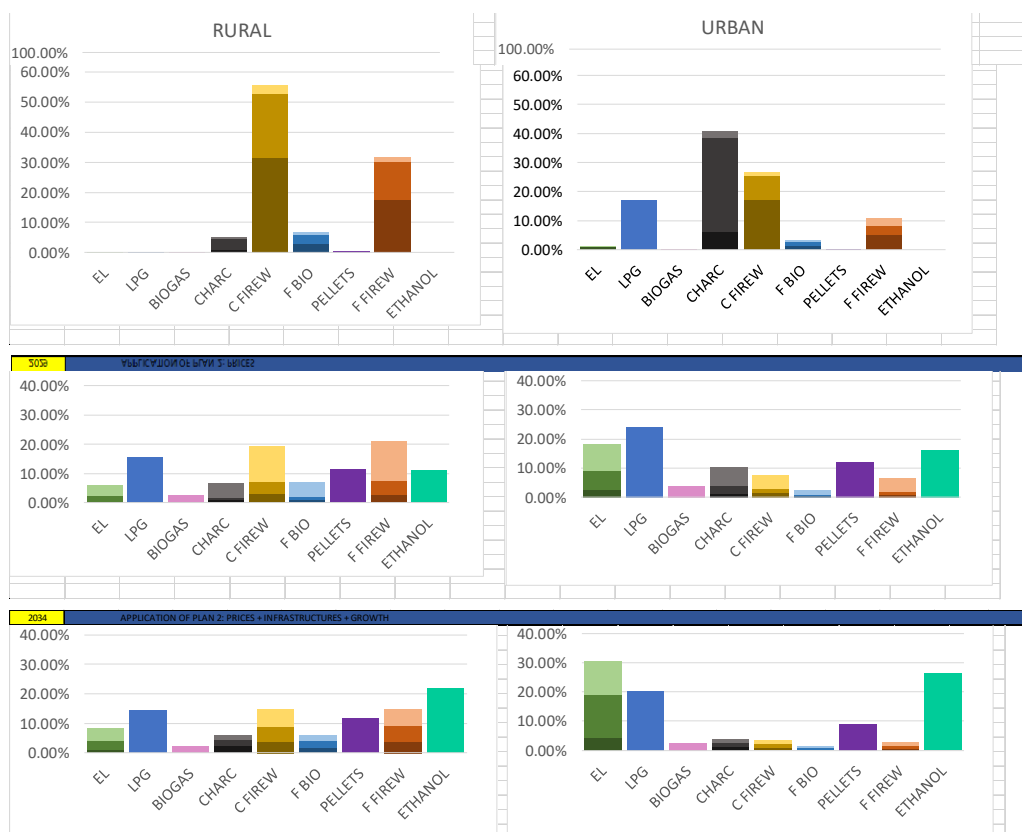
Figure 46 shows a graphical display of the evolution of the adoption of technologies in the reference years. Technologies using the same fuel are represented in the same column but with different shades of colour, following a bottom-up order of efficiency.

Figure 45. Adoption of technologies in reference years and annual evolution.

	TECHNOLOGIES: ADOPTION %															
Rural	El 0	El 1	El 2	LPG	Biogas	Charc 0	Charc 1	Charc 2	C Firw 0	C Firw 1	C Firw 2	Fr Bio 0	Fr Bio 1	Fr Bio 2	Pellets	F Firw
2023				0.12%		1.06%	3.57%	0.38%	31.48%	21.02%	3.14%	3.11%	2.75%	1.05%	0.36%	17.7
2029	0.49%	1.83%	3.44%	15.40%	2.48%	0.84%	0.98%	4.93%	3.05%	4.29%	12.11%	0.85%	1.18%	5.07%	11.24%	2.0
2034	1.05%	3.25%	4.07%	14.49%	2.42%	2.46%	1.98%	1.46%	3.76%	5.22%	5.84%	1.76%	2.17%	1.84%	11.75%	3.0
Urban	El 0	El 1	El 2	LPG	Biogas	Charc 0	Charc 1	Charc 2	C Firw 0	C Firw 1	C Firw 2	Fr Bio 0	Fr Bio 1	Fr Bio 2	Pellets	F Firw
2023	1.02%	0.12%		16.96%		6.01%	32.60%	2.43%	17.45%	7.85%	1.38%	1.46%	1.20%	0.54%	0.19%	5.0
2029	2.60%	6.45%	9.03%	23.91%	3.81%	1.11%	2.92%	6.26%	1.48%	1.29%	4.61%	0.36%	0.41%	1.40%	11.86%	0.0
2034	4.47%	14.40%	11.41%	20.49%	2.47%	1.23%	1.43%	1.22%	1.08%	1.15%	1.22%	0.39%	0.48%	0.51%	9.14%	0.0
TOTAL	El 0	El 1	El 2	LPG	Biogas	Charc 0	Charc 1	Charc 2	C Firw 0	C Firw 1	C Firw 2	Fr Bio 0	Fr Bio 1	Fr Bio 2	Pellets	F Firw
2023	0.34%			5.08%		2.52%	12.11%	0.98%	27.35%	17.15%	2.62%	2.62%	2.29%	0.90%	0.31%	13.8
2029	1.32%	3.64%	5.63%	18.73%	3.00%	0.94%	1.74%	5.45%	2.44%	3.12%	9.18%	0.66%	0.88%	3.64%	11.48%	1.9
2034	2.69%	8.60%	7.58%	17.37%	2.44%	1.87%	1.72%	1.34%	2.48%	3.27%	3.62%	1.10%	1.36%	1.20%	10.50%	2.0

	TECHNOLOGIES: ADOPTION %															
Rwanda	El 0	El 1	El 2	LPG	Biogas	Charc 0	Charc 1	Charc 2	C Firw 0	C Firw 1	C Firw 2	Fr Bio 0	Fr Bio 1	Fr Bio 2	Pellets	F Firw
2023	0.34%			5.08%		2.52%	12.11%	0.98%	27.35%	17.15%	2.62%	2.62%	2.29%	0.90%	0.31%	13.8
2024	0.50%	0.64%	0.96%	7.35%	0.55%	2.26%	10.38%	1.73%	23.20%	14.81%	3.71%	2.29%	2.06%	1.36%	2.17%	11.8
2025	0.67%	1.24%	1.90%	9.63%	1.04%	1.99%	8.65%	2.47%	19.05%	12.47%	4.81%	1.97%	1.82%	1.81%	4.03%	9.8
2026	0.83%	1.84%	2.83%	11.90%	1.53%	1.73%	6.93%	3.21%	14.90%	10.13%	5.90%	1.64%	1.59%	2.27%	5.90%	7.9
2027	0.99%	2.44%	3.76%	14.18%	2.02%	1.47%	5.20%	3.96%	10.74%	7.79%	6.99%	1.31%	1.35%	2.73%	7.76%	5.9
2028	1.15%	3.04%	4.70%	16.45%	2.51%	1.21%	3.47%	4.70%	6.59%	5.46%	8.08%	0.98%	1.12%	3.18%	9.62%	3.9
2029	1.32%	3.64%	5.63%	18.73%	3.00%	0.94%	1.74%	5.45%	2.44%	3.12%	9.18%	0.66%	0.88%	3.64%	11.48%	1.9
2030	1.59%	4.63%	6.02%	18.45%	2.89%	1.13%	1.74%	4.63%	2.44%	3.15%	8.07%	0.75%	0.98%	3.15%	11.28%	2.0
2031	1.87%	5.62%	6.41%	18.18%	2.78%	1.32%	1.73%	3.81%	2.45%	3.18%	6.95%	0.84%	1.07%	2.66%	11.09%	2.1
2032	2.14%	6.61%	6.80%	17.91%	2.67%	1.50%	1.73%	2.99%	2.46%	3.21%	5.84%	0.92%	1.17%	2.18%	10.89%	2.1
2033	2.41%	7.61%	7.19%	17.64%	2.55%	1.69%	1.72%	2.17%	2.47%	3.24%	4.73%	1.01%	1.26%	1.69%	10.70%	2.2
2034	2.69%	8.60%	7.58%	17.37%	2.44%	1.87%	1.72%	1.34%	2.48%	3.27%	3.62%	1.10%	1.36%	1.20%	10.50%	2.3

Figure 46. Graphical representations of the adoption of technologies.



The statistics about the relative adoption of fuels and their absolute annual consumption are also provided (see, for instance, Figure 47). There are also detailed outputs from the results of the representative states, describing the use of each fuel in each district and province and rural or urban consumers.

Figure 47. Relative adoption and absolute consumption of fuels.

	FUELS: ADOPTION %																
Rural	Electricity		LPG	Biogas	Charcoal			Commercial Firewood			Free Biomass			Pellets		Free Fire	
2023			0.12%		5.01%			55.64%			6.91%		0.36%			31.	
2029		5.76%	15.40%	2.48%	6.75%			19.45%			7.10%		11.24%			20.	
2034		8.37%	14.49%	2.42%	5.90%			14.81%			5.76%		11.75%			14.	
Urban	Electricity		LPG	Biogas	Charcoal			Commercial Firewood			Free Biomass			Pellets		Free Fire	
2023		1.22%	16.96%		41.04%			26.69%			3.20%		0.19%			10.	
2029		18.09%	23.91%	3.81%	10.29%			7.38%			2.18%		11.86%			6.	
2034		30.28%	20.49%	2.47%	3.88%			3.46%			1.38%		9.14%			2.	
TOTAL	Electricity		LPG	Biogas	Charcoal			Commercial Firewood			Free Biomass			Pellets		Free Fire	
2023		0.41%	5.08%		15.61%			47.12%			5.82%		0.31%			25.	
2029		10.58%	18.73%	3.00%	8.13%			14.73%			5.17%		11.48%			15.	
2034		18.87%	17.37%	2.44%	4.94%			9.37%			3.66%		10.50%			8.	
	FUEL CONSUMPTION: GWh/year, kton/year																
TOTAL	El 0	El 1	El 2	LPG	Biogas	Charc 0	Charc 1	Charc 2	C Firw 0	C Firw 1	C Firw 2	Fr Bio 0	Fr Bio 1	Fr Bio 2	Pellets	F Firw 0	F Firw 1
2023	20.697	1.774	0.922	22.614	0.583	87.898	246.538	14.385	3202.414	1003.730	102.333	286.907	125.464	32.828	4.542	1619.691	582.333
2029	97.341	191.850	218.889	101.244	34.484	39.965	42.992	96.916	346.108	221.544	434.616	87.034	58.416	161.064	204.224	280.148	233.222
2034	241.370	551.547	358.450	114.114	34.114	96.384	51.615	29.066	427.518	282.317	208.556	178.272	109.486	64.639	226.972	398.102	273.333

9.3. Economic results and annual cash-flows

The interactive tool provides incomes and costs (fixed and variable) for different sectors and in different states. These economic figures are handled in the quasi-static states as equivalent annuities. They are translated to annual incomes, annual expenses (OPEX), and incremental investments with respect to the previous state (CAPEX). In Figure 48, the accumulated incremental investments are shown in a green background.

Figure 48. Economic results in representative states for different sectors.

			Carbon economy:	Emissions evolution	CO2Eq MT/y	21.610	20.888	9.021	9.035	9.461			
				Deforest. evolution	Wood MT/y	9.297	8.991	3.529	3.509	3.336			
Income (tariff): annual every year						2023	2023	Plan1	2029	2029	Plan2	2034	
CAPEX: investments accumulated in this year						Base Year 0	P1 prices Year 0		P1 prices P1 MAX av	P2 prices P1 MAX av.		P2 prices P2 MAX av.	
OPEX: annual costs, every year						Dp00	Dp01		Dp11	Dp12		Dp22	
Sector/sub-sector description			Magnitude	Years Lifetime	Discount rate %	Annual % growth	M\$/year	M\$/year		M\$/year	M\$/year	M\$/year	
Electricity (total)	Grid	Distribution	Income (tariff)			0.0%	276.347	278.997	→	564.455	569.037	→	863.608
			CAPEX	35.0	10.0%	-1.0%	1721.563	3.555		859.484	10.962		913.254
		Generation	OPEX			-1.0%	9.395	9.415	→	13.554	13.614	→	17.931
			CAPEX	35.0	10.0%	-1.0%	639.926	6.585		697.658	11.934		833.547
	Off-Grid	Distribution	OPEX			-1.0%	39.161	39.590	→	81.278	82.054	→	131.116
			CAPEX	25.0	10.0%	-1.0%	260.027	0.715		96.452	-1.408		-150.696
		Generation	OPEX			-1.0%	1.508	1.512	→	1.983	1.974	→	1.004
			CAPEX	25.0	10.0%	-1.0%	96.655	1.061		87.851	0.101		-61.141
			OPEX			-1.0%	54.847	55.562	→	108.122	108.347	→	71.535
			E-Cooking-Heat fraction of electricity	Income (tariff)				0.0%	4.657	7.317	→	101.136	105.527
CAPEX					-1.0%	94.393	11.163		417.527	19.034		578.366	
OPEX					-1.0%	1.941	3.052	→	26.794	27.650	→	31.778	
LPG	Local	Processing	Income (tariff)			0.0%	22.978	18.070	→	82.302	101.799	→	115.954
			CAPEX	15.0	10.0%	-1.0%	0.105	0.009		0.977	0.000		0.084
		Transport	OPEX			-1.0%	4.332	4.264	→	19.333	19.137	→	20.896
			CAPEX	10.0	10.0%	0.0%	0.957	0.081		8.881	0.000		0.280
			OPEX			0.0%	1.854	1.851	→	9.813	9.741	→	10.464
	Upstream	Import	OPEX			0.0%	18.137	17.829	→	81.202	80.351	→	91.524
			Processing	CAPEX	15.0	10.0%	-1.0%	3.771	0.082		9.515	0.000	
		Transport	OPEX			-1.0%	0.794	0.789	→	2.979	2.956	→	2.716
			CAPEX	15.0	10.0%	0.0%	2.262	0.049		5.572	0.000		-0.079
			OPEX			0.0%	0.343	0.341	→	1.275	1.266	→	1.173
Rest of subsidies or taxes	Electricity	Appliances	OPEX			-1.0%	0.000	-0.235	→	-5.558	-2.746	→	-5.074
			LPG	Appliances	OPEX			-0.5%	0.000	-3.018	→	-13.339	-5.775
	Biogas	Fuel	OPEX			-1.0%	0.000	-0.339	→	-7.110	0.000	→	0.000
			Appliances	OPEX			-0.5%	0.000	-0.099	→	-2.136	-1.313	→
	Charcoal	Fuel	OPEX			1.0%	0.000	18.709	→	9.908	17.024	→	17.723
			Appliances	OPEX			-0.2%	0.000	-0.934	→	-4.278	0.000	→
	Com. Firew.	Fuel	OPEX			1.0%	0.000	49.288	→	12.907	22.629	→	21.683
			Pellets	Fuel	OPEX			-1.0%	0.000	-0.347	→	-10.569	0.000
	Appliances	OPEX			-1.0%	0.000	-0.276	→	-8.397	-4.155	→	-4.439	
		Biomass ICS	Appliances	OPEX			-0.2%	0.000	-4.200	→	-14.271	0.000	→
	Ethanol	Fuel	OPEX			-1.0%	0.000	-0.642	→	-20.156	0.000	→	0.000
			Appliances	OPEX			-1.0%	0.000	-0.169	→	-5.301	-2.108	→

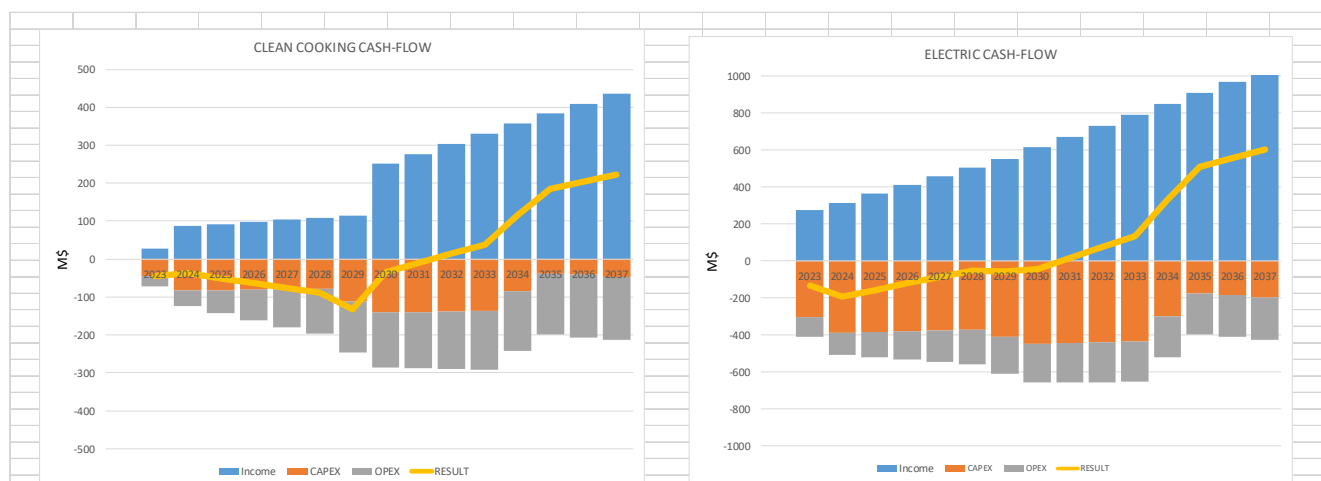
The top of Figure 48 also shows annual results for emissions and deforestation in absolute magnitudes. These are included in the economic results because of their potential conversion to carbon credits. The sectors of interest are the electric sector in full, the fraction of the electric sector that is assigned to electric cooking (incremental costs and incomes due to electric cooking demand), the LPG sector, and the different taxes and subsidies applied to fuels and appliances, classified by the incumbent fuel. Figure 49 shows the cash-flow translation of these economic results for the same level of granularity (sectors and fuels).

Figure 49. Breakdown of cash-flows for different sectors.

			2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037		
CLEAN-COOKING CASH-FLOW RES.			Income	27.636	87.058	92.363	97.734	103.168	108.658	114.200	250.731	277.208	303.703	330.215	356.743	383.277	409.809	436.341	
			CAPEX	45.548	82.374	81.577	80.788	80.007	79.233	110.660	141.602	140.201	138.815	137.442	85.451	38.136	42.097	46.488	
			OPEX	27.383	42.527	61.608	80.548	99.348	118.010	136.536	143.720	147.188	150.628	154.042	157.430	160.809	164.190	167.571	
				-45.295	-37.842	-50.822	-63.602	-76.187	-88.585	-132.996	-34.591	-10.181	14.260	38.731	113.863	184.332	203.522	222.283	M\$
			2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037		
Carbon economy:			Emissions evolution	21.610	19.404	17.427	15.449	13.471	11.493	9.516	9.099	9.184	9.269	9.354	9.440	9.525	9.610	9.695	CO2Eq MT
			Deforest. evolution	9.297	8.308	7.398	6.488	5.578	4.667	3.757	3.483	3.449	3.414	3.379	3.345	3.310	3.276	3.241	Wood MT
CASH-FLOW RESULTS BY SECTORS			OUTPUTS																
Sector/sub-sector description			Magnit.	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	
Electricity (total)			Income	276.347	314.679	362.255	409.832	457.408	504.984	552.561	613.223	672.137	731.051	789.965	848.880	907.794	966.708	1025.623	
Grid	Distribution	CAPEX	169.323	199.414	197.420	195.445	193.491	191.556	226.460	260.831	258.222	255.640	253.084	172.220	99.333	105.540	112.134		
		OPEX	9.372	9.953	10.657	11.346	12.021	12.681	13.327	14.277	15.146	15.996	16.827	17.640	18.447	19.256	20.064		
	Generation	CAPEX	96.684	141.107	139.696	138.299	136.916	135.547	174.238	212.341	210.217	208.115	206.034	131.912	63.204	67.153	71.349		
		OPEX	39.063	45.033	52.166	59.152	65.993	72.691	79.249	89.638	99.575	109.304	118.829	128.153	137.414	146.687	155.961		
	Off-Grid	Distribution	CAPEX	24.130	27.251	26.978	26.709	26.442	26.177	3.887	-18.070	-17.889	-17.710	-17.533	-5.255	7.340	7.798	8.286	
		OPEX	1.504	1.573	1.653	1.731	1.807	1.882	1.955	1.822	1.622	1.426	1.234	1.046	0.858	0.671	0.483		
	Generation	CAPEX	13.615	19.351	19.158	18.966	18.777	18.589	6.417	-5.573	-5.518	-5.463	-5.408	-0.495	4.663	4.954	5.264		
		OPEX	54.709	62.421	71.411	80.214	88.834	97.274	105.536	102.550	94.941	87.473	80.146	72.956	65.810	58.654	51.499		
				-132.053	-191.424	-156.883	-122.031	-86.873	-51.413	-58.508	-44.593	15.820	76.269	136.752	330.703	510.725	555.995	600.583	M\$
Sector/sub-sector description			Magnit.	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	
E-Cooking-Heat fraction of electricity			Income	4.657	19.045	34.681	50.318	65.954	81.591	97.227	124.072	148.798	173.523	198.249	222.975	247.700	272.426	297.152	
			CAPEX	42.865	77.592	76.816	76.048	75.288	74.535	107.005	138.984	137.594	136.218	134.856	82.923	35.604	39.512	43.848	
			OPEX	1.936	6.161	10.237	14.230	18.143	21.976	25.731	28.275	29.093	29.891	30.670	31.431	32.186	32.942	33.698	
				-40.144	-64.709	-52.372	-39.961	-27.477	-14.921	-35.509	-43.188	-17.889	7.414	32.723	108.621	179.911	199.973	219.607	M\$
Sector/sub-sector description			Magnit.	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	
LPG			Income	22.978	26.099	36.804	47.510	58.215	68.920	79.626	103.923	106.754	109.585	112.416	115.247	118.077	120.908	123.739	
Local	Processing	CAPEX	0.094	0.179	0.177	0.176	0.174	0.172	0.130	0.089	0.088	0.087	0.086	0.080	0.075	0.076	0.077		
		OPEX	4.321	6.236	8.822	11.355	13.836	16.267	18.647	19.399	19.740	20.073	20.398	20.713	21.027	21.340	21.654		
	Transport	CAPEX	0.833	1.589	1.589	1.589	1.589	1.589	1.319	1.048	1.048	1.048	1.048	1.034	1.045	1.072	1.098		
		OPEX	1.854	2.846	4.173	5.500	6.827	8.154	9.481	9.850	9.994	10.139	10.283	10.428	10.573	10.717	10.862		
	Upstream	Import	CAPEX	18.137	25.750	36.313	46.875	57.437	67.999	78.562	82.027	84.262	86.496	88.731	90.965	93.200	95.434	97.669	
		Processing	CAPEX	1.121	1.925	1.906	1.887	1.868	1.849	1.407	0.972	0.962	0.952	0.943	0.899	0.878	0.891	0.904	
	Transport	OPEX	0.792	1.075	1.451	1.819	2.180	2.533	2.879	2.917	2.865	2.814	2.764	2.715	2.665	2.616	2.567		
		CAPEX	0.634	1.088	1.088	1.088	1.088	1.088	0.799	0.510	0.510	0.510	0.510	0.510	0.515	0.533	0.547	0.560	
		OPEX	0.343	0.458	0.614	0.769	0.925	1.080	1.236	1.252	1.233	1.215	1.196	1.178	1.159	1.141	1.122		
				-5.151	-15.048	-19.328	-23.547	-27.709	-31.812	-34.834	-34.140	-33.949	-33.750	-33.549	-33.280	-33.078	-32.925	-32.774	M\$
Sector/sub-sector description			Magnit.	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	
Rest of subsidies or taxes	Electricity	Appliances	Income	-0.000	-0.932	-1.846	-2.741	-3.619	-4.479	-5.322	-3.107	-3.579	-4.042	-4.495	-4.939	-5.380	-5.822	-6.264	
		LPG	Appliances	Income	-0.000	-4.338	-6.083	-7.810	-9.520	-11.213	-12.889	-5.870	-5.997	-6.122	-6.246	-6.368	-6.490	-6.612	-6.734
	Biogas	Fuel	Income	-0.000	-1.226	-2.389	-3.528	-4.645	-5.738	-6.810									
		Appliances	Income	-0.000	-0.359	-0.704	-1.045	-1.383	-1.717	-2.048	-1.309	-1.303	-1.298	-1.292	-1.287	-1.281	-1.276	-1.271	
	Charcoal	Fuel	Income	-0.000	17.673	16.268	14.833	13.367	11.871	10.343	17.140	17.296	17.453	17.611	17.772	17.932	18.093	18.253	
		Appliances	Income	-0.000	-1.355	-1.915	-2.474	-3.030	-3.584	-4.137									
	Com. Firew.	Fuel	Income	-0.000	44.985	39.148	33.190	27.109	20.903	14.570	22.511	22.351	22.185	22.013	21.836	21.657	21.478	21.300	
		Pellets	Fuel	Income	-0.000	-1.686	-3.441	-5.162	-6.847	-8.499	-10.116								
		Appliances	Income	-0.000	-1.339	-2.734	-4.101	-5.440	-6.752	-8.037	-4.196	-4.251	-4.304	-4.355	-4.405	-4.454	-4.504	-4.553	
		Biomass ICS	Appliances	Income	-0.000	-5.468	-7.155	-8.835	-10.511	-12.180	-13.844								
	Ethanol	Fuel	Income	-0.000	-3.198	-6.549	-9.833	-13.051	-16.203	-19.291									
			Appliances	Income	-0.000	-0.841	-1.723	-2.586	-3.432	-4.262	-5.074	-2.433	-2.859	-3.277	-3.686	-4.086	-4.484	-4.882	-5.280
				41.915	20.877	-0.093	-21.001	-41.853	-62.653	-83.453	-104.253	-125.053	-145.853	-166.653	-187.453	-208.253	-229.053	-249.853	M\$

Annual cash flows are interesting for the techno-economic planner, as well as the inputs to the financial model. Variable costs are translated to OPEX, and fixed costs are split into OPEX (due to maintenance tasks) and annualised CAPEX, using the same discount rates and lifetimes of assets used off-line to compute the annuities. To deploy these values over time, some assumptions are made about the pace of investments along each stage (assumed to be linear).

Figure 50. Graphical representation of the main cash flows of the Plan.



9.4. Resources and markets

Other relevant results are the expected sizes of markets (fuels and appliances) over time under the policies applied by the Plan. These estimations are relevant for the State and the private sectors.

The tool provides statistics about raw materials (including electricity generation and imported LPG, see Figure 51), fuels with the separate uses of electricity, as in Figure 52, and appliances, shown in Figure 53 for the reference years and in Figure 54 for the annual evolution of expected sales.

Figure 51. Consumption of raw materials in reference years (includes generation of electricity and imported LPG).

GWh/year	RAW MATERIALS: kton/year, GWh/year					
kton/year	Gen-Electr	Imp. LPG	Livest. wte	Wood	Crops wte	Ethanol
2023	1542.974	23.075	12.863	9298.390	445.198	
2029	3151.617	103.311	760.906	3528.796	306.515	630.671
2034	4821.933	116.443	752.726	3334.122	352.396	1403.506

Figure 52. Expected demands for electricity and other fuels in reference years.

	E-Dem. (no cook-heat)			E-Cooking-Heat Dem.			TOTAL ELECTRIC Demand		
GWh/year	Rural	Urban	TOTAL	Rural	Urban	TOTAL	Rural	Urban	TOTAL
2023	705.838	659.435	1365.273	2.916	20.488	23.404	708.753	679.924	1388.677
2029	1028.484	1299.748	2328.232	162.477	345.746	508.223	1190.960	1645.495	2836.455
2034	1062.434	2125.768	3188.202	257.638	893.901	1151.538	1320.072	3019.668	4339.740

	FUEL CONSUMPTION kton/year							
kton/year	LPG	Biogas	Charcoal	CommFirw	Free Bio	Pellets	Free Firw	Ethanol
2023	22.614	0.583	348.821	4308.477	445.198	4.542	2272.683	
2029	101.244	34.484	179.873	1002.268	306.515	204.224	980.935	618.057
2034	114.114	34.114	177.065	918.392	352.396	226.972	872.455	1375.436

Figure 53. Expected annual sales of appliances in reference years.

	APPLIANCES market: KUnits/year										
KUnits/y	El 0	El 1	El 2	LPG	Biogas	Charc 1	Charc 2	FW-B 1	FW-B 2	Pellets	Ethanol
2023	2.835	0.340	0.240	56.440	0.684	403.938	16.368	980.342	88.880	3.446	
2029	13.334	36.793	56.971	252.687	40.488	70.440	110.272	294.651	459.280	154.934	176.090
2034	33.064	105.776	93.295	284.806	40.053	84.568	33.072	383.434	204.546	172.192	391.875

Figure 54. Expected annual evolution of the sales of appliances.

	APPLIANCES market: KUnits/year											
	EI 0	EI 1	EI 2	E-Cooking	LPG	Biogas	Ch (Tier 2)	Ch (Tier 3+)	Fw(Tier 2)	Fw(Tier 3+)	Pellets	Ethanol
2023	2.835	0.340	0.240	3.415	56.440	0.684	403.938	16.368	980.342	88.880	3.446	
2024	4.585	6.416	9.695	20.696	89.147	7.318	348.355	32.018	866.060	150.613	28.694	29.348
2025	6.335	12.491	19.150	37.976	121.855	13.952	292.772	47.669	751.778	212.346	53.942	58.697
2026	8.085	18.567	28.606	55.257	154.563	20.586	237.189	63.320	637.496	274.080	79.190	88.045
2027	9.835	24.642	38.061	72.538	187.271	27.220	181.606	78.970	523.215	335.813	104.438	117.394
2028	11.584	30.718	47.516	89.818	219.979	33.854	126.023	94.621	408.933	397.546	129.686	146.742
2029	13.334	36.793	56.971	107.099	252.687	40.488	70.440	110.272	294.651	459.280	154.934	176.090
2030	17.280	50.590	64.236	132.106	259.111	40.401	73.265	94.832	312.408	408.333	158.386	219.247
2031	21.226	64.386	71.501	157.113	265.534	40.314	76.091	79.392	330.164	357.386	161.837	262.404
2032	25.172	78.183	78.766	182.121	271.958	40.227	78.917	63.952	347.921	306.440	165.289	305.561
2033	29.118	91.980	86.030	207.128	278.382	40.140	81.742	48.512	365.677	255.493	168.740	348.718
2034	33.064	105.776	93.295	232.136	284.806	40.053	84.568	33.072	383.434	204.546	172.192	391.875

The estimation of annual sales of appliances is made by dividing the total annual usage of each type of appliance (country level) by the lifetime of the type of appliance, both in cooking demand units (cooks). Therefore, it represents the number of appliances "consumed" annually, which in a steady state would coincide with the annual needs for appliances.

9.5. Post-processed outputs

The tool's outputs may feed other tools (like the financial model) or be processed to obtain additional outputs to help understand the results and inform decision-makers. Some of these reporting functionalities may be partially automated. This section presents some examples of processed outputs, all of them related to the example plan labelled as "Clean Step".

Figure 55. Estimation of net investment required for each analysed plan for 2024-2029.

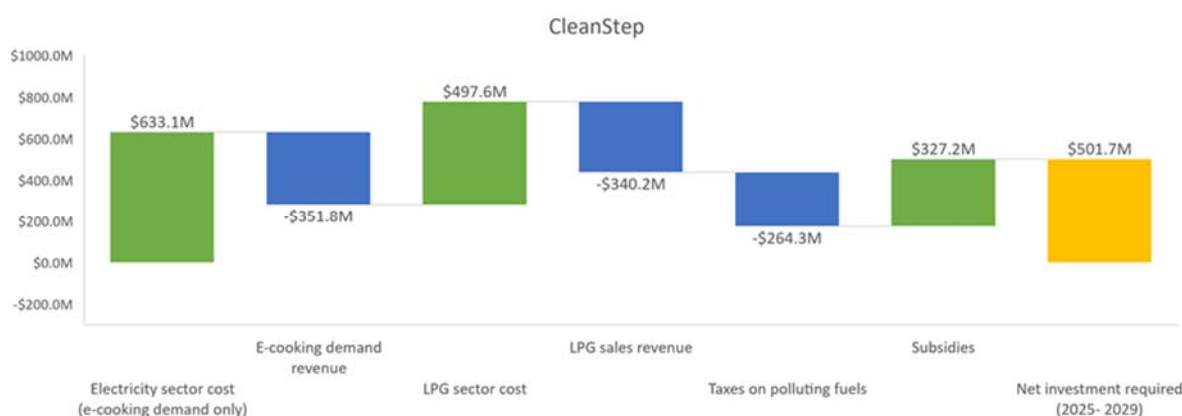


Figure 55 shows a graphical representation of the cash-flow breakdown (and the total cost) for the clean-cooking sector, accumulated for the first stage of the plan (the initial year 2023 is ignored). It is fed by the cash-flow data shown in Figure 49.

Other examples of graphical displays directly fed by numerical results are shown below. Figure 56 displays the numerical results already presented in Figure 45 (annual evolution of the adoption of technologies), and Figure 57 displays the results shown in Figure 54 (expected annual sales of different types of appliances).

Figure 56. Annual adoption of clean cooking technologies, from the baseline year to 2034.

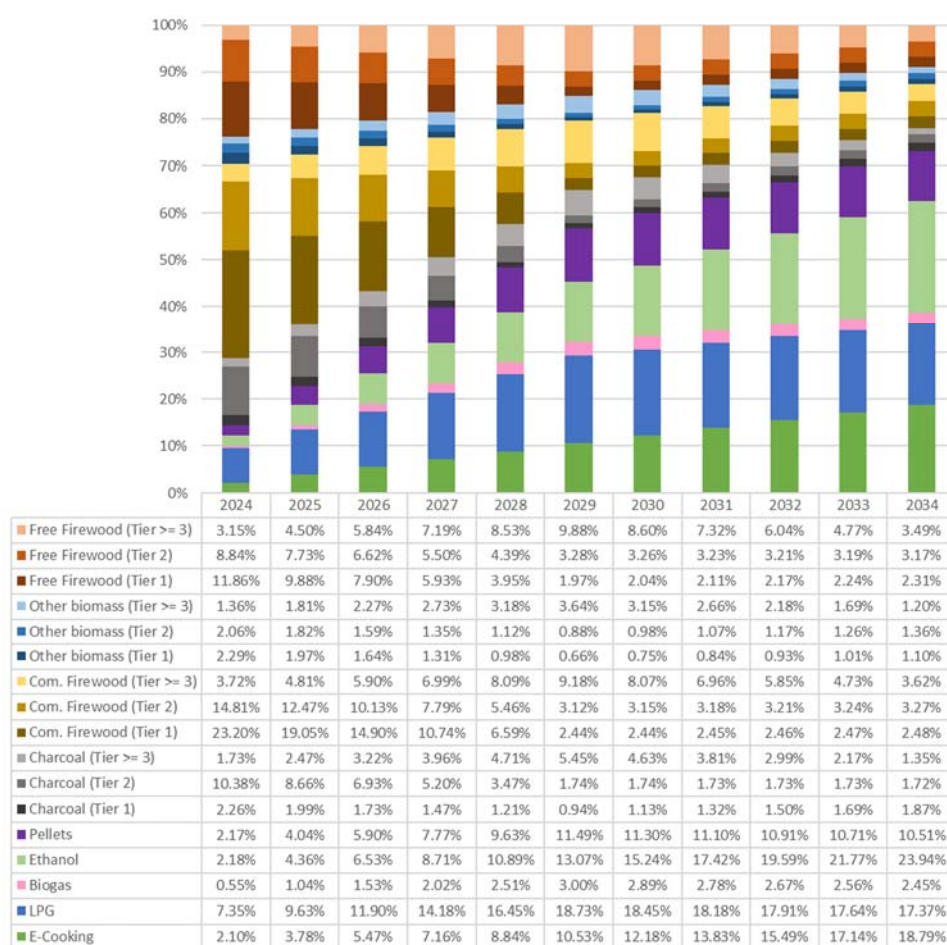
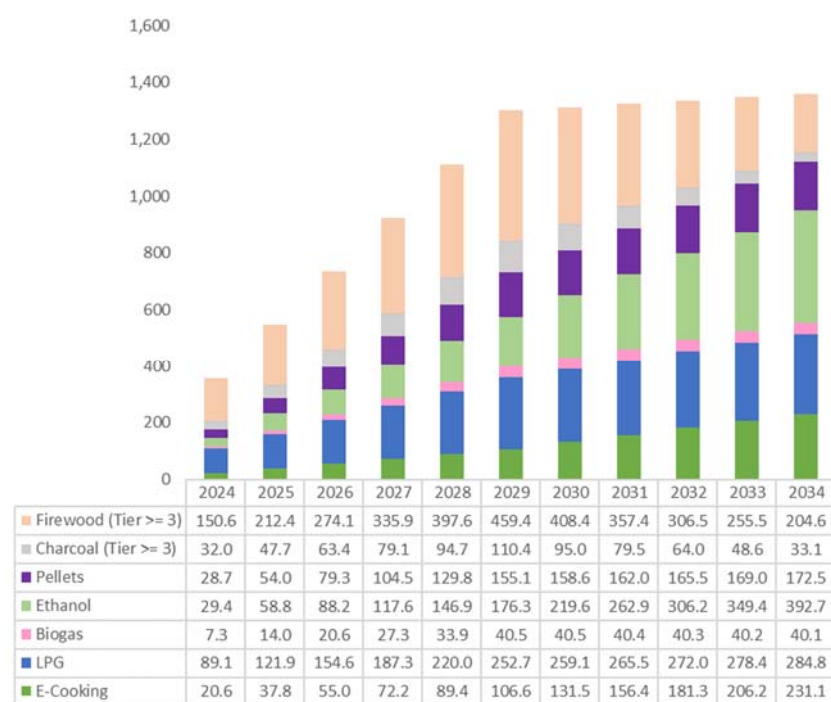


Figure 57. Deployment capacity of clean cooking appliances required for the analysed period ((thousands of appliances per year).



Processed outputs may relate numerical results to spatial information. For instance, Figure 58 lists areas expected to have many buildings without e-cooking capacity (most are rural areas). These areas could, therefore, be prioritised for an early deployment of LPG Infrastructure to compensate for the insufficient e-cooking capacity.

Figure 58. LPG priority areas for deployment.

Province	District	Area	#Buildings without e-cooking
Southern	Nyanza	Rural	51370
	Nyaruguru	Rural	50681
	Nyamagabe	Rural	65937
		Urban	11275
Western	Karongi	Rural	49765
	Rutsiro	Rural	41731
	Ngororero	Rural	71052
	Nyamasheke	Rural	50445
Northern	Rulindo	Rural	50605
	Gakenke	Rural	63369
	Gicumbi	Rural	62364
Eastern	Gatsibo	Rural	101261
		Urban	16701
	Kayanza	Rural	75286
	Kirehe	Rural	66396

Figure 59. Geographical evolution of the adoption of Electricity, LPG and Ethanol.

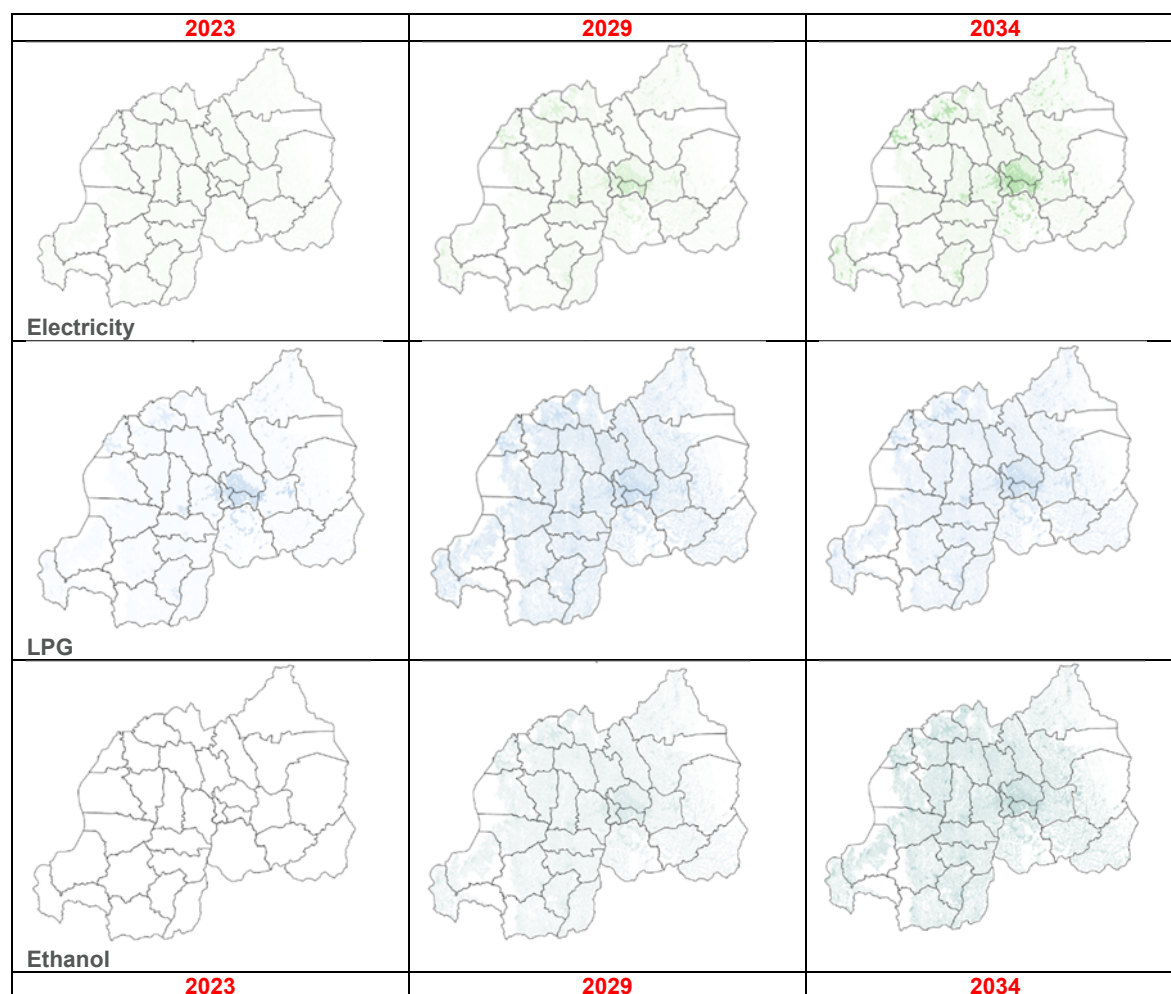
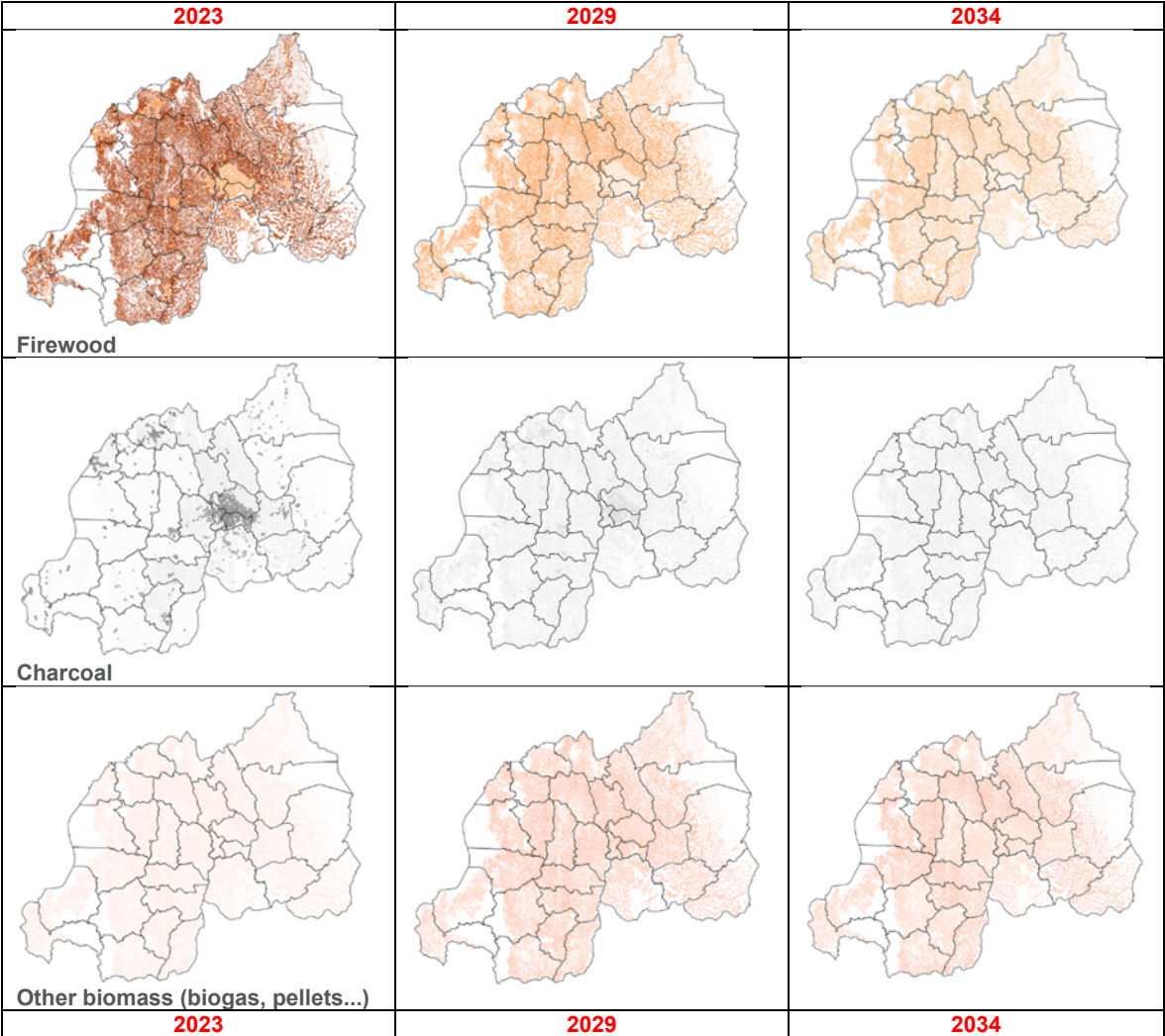


Figure 59 and Figure 60 show the geographical evolution of the adoption of technologies (fuels in this case) over time in different reference years. This geospatial representation shows where the fuels are consumed, not where they are extracted. However, this can be a good proxy for fuels that are gathered locally (e.g., free firewood). A map of districts and buildings represents space. Each fuel is identified by a colour, and each building is represented as a small polygon displayed with a colour intensity scaled from 0 (0%) to 1 (100%), which indicates the levels of adoption of each fuel by each building, representing the usage of multiple fuels to meet the building's cooking needs (fuel stacking).

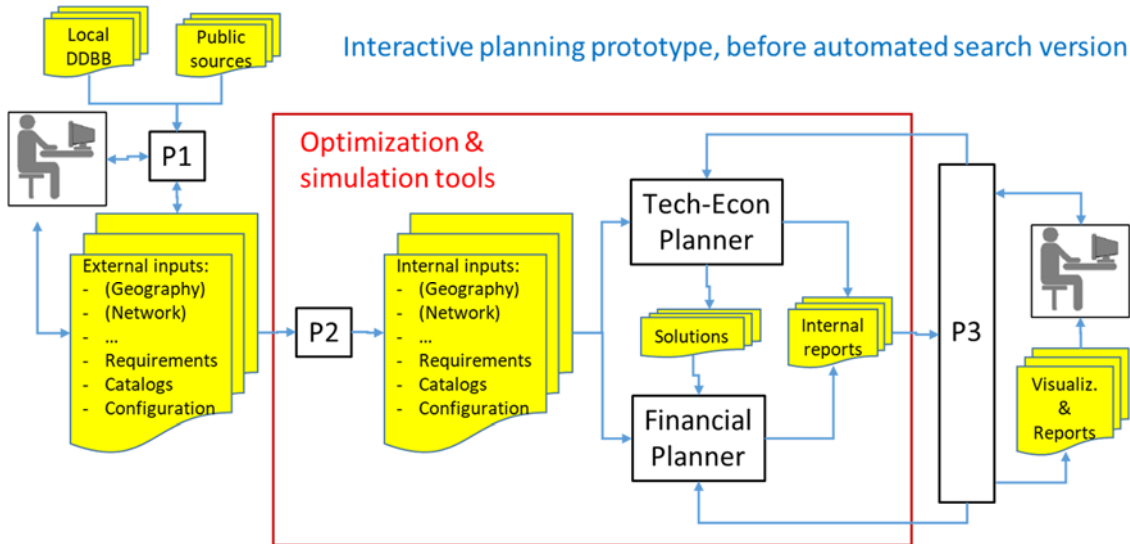
Figure 60. Geographical evolution of the adoption of Firewood, Charcoal and other biomass fuels (Pellets, Biogas, Crop waste).



10. The Financial Planner

The Financial Planner evaluates key aspects of the plans generated using the Techno-economic Planner (see Figure 61), so it can be labelled as a specialised post-processing tool. The model incorporates a variety of financing mechanisms, including blended finance options, and develops sustainable tariff strategies while assessing potential risks to project feasibility. It involves multiple financial institutions, from development finance entities and private companies to international organisations, supplemented by philanthropic contributions.

Figure 61. Proposed architecture for the tools in Phase-II prototype.



The financial strategy aims to attract a broad spectrum of investors by highlighting the project's potential for financial returns and socio-economic impacts. It demonstrates the capability of plans for financial sustainability with minimal reliance on external subsidies, adherence to crucial financial ratios for private investments, and compliance with national macroeconomic policies. The model outlines two potential outcomes: one where the plan achieves financial sustainability and another providing insights for enhancing viability if initial financial independence is unattainable. This approach ensures the clean cooking initiative is aligned with the country's existing energy frameworks (Rwanda in this application) and adaptable, promoting a comprehensive strategy for national clean cooking solutions.

10.1. General approach

The methodology encompasses a detailed assessment where each sector's financial health is examined individually and then integrated into a broader financial strategy. This integration allows for a nuanced understanding of how each clean cooking solution contributes to the overall economic objectives of clean-cooking plans. The financial model leverages data from techno-economic evaluations, projecting the costs and benefits over time and ensuring that strategic decisions are grounded in solid economic analysis.

The Financial Planner has been designed to analyse and compare two alternative plans generated using the Techno-economic Planner. There are several reasons for this decision:

- Since the techno-economic problem is multi-attribute, the output from an interactive planning process may be a list of alternative plans, all promising enough. The financial model may help decide which ones are more sustainable and/or preferable, and one-to-one competition seems a useful feature.
- A particular case of one-to-one competition involves two alternative plans with similar policies and comparable final results but with different time frames. Financial aspects are closely related to time, so this comparison helps choose the best timing option.
- One of the alternative plans compared may be a default evolution or "business-as-usual" option, while the other may be a specific plan with proactive measures. The comparison between these two options provides a fair evaluation of the plan because its incremental financial burden can be identified.

E-Cooking approach

The strategy for e-cooking begins with evaluating how e-cooking will integrate into and impact Rwanda's broader electrification efforts. This involves a detailed assessment led by the Energy Development Corporation Limited (EDCL) and the Rwanda Energy Group (REG), which focuses on adapting the existing electrification strategies to incorporate e-cooking seamlessly. A critical element of this strategic integration involves estimating the additional capital expenditure (CAPEX) and operational expenditure (OPEX) required to support the enhanced infrastructure and service demands introduced by e-cooking.

Financial considerations are central to this strategy. Initial financial assessments start with tariff projections based on the adoption models, which are iteratively refined to strike a balance between the financial sustainability of the initiative and affordability for consumers. Achieving this balance necessitates exploring various financing mechanisms, including grants to the CAPEX investments and incentives to encourage the widespread adoption of e-cooking technologies.

LPG approach

The financial strategy for LPG involves setting up a comprehensive infrastructure capable of managing the entire LPG supply chain, from import to bottling, storage, transportation, and fee collection. This infrastructure plan, likely overseen by a public entity, is designed to guarantee efficient and reliable LPG distribution throughout Rwanda. The model considers the potential for private sector participation in certain supply chain segments, impacting the overall financial dynamics through variations in capital costs.

A critical component of the LPG financial model is its sustainability. It recognises the potential for financial shortfalls within the LPG supply chain, requiring necessary subsidies from the GoR when committing to rural expansion. The market for LPG, shaped by major providers under the regulatory oversight of the Rwanda Utilities Regulatory Authority (RURA), operates within a competitive, free-market framework. This structure promotes competitive pricing and adherence to safety standards but also faces challenges in reaching less profitable, remote, or economically disadvantaged areas due to higher operational costs. To mitigate this, the financial model includes strategies such as government subsidies to ensure LPG benefits are equitably distributed across all regions of Rwanda.

Regulatory, market, and technological considerations

The e-cooking and LPG financial models are intricately tied to the regulatory landscape, market dynamics, consumer behaviour, and technological advancements. These models are designed to be flexible and adaptive, responding to global energy trends, local economic shifts, and changing consumer preferences. The overarching aim is to foster a sustainable, inclusive clean cooking ecosystem in Rwanda that not only meets immediate energy and environmental needs but also contributes to the country's long-term socio-economic development.

Deployment and financing of Clean-Cooking technologies

The deployment strategy for clean cooking technologies includes promoting appliances through a business model focused on Results-Based Financing (RBF) to manufacturers/retailers per appliance delivered or direct consumer subsidies per appliance purchased. This approach is anticipated to be effective given the expected durability of cooking appliances and the significant technological shift they represent. For improved cookstoves (ICS), the financial plan also accommodates the need for more frequent appliance replacements to maintain sustainability.

In addition, carbon credits could provide financial support if pricing and implementation costs are favourable, with revenue from these credits potentially funding long-term appliance subsidies. A proposal for the potential revenue from these measures is presented.

A comprehensive feasibility study will set the parameters for RBF grants and establish eligibility criteria for vendors, technologies, and users, including strategies to ensure effective deployment in rural areas and robust recycling policies. The techno-economic analysis will forecast additional adoption and emissions reductions at various levels of subsidy support and incorporate these projections into a 20-year financial plan for the RBF grants.

10.2. Main inputs and outputs

The financial analysis will simulate the flow of economic resources in an Excel-based model under different regulatory conditions during the period agreed in the concession for the implementation and execution of the clean cooking plan. This model facilitates decision-making through structured modules, each addressing key aspects necessary to deploy and sustain clean cooking infrastructures successfully.

Integration of diverse data inputs

The financial model is built from a comprehensive integration of multiple inputs essential for a nuanced understanding of the economic and financial landscapes. These include:

- **Techno-economic analysis.** This foundational analysis calculates capital and operating expenditures based on expected adoption rates and specific requirements of clean cooking technologies. It considers every aspect of the initial investment and ongoing costs critical to the project's long-term viability.
- **Macroeconomic context.** Economic indicators such as GDP growth, demand growth, and infrastructure costs provide a macroeconomic context. These data ensure that the project is aligned with national economic conditions and ambitions.
- **Regulatory framework.** Tariffs and cross-subsidy policies are critical inputs that define the operational landscape for clean cooking solutions. Understanding these regulatory elements enables modelling of the economic environment in which these technologies will operate.
- **Financing options.** Exploring different financing mechanisms, including commercial and concessional debt, equity, and grants, is critical. This aspect of the model addresses capital requirements and outlines potential financing options to support the initiative's deployment and ongoing operations.

Strategic modules that drive the financial plan

The financial model is divided into several strategic modules, each designed to address specific challenges and objectives:

- **CAPEX roll-out plan.** The model emphasises the strategic deployment of infrastructure, which is planned in phases to match the projected uptake of clean cooking technologies in the country. This ensures efficient and equitable distribution, with a comprehensive capital expenditure payback schedule that reflects the expected lifespan of the infrastructure.
- **Revenue streams and operating income.** The model includes a well-structured tariff system that balances users' affordability with the supply chain's financial needs to sustain the infrastructure financially. It also considers additional revenue streams, such as fees for new connections and non-energy services, which are essential to offset initial set-up costs and contribute to the financial health of the initiative.
- **Cost management.** Operating costs are carefully analysed, including purchasing energy resources, infrastructure maintenance, and administrative overhead. This ensures the long-term reliability and efficiency of the supply chain, with administrative costs factored in to increase customer satisfaction and operational success.
- **Working capital and financial management.** Effective working capital management is critical to the smooth operation of the supply chain and includes efficient inventory management and financial transactions. The model also incorporates a strategic tax approach, considering incentives such as tax rebates or holidays to encourage investment.
- **Comprehensive financing structure.** The financial model employs a multi-faceted financing strategy that includes securing loans on favourable terms, leveraging government subsidies, and attracting equity investments from key stakeholders. This strategy is critical to cover the significant upfront capital costs and ensure ongoing financial sustainability.
- **Use of carbon credits.** Finally, the model integrates the innovative use of carbon credits, which can provide an alternative revenue stream by capitalising on the environmental benefits of clean cooking solutions. This strategy includes detailed plans for certification, market engagement, and maximising the value of carbon credits.

Output Generation and Strategic Implementation

The outputs from this financial model include developed financial statements and ratios, detailed assessments of funding uses and sources, and visual plans for implementation and investment. Continuous refinement of these outputs ensures that the financial model remains adaptable and robust, effectively supporting a sustainable and inclusive clean cooking ecosystem. The outputs of this comprehensive model include:

- **Financial statements and metrics.** Provides insight into the program's financial health over time.
- **Uses and sources of funds.** Details of financial flows, showing how funds are allocated and used throughout the project's life.

- Implementation and investment plans. Visualises the timing and scope of investments and regulatory strategies, ensuring stakeholders have a clear view of the project's progress.

Overview of financial dynamics

The following are the sources of financing considered in this analysis:

- Tariff income represents the direct revenue generated from users of the clean cooking technologies, reflecting the market's contribution to the financing of the company's expansion.
- Viability gap funding is provided to bridge the gap between the revenue generated by users of clean cooking technologies and the costs of expanding the market. Essential subsidies are provided to ensure the financial viability of the projects, covering gaps where user tariffs alone would not fully fund operational and capital expenditures.
- Concessional loans and grants. Soft loans and grants from various development partners provide essential low-cost financing to support infrastructure development and initial operational costs.
- Equity: These are investments directly made by stakeholders, demonstrating confidence in the long-term viability of clean cooking solutions.

The following are examples of how financing can be used:

- CAPEX refers to the outlay of funds to purchase tangible assets. Significant investment in physical infrastructure is required to deploy some clean cooking technologies.
- OPEX (Operational Expenditure). Costs associated with the maintenance and operation of systems.
- Debt repayment and financial expenses. Repayment of borrowed funds and financial obligations.
- Dividends. Potential returns paid to investors related to profitability and financial health.

The balance between the sources and uses of funds demonstrates the importance of careful financial planning and management. All financial needs must be met without deficits, which is crucial for the long-term viability of the initiatives. This equilibrium also demonstrates the strategic allocation of funds, with a significant proportion of capital directed towards the construction and maintenance of the necessary infrastructure to support the energy transition goals.

10.3. Main assumptions and limitations

The financial model for a clean cooking strategy is based on several key assumptions that underpin the projected financial dynamics and outcomes. This model operates exclusively in U.S. dollars, ensuring uniform financial transactions and streamlined international transactions.

Assumptions

A key element of the financing strategy is concessionary debt, which carries an interest rate of 8% with a substantial grace period of five years and an initial term of ten years. This term can be extended as necessary, providing flexibility in managing long-term financial commitments. Grants are integrated with equity deployments under a stringent 2:1 ratio, meaning that for every two parts of the grant, one part of equity is used. This integration is reflected in the profit and loss statement in proportion to the percentage of annual capital expenditures deployed relative to the total capital expenditures, with no repayment obligations assumed.

The financial model is designed with a conservative approach to dividend policies. While a 0% pay-out policy is assumed, meaning no regular dividends are distributed, there is a provision for dividends to be paid if Free Cash Flow to Equity remains positive. This highlights a flexible approach to profit distribution based on actual financial performance.

It is important to consider operational expenses, particularly in sectors like LPG, where tariff income may not fully cover operational costs. In such cases, a percentage of annual subsidies is incorporated into the financial plan to bridge the funding gap. However, this reliance on subsidies can be reduced through strategic adjustments to tariffs to support the rural expansion needs of the LPG sector.

The model anticipates non-technical losses, accounting for approximately 5% of the tariff income, which reflects realistic expectations of system inefficiencies. Additionally, a corporate tax rate of 28% is applied, following current tax laws and regulations.

The operational logistics within the network, including roll-out and investment costs, are based on a mid-year convention. The values are extrapolated between the various states of the solution as defined in the techno-economic analysis. This assumption is based on the premise that all activities related to capital expenditure and new customer connections are evenly distributed throughout the year. This approach simplifies the financial calculations by allowing for a straightforward linear projection of costs and activities. The same mid-year assumption is applied to other recurring costs, including upstream energy costs, operations and maintenance expenses, and administrative expenses. This provides a consistent basis for financial planning.

Lastly, working capital assumptions are carefully defined, with trade receivables and payables set at 30 days. This approach to cash flow management ensures that the company maintains liquidity while effectively managing its credit terms and payment obligations to suppliers.

Limitations

This financial model has inherent limitations that could impact its effectiveness and accuracy. These limitations originate from the model's dependence on specific assumptions and external variables:

- Data accuracy and timeliness. The model depends on accurate and timely input data, including macroeconomic indicators, consumer behaviour forecasts, and regulatory changes. Any discrepancies or delays in updating these data points could result in inaccurate financial projections, potentially influencing strategic decisions.
- Market and technology volatility. The rapid pace of technological advancement and market evolution can render the assumptions embedded within the model obsolete. Frequent updates are, therefore, essential to ensure the model's continued relevance. Furthermore, the model may not fully account for the interplay between local and global trends influencing technology adoption. This could result in discrepancies between projected and actual outcomes.
- Fluctuations in regulatory and socioeconomic factors. Changes in regulatory frameworks or government policies, as well as broader socioeconomic shifts such as changes in GDP growth or consumer purchasing power, can significantly impact a project's economic landscape and financial viability.
- Financing assumptions and Return on Equity (ROE). When making assumptions, it is essential to consider the availability of financing, including grants and concessionary loans. Fluctuations in financial markets or changes in lending policies can impact these assumptions, influencing the project's capital structure. Furthermore, if the actual ROE is lower than projected, it could deter investment and affect the initiative's sustainability.
- Environmental and social impact. The model's incorporation of environmental benefits, like carbon credits, may not fully account for the broader impacts of clean cooking solutions. Furthermore, the model may not adequately address the distribution of benefits and costs across different communities, which could raise concerns about equity in deploying technologies.

Acknowledging these assumptions and limitations is essential for the ongoing refinement of the financial model. Stakeholders must remain flexible, updating assumptions and recalibrating strategies as conditions evolve to ensure the model provides valuable guidance for Rwanda's clean cooking strategy.

10.4. Examples of graphical outputs

The outputs include multiple spreadsheets of considerable size and level of detail. In addition, graphical results are provided for easier understanding of the main features of each plan evaluated, as well as comparative features between them. Some examples of simplified graphical outputs are provided below. For those results displaying individual aspects of a plan, the "Clean Step" alternative is shown; in those comparing two alternatives, the "Clean Step" plan is confronted with another alternative presented, labelled as the "Aligned" plan.

Figure 62 shows the evolution of CAPEX over time for the two plans analysed, particularly for the e-cooking sector. Similar outputs are generated for the full electric and the LPG sectors. Figure 63 shows this information but accumulated by periods (full plan and first stage) and only for the Clean Step plan.

Figure 62. Annual CAPEX investments (M USD) for the e-cooking share in both plans.

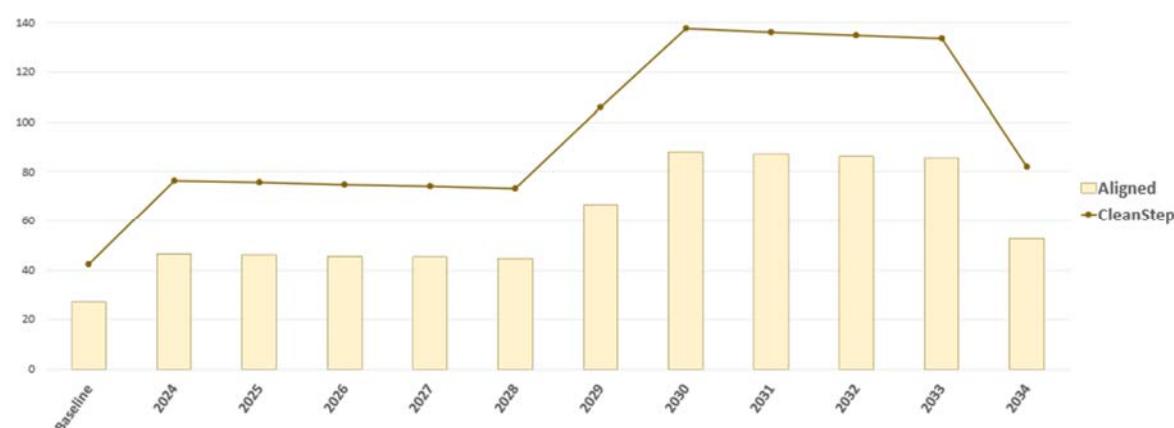
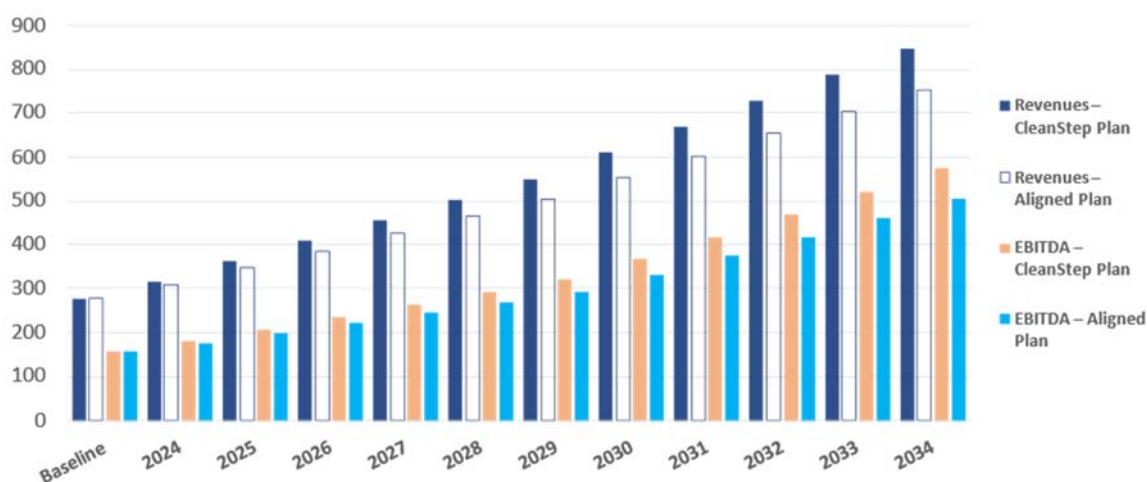


Figure 63. Accumulated CAPEX investments (USD M) for the full period and the first stage of the Clean Step plan, only for the e-cooking share.



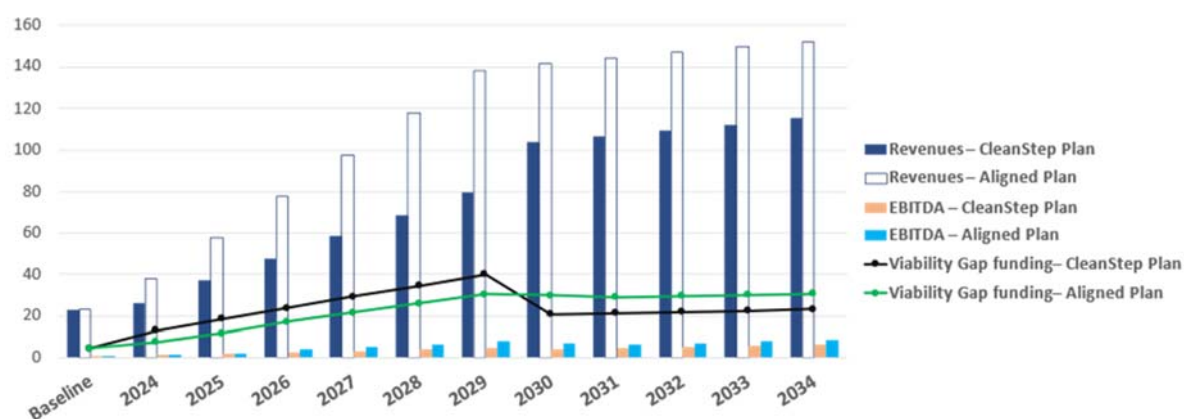
The revenue generation and operating margins need to be estimated to evaluate the financial viability of both analysed plans. Figure 64 shows these parameters for the full electric sector in the two plans analysed.

Figure 64. Revenues / EBITDA (USD M) for the total electricity sector in both plans.



Viability gap funding is the subsidy required to cover operational costs above tariff income. This funding guarantees competitive pricing and operational continuity, particularly in rural or underserved markets. Maintaining competitive pricing or operational viability would be challenging without such subsidies. Figure 65 shows these results for the LPG sector in both plans.

Figure 65. Revenues / EBITDA / Viability gap (USD M) funding for the LPG sector in both plans.



The model also provides a suggested capital structure for each plan and sector. Figure 66 shows the results for the full electricity sector and both plans. Figure 67 presents a different format for capital structure, with the total results of a period for one plan (in this case, the first period and only the e-cooking share of the electric sector).

Figure 66. Accumulated capital structure (USD M) for the full electricity sector in both plans.

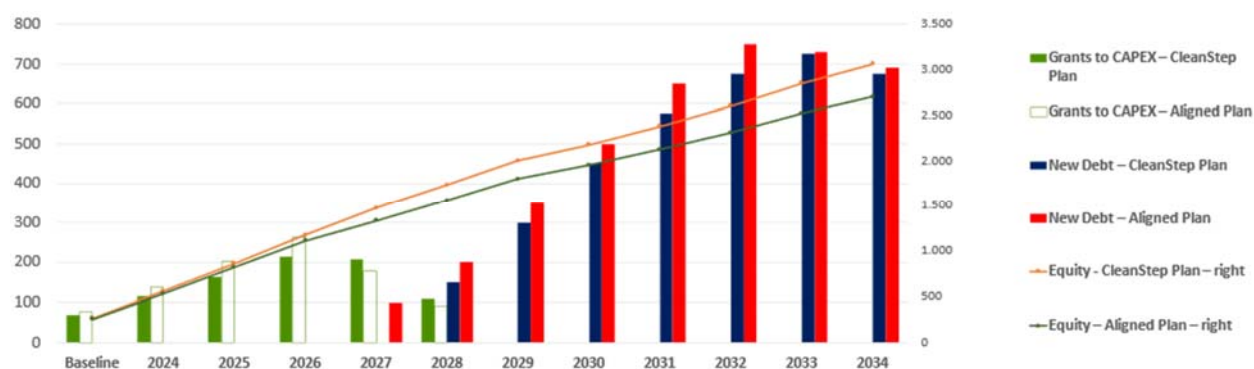


Figure 67. Uses/sources of financing for the e-cooking share in the Clean Step plan until 2029.

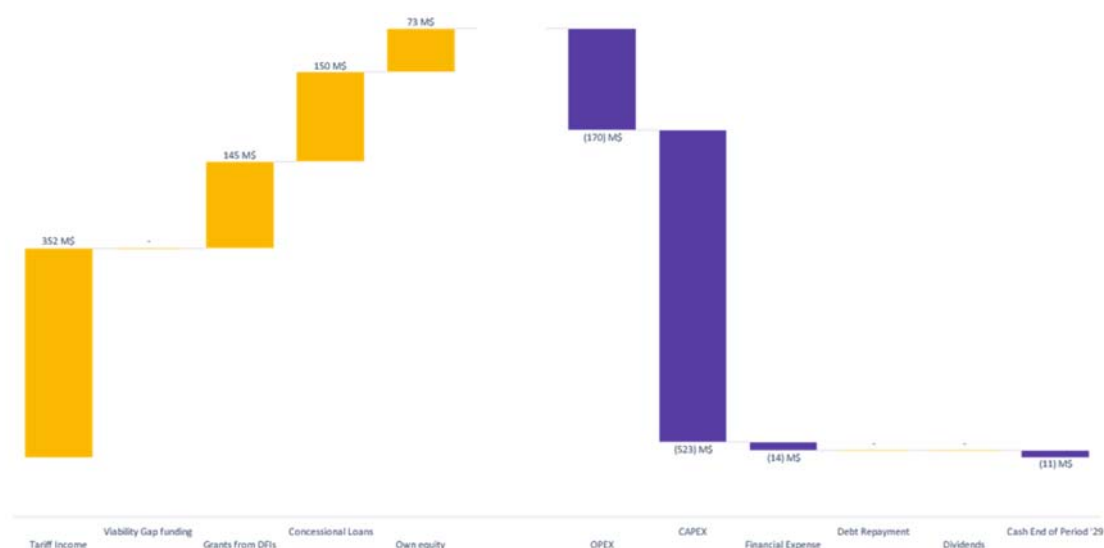


Figure 68. Taxes and subsidies (USD M) to diverse cooking technologies in the Clean Step plan.

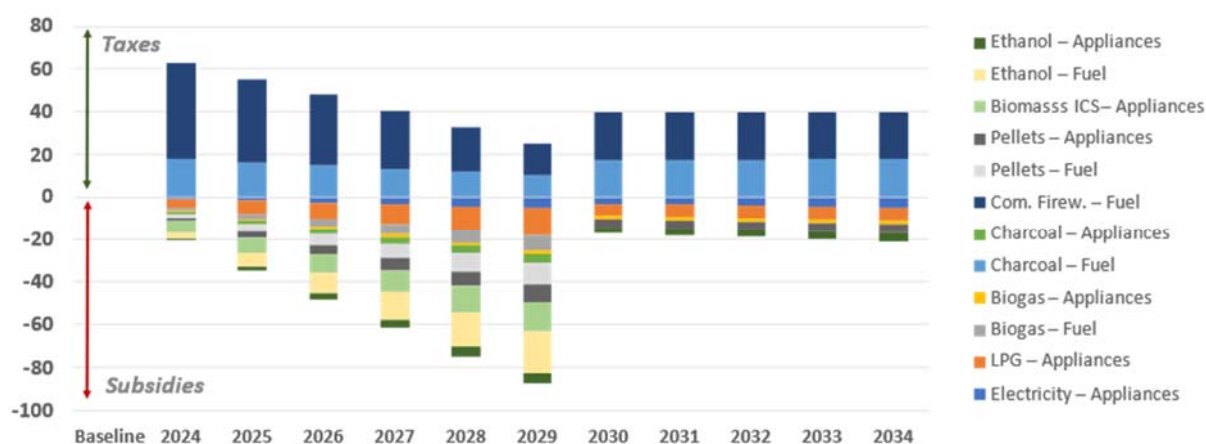
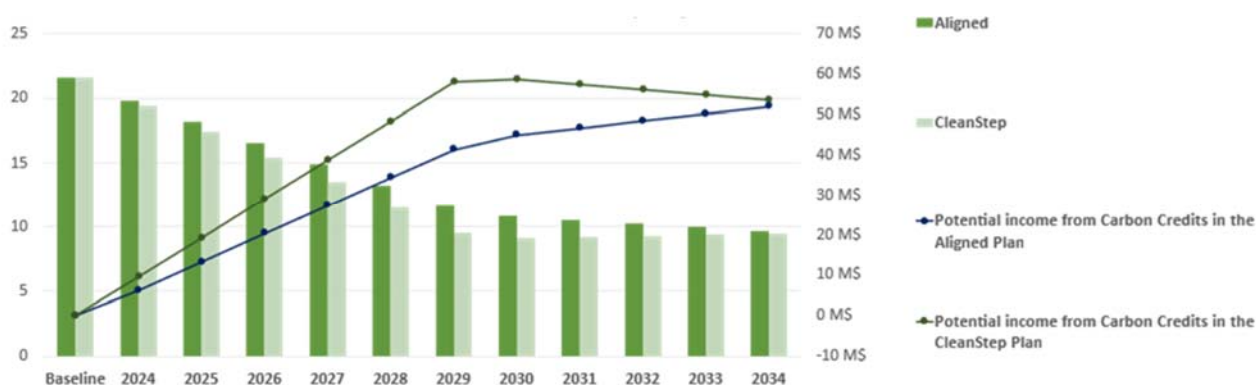
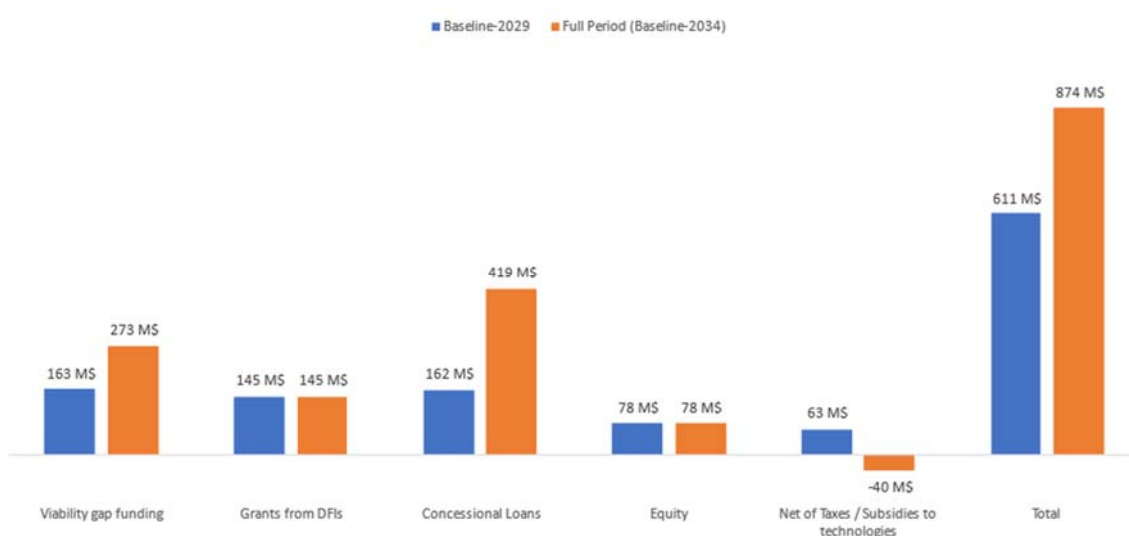


Figure 69. Avoided CO₂ emissions (CO₂Eq MT/y) and potential income (USD M) from carbon credits in both plans.



The financial effects of different taxes and subsidies are also represented annually, as in Figure 68. Figure 69 shows emissions reduction in both plans and their potential income over time from carbon credit markets, a potential funding source to be considered. Finally, Figure 70 represents the total funding required for implementing a clean-cooking plan, by period, and by the different sources of funds (carbon economy not included).

Figure 70. Summary of the total sources of funding needed to implement the Clean Step plan.



11. Conclusions

The models and tools presented in this paper are the result of trying to solve a specific case example as a particularisation of a general approach. The problem is the Integrated Clean-Cooking Planning at a country level, and the case example is Rwanda.

From a modelling perspective, this problem is very complex. It requires geo-referenced data (demand, costs, supply, geography) with adequate levels of granularity. Plans and results include their evolution over time, subject to alternative future scenarios (uncertain factors). Multiple cooking technologies (fuels and appliances) must be considered. While the total cooking demand of different types of consumers may be assumed, their technology choices depend on pricing, availability, and behavioural features. Regulated and centralised businesses coexist with free-market distributed ones.

The planning problem statement is complex as well. Top-level planning decisions are made by the Government, but public and private companies and consumers make their own “optimal” decisions. Optimisation criteria are diverse and, in some cases, conflictive: economic or financial costs are in general conflictive with social costs, such as health damages, time wasted (gender-biased), deforestation, and emissions.

The general features of the approach proposed (and applied) here are the following:

- Structured breakdown of the problem into subproblems. The solutions may be approached in successive phases (using simplified models and/or simplified spaces of search), and each phase may be structured into partial optimisations and simulations.
- Planning by detailed designs. It is based on the systematic search for planning solutions using detailed (and optimal) designs to evaluate each proposed plan. This alternative approach is possible by using off-line and interactive tools that perform detailed designs and simulations of alternatives.
- Interactive planning. Multiple plans can be tested and systematically improved. Each plan can be tested against uncertain factors to check its sensitivity and robustness.
- Combination of off-line tools that provide accurate and incremental (sensitivity) results with interactive tools that apply weighted averages, interpolation, extrapolation, and aggregation. This feature makes detailed designs compatible with real-time interaction.
- Multi-stage model. Successive planning stages can be defined.
- Financial planner. Refine cost models with the financial assessment of diverse agents, such as the State, economic sectors, or companies. The estimation of supply-chain emission reductions may be applied to carbon-credit markets.

Some distinctive features of the approach at the detailed modelling level are:

- Granularity down to the “building” level. This is used in the off-line pre-design of centralised infrastructures, specifically for Electricity and LPG. Multiple types of buildings and demand profiles are considered, together with detailed street maps, roads, and other geographical data. This is relevant to estimate the supply costs accurately, although consumers may be aggregated to estimate the demand response.
- Explicit technology adoption model. Matching supply and demand by adjustable models for the consumers’ behaviour and considering multiple consumer profiles. In fact, the target is not “universal access” to clean technologies but their “universal adoption”.
- Integrated general model for cooking technologies. Among other features, this includes the normalisation of parameters, the stacking model for aggregate consumers, and the definition (and use) of a standard cooking-demand unit, the “Cook”.
- Multi-effect model. Handle separately (and jointly when needed) multiple effects in the evaluation of plans, such as economic costs and the different components of social costs.

The approach presents some conceptual limitations, meaning that some aspects of the real-world problem have not been modelled yet (and maybe not modelled ever), like forest management or the geo-referenced commercial flows of Charcoal and Firewood. Other limitations are temporary, due to the version of the set of tools used in elaborating the plans, a partial implementation or prototype (Version 1). However, the results obtained so far are not only useful but quite promising, proving that the overall method is consistent and susceptible to further improvements.

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