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Modelling the integrated achievement of clean cooking access and climate mitigation goals: An energy systems optimization approach

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ABSTRACT

The United Nations Sustainable Development Goal target 7.1, to provide universal access to affordable, reliable and modern energy by 2030, must be achieved in the context of rapid reductions in global greenhouse gas (GHG) emissions. While replacing solid cooking fuels with liquid petroleum gas (LPG) opens questions about the compatibility of energy access and climate mitigation objectives, the environmental impact of 2.6 billion people continuing to rely on solid fuel for cooking and heating is significant. However, models used to map deep decarbonization pathways typically do not feature a granular pathway for universal clean cooking access, which limits the representation of these two interconnected transitions, mitigating climate change and achieving universal energy access. Here, we present a novel methodology for representing residential cooking pathways within the TIMES energy systems optimization model (ESOM) framework. The methodology is demonstrated using India as a proof-of-concept case study, where scenario analysis explores solutions that reach universal clean cooking access in the context of GHG emissions reductions. The model presented here is published and publicly available to access.

1. Introduction

1.1. Background

The United Nations (UN) Sustainable Development Goal (SDG) target 7.1, aims for universal provision of "modern, reliable and affordable energy services" by 2030 [1]. In this context the term 'energy services' refers to the two key services of electricity and clean cooking facilities. Access to these services is monitored by SDG indicators 7.1.1 and 7.1.2 respectively; where 7.1.2 measures the number of people who primarily depend on solid fuel at the household level. The SDGs have a target year of 2030; but with roughly 35% of the global population lacking access in 2019 [2] this goal is not currently on course for success [3]. Moreover, the impact of the Covid 19 pandemic and its resultant economic hardship threatens to further stall progress in this area [4].

Realizing universal access goals is an essential component for facilitating sustainable and equitable global development. Of the 2.6 billion people who remain dependent on solid fuels for heating and cooking, the majority are concentrated in developing economies such as sub-Saharan Africa, Asia and Latin America [2,3,5]. The lack of access to clean cooking facilities is associated with reduced rates of education, stunted economic development and poor heath outcomes, all of which disproportionately effect women and children from lower socioeconomic backgrounds [5]. In particular, annual premature mortality due to Household Air Pollution (HAP) arising from solid fuel use, stands at an estimated 3 million [6,7]. Prolonged exposure to the cooking environment means that HAP represents the largest environmental risk factor in female mortality [8] and raises the risk of adverse pregnancy outcomes [9,10]. Similarly, children under five years of age are particularly vulnerable to developing Acute Respiratory Infection (ARI) as a result of HAP exposure [11], accounting for roughly 500,000 premature deaths every year [12].

SDG 13, aims to "Take urgent action to combat climate change and its impacts" [1] and is aligned with the Paris Agreements target of limiting end-of-century warming to well below 2 °C, aiming for below 1.5 °C; above pre-industrial levels [13]. There is strong scientific consensus that falling short of this goal will result in profound and widespread consequences for many of the Earth's systems, which are likely to be disastrous in nature and global in scale [14]. Achieving the Paris Agreement goal requires net-zero carbon emissions by the year 2050 [15], which must be facilitated by the deep decarbonization of the global energy system [16]. Although representing just a small component of global energy demand, ensuring access to clean cooking facilities needs to be considered as part of a coordinated decarbonization strategy.

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Abbreviations

CO_2e	Carbon Dioxide equivalent
ARI	Acute Respiratory Infection
CCM	Clean Cooking Model
CCM	Clean Cooking Model
CNG	Compressed Natural Gas
ESOM	Energy System Optimization Model
GAINS	Greenhouse Gas — Air Pollution Interactions and Synergies
GHG	Green House Gas
Gt	Giga tonnes
GVW	Gross Vehicle Weight
HAP	Household Air Pollution
HGV	Heavy Goods Vehicle
IAM	Integrated Assessment Model
ICS	Improved Biomass Cookstove
IEA	International Energy Agency
IMAGE	Integrated Model to Assess the Global Environment
IPCC	Intergovernmental Panel on Climate Change
kt	Kilo tonnes
kWh	kilo-Watt hour
LPG	Liquid Petroleum Gas
MAGICC	Model for the Assessment of Greenhouse Gas Induced Climate Change
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
MSW	Municipal Solid Waste
Mt	Mega tonnes
mU	Million Units
mUSD	million United States Dollars
OSeMSYS	Open Source Energy Modelling System
PJ	Peta-Joule
PNG	Piped Natural Gas
PV	Photovoltaic
REMG	Residential Energy Model Global
RES	Reference Energy System
SDG	Sustainable Development Goal
SDS	Sustainable Development Scenario
SPS	Stated Policy Scenario
TCS	Traditional Cookstove
TIAM	TIMES Integrated Assessment Model
TIMES	The Integrated MARKAL-EFOM System
TSF	Traditional Solid Fuel
UN	United Nations
VKM	Vehicle Kilometre
WEM	World Energy Model

The link between the clean cooking access and climate change objectives derives from the conflict between demands for solid biomass fuels, which are used in Traditional Cookstoves (TCSs), and the crucial role that forested land plays in carbon sequestration. High demand for fuelwood often results in unsustainable harvesting, leading to deforestation and land degradation [17,18]. The burning of biomass fuelwood is also a source of several short- and long-term climate forcers [19]. It has been estimated that, globally, fuelwood burning releases around 1.0 to 1.2 Giga tonnes (Gt) of Carbon Dioxide equivalent (CO_2e) per year, making up roughly 1.9 to 2.3% of annual global Green House Gas (GHG) emissions [20]. Improved Biomass Cookstoves (ICSs) and Liquid Petroleum Gas (LPG) burners are the most common replacements for TCSs [21–26], however ICSs often do not reduce HAP enough to be considered 'clean' [5]; and LPG is fossil fuel solution which may be at odds with decarbonization objectives. Some studies have determined that delivering on clean cooking access goals results in reduced GHG emissions, even when achieved via deployment of LPG [5,27]. On the other hand, as LPG is by-product of the wider fossil fuel industry, the future availability of this fuel in the context of energy sector decarbonization is unclear [5].

Energy access goals are achievable though targeted policy measures. Unfortunately, many polices are poorly designed for the regions they target, often not accounting for local culinary practices and support infrastructure [28]. There are also several social and cultural factors which should be considered to promote long-lived cookstove switching behaviour [8,29]. For example, the limited functionality of replacement stoves can stall stove switching behaviour, hence when developing dissemination programs, it is important to understand the bundling of cookstoves to fulfil all cooking requirements [30]. Furthermore, it is common for energy access policies to miss opportunities to integrate with other targets and maximize positive outcomes [31]. When shaping the future of low carbon energy systems, policymakers are supported by energy models. At the global level, Integrated Assessment Models (IAMs) account for the interaction between energy, environment and economy, and are a key analytical tools for determining national and international decarbonization strategy, and most notably are at the heart of Intergovernmental Panel on Climate Change (IPCC) mitigation scenarios [14,15]. Therefore, IAMs hold much promise for exploring integrated SDG 7.1 and SDG 13 solutions.

The remainder of this paper is structured as follows. The following Section 1.2 details a literature review of the inclusion of energy access objectives within deep-decarbonizaton modelling, followed by a comparison of modelling methods applied to the clean cooking issue. Section 2 is broken into three subsections; Section 2.1 presents a novel modelling methodology for analysing clean cooking objectives, Section 2.2 details the data used to demonstrate the methodology in a proof-of-concept case study and Section 2.3 gives an overview of the scenarios constructed for the case study. The results of the case study are presented in Section 3. Discussion and conclusions regarding the interpretation of case study results, validity of the methodology and potential future applications are found in Sections 4 and 5 respectively.

1.2. Literature review

Clean cooking access is a nuanced, often misunderstood, issue which is commonly overlooked or oversimplified within the global scale decarbonization IAM literature. Without dedicated attention it is easy for modelling studies to omit consideration of its social complexities, intrinsic interconnection with climate change and heterogeneous nature of the solutions. Overall, there is very little overlap between studies that model decarbonization pathways for the energy sector with studies that target providing universal clean cooking access. When these goals are addressed in parallel, clean cooking access is frequently reduced to a single technology solution, often not fully integrated with the economy-wide decarbonization pathway. Moreover, when modelling studies do explicitly target clean cooking goals they typically focus on estimating the policy costs associated with the transition with lesser attention given to developing technically-granular, cost-optimal solutions.

Of the modelling studies which make up the IPCCs special report on achieving 1.5 °C end of century warming [32], most do not explicitly address energy access issues [33–36]. Others cite the need for the integrated investigation of access objectives but do not conduct it themselves [37–39]. Two studies [40,41] do consider energy access goals, but only by analysing the impact of their scenarios on SDG objectives, as opposed to integrating the objectives within mitigation scenarios.

Just two global scale IAM investigations integrate the achievement of clean cooking goals into their analysis [42,43], but do so by assuming that access objectives are achieved via universal deployment specific cookstoves.

Moving on from IAMs and the IPCC scenarios, the forms of modelling which have been used to study achieving clean cooking access under SDG 7.1, include:

- Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE), used in conjunction with Access. [44–48]
- Integrated Model to Assess the Global Environment (IMAGE), used in conjunction with Residential Energy Model Global (REMG). [43,45,48,49]
- The Integrated MARKAL-EFOM System (TIMES). [50]
- Open Source Energy Modelling System (OSeMSYS). [51]
- World Energy Model (WEM). [5,52]

The above frameworks all differ in their underlying philosophies and assumptions, but can broadly be categorized as optimization (MESSAGE, OSeMSYS, TIMES) and simulation (IMAGE, WEM). ACCESS and REMG are 'micro-simulation' extensions to their IAM counterparts. Optimization frameworks take descriptions of specific technologies and commodities and project an energy system that meets a defined target at the lowest cost within set constraints. Conversely, simulation frameworks project energy systems based on quantitative descriptions of energy demand and conversion based on endogenously determined drivers and technical data [53].

Mostly with a view to informing energy access policy, several of the issues which centre around clean cooking access transitions have been represented within modelling frameworks and studied at local, national and global scales. The features of the cooking energy transition which have been modelled include: health impacts [46,47,49], air pollution and HAP [43,46,47,50], solid fuel dependence [49,54], cookstove switching behaviour [45,55], fuel prices [43,43,55], energy security [47], GHG emissions [47,49,50], policy costs [43,45–47,55] and the comparative costs of specific fuel-stove combinations [50,51, 54].

Sometimes used in parallel [45,48], the most prolific forms of energy access modelling are the well established methodologies, MESSAGE-Access [44] and IMAGE-REMG [56]. These methods use a 'soft-link', where fuel prices generated by the IAMs MESSAGE and IMAGE are used as primary inputs to Access and REMG respectively. Both Access and REMG combine the fuel prices with income specific discount rates and internalized non-monetary costs to allocate cookstoves across a heterogeneous population. Although similar in premise, these models use differing underlying philosophies to allocate cookstoves. For example, while 'knife-edge' stove switching features in Access, REMG accounts for the inertia associated with household energy transitions. Scenarios for these models typically determine the rates of fuel subsidies and micro-finance that facilitate a transition to cleaner fuel [45–47,55,57], often taking LPG as universally representative of clean cooking access [45–47,57].

Both MESSAGE-Access and IMAGE-REMG are well-developed, robust methodologies for determining the level of financial support required to allow fuel switching behaviour across multiple demographics. In addition, the atmospheric models Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC) and Greenhouse Gas — Air Pollution Interactions and Synergies (GAINS) can be used in conjunction with MESSAGE and IMAGE respectively to determine energy sector development scenarios that are consistent with end of century warming targets [46,47,55,57]. Although these studies provide useful insights regarding the impact of climate polices on energy access, they are not designed to map fully-integrated pathways to meeting both clean cooking and climate goals.

There are several examples of technically-detailed, modelling tools focusing on clean cooking targets [49–51,54,58]. These include a spreadsheet-based simulation model [54] and a Reference Energy System (RES) built using OSeMSYS [51]. Both of these studies develop novel methods to determine the comparative household level costs and impacts of cooking with different technologies in localized case studies. However, the scenarios used by these studies calculate the cost of predetermined technology portfolios as opposed to modelling least-cost technology deployment pathways.

The TINERES [50] model developed within the TIMES optimization framework for the region of Nigeria is an example of a bottom-up, cost-optimization model developed to represent the cooking sector in a transition towards universal clean cooking access amongst other energy related targets. The core scenario in this study assumes a full transition to LPG by 2030, resulting in significantly increased CO_2e emissions from the system. Other scenarios did explore alternative stove options as well as internalized 'costs to society' with a finding that biogas was the cost optimal solution for the region. Whilst this study did focus on a technically-granular solutions and GHGs from the residential cooking sector, biomass was assumed as a carbon-neutral fuel source and the fuel supply chains did not represent emissions associated with fuel supply and distribution.

The WEM [58] developed by the International Energy Agency (IEA) is the only example of a global energy model used to map technically-detailed solutions to clean cooking goals in a way that is fully integrated with carbon mitigation objectives. The Sustainable Development Scenario (SDS) explicitly targets the integrated achievement of the three energy related SDGs; energy access, climate change and air quality. The portfolio of clean cookstoves in the SDS is determined though the historic drivers of fuel choice in different regions and according to urban and rural fuel availability. In addition, through the drivers of fuel choice, the WEM, which is based on a simulation framework, allocates technologies across the population in a manner that prioritizes cost effectiveness [58].

Despite the known emissions and sustainable development implications of cookstove choices, there has been very limited representation of clean cooking access goals within deep decarbonization modelling studies, and those that do often only consider single technology solutions. There is a particular gap in the field of energy systems optimization modelling. Furthermore, modelling work specifically in the area of clean cooking access has typically focused on understanding the policy costs of meeting goals, with much less weight given to understanding the application and implications of specific technical solutions. This paper seeks to address the gap by presenting a novel methodology for analysing technically granular pathways towards reaching universal clean cooking and climate change objectives within an Energy System Optimization Model (ESOM) framework.

2. Materials and methods

This paper presents the novel Clean Cooking Model (CCM) which addresses a gap in the literature regarding technically-granular representations of clean cooking access pathways in the residential sector. The CCM is implemented within the ESOM TIMES to allow for cost-optimization analysis of pathways towards achieving SDG 7.1. The CCM instance of TIMES is then applied in a proof-of-concept case study where scenario analysis is used to explore pathways which reach universal clean cooking access in conjunction with reduced GHG emissions for India. The CCM is published in open access form, complete with data points used for the case study [59].

2.1. Model development

With a similar underlying framework to MESSAGE, TIMES is a technology-rich, bottom-up, partial-equilibrium model generator used for constrained, linear, cost-optimization analysis of the energy sector over a medium- to long-term time horizon, with a"system planner" perspective. The partial-equilibrium with perfect foresight approach ensures that supply is balanced with demand across all stages of the energy system represented within the model. The model outputs a least-cost energy system that meets the demand within given constraints. A detailed description of the modelling framework is contained in the TIMES documentation parts I [60] and II [61]. TIMES and the extended global IAM version 'TIMES Integrated Assessment Model (TIAM)' [62], have been used extensively to explore low carbon energy futures in technical detail, at both national [63,64] and global scales [65–67], but have yet to be applied to the area of cooking energy access.

The CCM instance of TIMES can be implemented to investigate regional or national technology-explicit pathways to clean cooking access. The CCM has a RES structure which represents the fuel supply chains and demands making up the residential cooking energy sector. A combination of technologies, commodities and commodity flows describe the production, processing, distribution and use of each cooking fuel from primary resource all the way to end-use cooking energy demands. A number of techno-economic and environmental parameters define each technology within the CCM both for the base year energy system and in the future time horizon. The chosen parameters capture costs, emissions, losses and technical constraints on the system. To represent the SDG timeline, the core system settings are calibrated to a 2020 base year, with a 10 year time horizon in the future. To capture the discounting of costs over the time horizon, a standard social planners discount rate of 5% is applied.

The CCM accounts for the production, distribution and end-use of Traditional Solid Fuel (TSF) and modern cooking fuels, including more advanced options such as biogas, advanced biomass and off-grid electricity. Fig. 1 shows a simplified RES for the CCM, showing all the included technologies and their respective commodity flows. The whole system can be broken down into four commodity groupings: Primary, intermediate, residential and demand.

- ***Primary (Blue lines** Fig. 1**):*** Unprocessed, energy commodities that enter the system.
- ***Intermediate (Red lines** Fig. 1**):*** Partly/fully processed fuel commodities, not yet available to households.
- ***Residential (Green/Yellow lines** Fig. 1**):*** Fuel commodities directly available to feed household end-use demands.
- ***Demand (Purple lines** Fig. 1**):*** Household end-use cooking demand commodities.

The primary commodity sector defines the energy commodities as either imports or domestic resources as they enter the system, these resources are: Fuelwood, crop residue, dung, Municipal Solid Waste (MSW), coal, diesel oil, natural gas, LPG, grid electricity and solar radiance. The production process of each resources is defined by annual availability as well as the costs and emissions factors of associated production.

Primary commodities flow through several processes which represent the fuel supply chains. These processes produce intermediate commodities and include bottling, refining, grid distribution, kiln firing, collection, anaerobic digestion, pelleting and off-grid generation processes. In addition, the supply chain for TSF is simplified by amalgamating the commodities coal, fuelwood, crop residues, dung and (after kiln processing) charcoal into a single commodity. The definition of each process within the model captures efficiency losses, operation and maintenance costs, capital investment, processing capacity, fuel consumption and emissions factors.

When applying the CCM to a case study, each process within the model must be defined using region-specific data. For processes within the fuel supply chains, the costs of production must account for maintenance and repair as well as labour costs, expressed in terms of energy unit produced. This can be estimated using Eq. (1). Similarly, the efficiency of a process can be determined using Eq. (2) which accounts for material losses as well as the energy intensity of a process. Fig. 2 visualizes the efficiency losses associated with transforming a primary commodity to an intermediate commodity.

$$Activity\ Cost_{Process} = \frac{X}{Y} + (Labour \times Price_{Labour}) \tag{1}$$

$$\eta_{Process} = \frac{Y}{(Y \times (1 + losses)) + (I_{Process} \times Y)} \tag{2}$$

Where

$\eta_{Process}$ = Energy efficiency of the process [%]
X = Annual maintenance and repair costs [mUSD/mU]
Y = Annual production [PJ/mU]
losses = Material losses incurred through a process [%]
$I_{Process}$ = Energy intensity of process $[PJ_{Consumed}/PJ_{Fuel\ Produced}]$
$Price_{Labour}$ = Cost of labour [mUSD/hour]
Labour = Man hours of work required [hours/PJ_{Fuel} Produced]

Once processed, the commodities must be distributed into the residential fuel market. Natural gas and electricity can be distributed via grid infrastructure, whereas the majority rely on freight transport for dissemination into the urban or rural residential cooking sectors. The transport requirements of cooking fuels can differ based on the nature of the supply chain for each commodity type and on whether the destination is urban or rural. The annual transportation capacity, emissions per unit of fuel delivered and diesel oil consumption per unit delivered can be estimated for each fuel type using the Eqs. (3), (4) and (5) below.

$$Transport\ Capacity\ [PJ/year] = P \times \epsilon_{Commodity} \times \frac{No.trips}{day} \times \frac{No.days\ operating}{year} \tag{3}$$

$$Transport\ Emissions\ Factor\ [kt\mathrm{CO_2e}/PJ_{delivered}] = \frac{Emi \times D}{P \times \epsilon_{Commodity}} \tag{4}$$

$$Fuel\ Consumption\ of\ Transportation\ [PJ_{Consumed}/PJ_{delivered}] = \frac{I_{Transport} \times D}{P \times \epsilon_{Commodity}} \tag{5}$$

Where,

P = Vehicle Payload [t]
D = Distance transported [km]
Emi = Vehicle emissions factor [ktCO_2/km]
$I_{Transport}$ = Vehicle oil consumption [PJ/km]
$\epsilon_{Commodity}$ =Energy density of commodity being transported [PJ/kt]

CCM includes TCS, ICS, gasifier and rocket style advanced cookstoves; LPG, natural gas and biogas burner cookstoves; as well as the electric options of induction hot plates and pressure cookers. Each cookstove is characterized separately for rural and urban households. Each cookstove option is defined by a unit cost, efficiency, technical lifetime, activity bound (ie, how much of the annual demand it can meet) and base year installed capacity.

The cookstove selection for rural and urban supply is defined separately to better capture the differences in fuel supply chains and demands. This allows the model to select the optimal technology portfolio for each type of home. The demand commodities are then further split into the need to boil cook and flame cook different foods. This results in four distinct demands. The distinction between boiling and flame cooking is important as some cookstoves are not capable of fulfilling both types of demand. As the costs, thermal efficiency and cooking practices can differ, regionally specific data points should be used to define cookstoves and energy demands.

$$RKB_i = E \times No.Households_i \times \%Boiled_i \tag{6}$$

$$RKF_i = E \times No.Households_i \times \%Flame_i \tag{7}$$

Where,

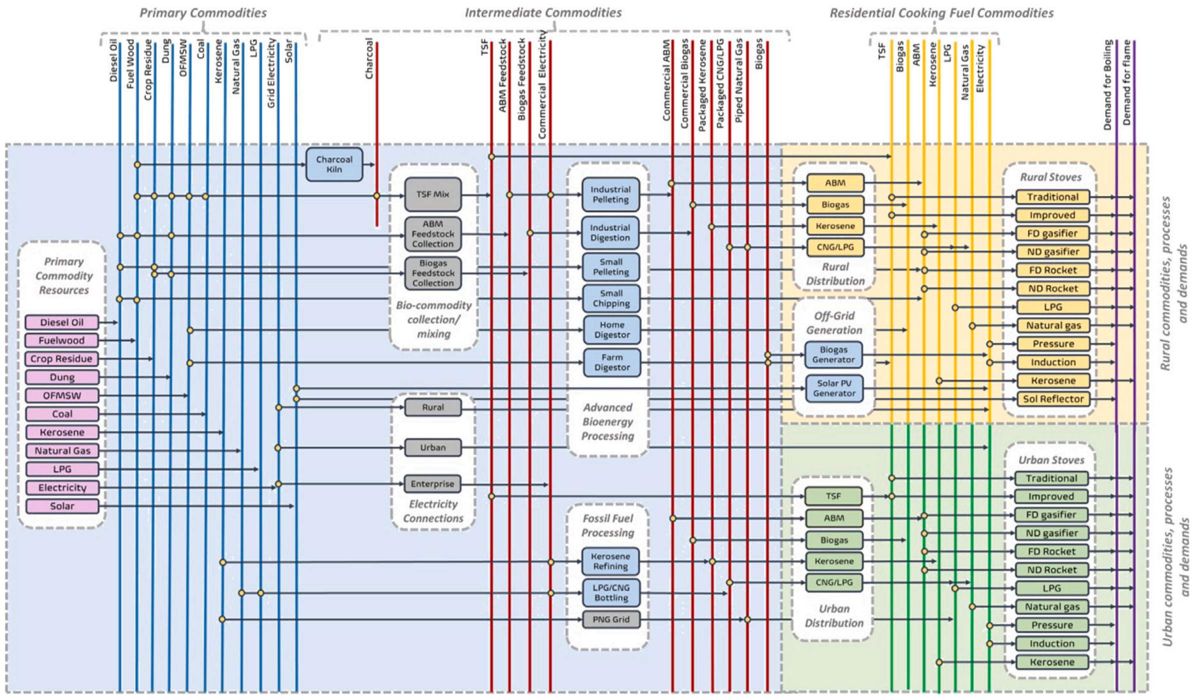

Fig. 1. This figure shows the reference energy system for CCM. The diagram is read from left to right. Vertical lines represent commodities, blocks show processes and arrows represent commodity flows between them. The colour of the block represents the type of process. Pink: primary resource; grey: mix/split process; blue: fuel conversion/processing; yellow: rural infrastructure; green: urban infrastructure.

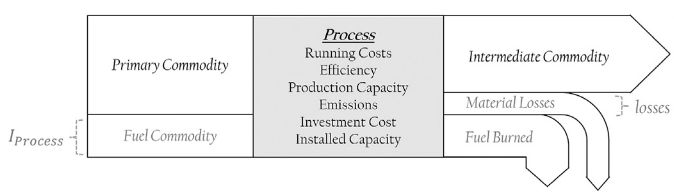

Fig. 2. Sankey diagram visualizing the losses which occur as a primary commodity is processed. Primary commodities enter a process at a set ratio. The efficiency losses of the process capture the material losses and fuel burned in producing intermediate commodities. See Eq. (2) for a numeric description of efficiency losses.

$i = household\ categorization\ by\ type\ (Where,\ i = urban\ or\ i = rural)$
$No.Households_i = Total\ number\ of\ type\ i\ households$
$RKB_i = Annual\ residential\ energy\ demand\ for\ boiling\ foods,\ household\ type\ i\ [PJ]$
$RKF_i = Annual\ residential\ energy\ demand\ for\ flame\ cooking,\ household\ type\ i\ [PJ]$
$E = Annual\ cooking\ energy\ demand\ for\ a\ single\ household\ [PJ]$
$\%Flame_i = Portion\ of\ cooking\ energy\ used\ to\ flame\ cook\ foods\ in\ type\ i\ households$
$\%Boiled_i = Portion\ of\ cooking\ energy\ used\ to\ boil\ cook\ foods\ in\ type\ i\ household$

2.2. Case study data input

India has a population of 1.38 billion people, roughly 30% of whom do not have access to clean cooking fuels in 2020 [6]. This is in contrast to near universal rates of electricity access [68]. Annually, approximately 2.3% of the population gains access to clean cooking facilities, a rate of progress which is insufficient to reach universal energy access goals by 2030. In addition, India has a history of clean cooking access policies dating back to the 1970s [26,69] and has stated ambitious commitments to climate mitigation objectives [68]. Here, the CCM is applied in a proof-of-concept case study using data points from the literature, household surveys, online resources and regional markets to represent the technologies and fuels that are applicable to the region of India.

The standard units for costs, energy flows and emissions within the CCM are million United States Dollars (mUSD), Peta-Joule (PJ) and Kilo tonnes (kt) CO_2e respectively. Primary commodities are the first to be defined. As fuelwood, crop residue, dung and MSW are bio-energy resources typically collected and prepared by hand, there are no costs or emissions associated with their production, hence these commodities are defined only by limits on annual availability. For crop residues, around 600 Mt is produced by the Indian agricultural sector every year [70], of which 34% is considered surplus [71]. Similarly, India has a population of 300,827 thousand large animals (cattle, buffalo, donkeys and horses) which collectively produce around 568,040 t of dung per day; of which 85% is considered surplus [72]. Although highly variable, roughly 0.3 kg of MSW is generated per person per day in India [73], of which the Organic Fraction (OF) is around 40% [72]. As the supply of MSW is linked to population, the production limit on this commodity is defined for each year of the time horizon, assuming historic rates of population growth, see Table 3. No bound is set on fuelwood, as current consumption is significantly higher than the 1.23 Mega tonnes (Mt) that can be sustainably harvested [74,75]. See Table 1 for a compilation of data points and sources used to estimate the annual availability of bio-energy resources.

A production bound is not set on fossil fuels (LPG, kerosene, natural gas and coal) as much of these resources are imports and, with the exception of LPG, consumption within the Indian residential cooking sector is limited [77]. As of 2020, 77% of Indian LPG supply is imported and approximately 88% of the total supply fulfils end use demands in

Table 1
Numerical data used to determine the annual production bounds on bio-energy commodities. References are given to the left of each data point. Here, *quantity* refers to the amount of material generated each year and *density* refers to the energy content per unit weight of the material. * Data point for the base year 2020. ** Estimated assuming 2020 base year population, see Table 3.

Commodity	Quantity		Density		Available		Energy resource
	Mt/year	Ref	GJ/t	Ref	%	Ref	PJ/year
Crop Residue	600.0	[70]	12.8	[76]	34	[71]	4150
Dung	207.3	[72]	11.9	[76]	85	[72]	2488
OF-MSW	151.0**		7.3	[73]	40	[72]	1039*

Table 2
Numerical data used to estimate the costs and emissions associated with the production of fossil fuel commodities. Here *density* refers to the energy content per unit weight of the material. The price of fuel commodities can vary between regions, but here they have been assumed constant for the purpose of simplification. *Estimated using fuel price data and currency conversion, see Table 3. **Assuming 21% LPG sourced from natural gas processing and 79% from crude oil refining [81]. ***Data from LCA China [81] used as a substitute.

Fuel	Density		Price*		Emissions	
	MJ/kg	Ref	mUSD/PJ	Ref	ktCO_2e/PJ	Ref
LPG	45.2	[76]	30.0	[80]	11.2	[81] **
Kerosene	42.8	[76]	20.4	[79]	13.9	[81]
Natural Gas	51.3	[81]	11.5	[82]	39.4	[81]***
Coal	11.7	[76]	5.1	[83]	16.2	[81]

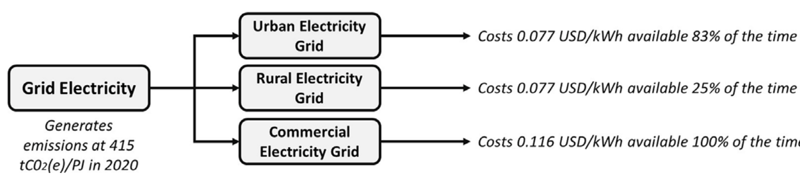

Fig. 3. Visualization of how electricity supply is differentiated between urban, rural and commercial supplies. The emissions factor is the only characteristic attached to the primary input process as this characteristic is common regardless of the consumer.

the residential sector [78]. The costs and emissions factors associated with the production of fossil fuels used in the cooking sector are sourced from online fuel price resources [79,80] and a life cycle analysis of Indian cooking fuels [81]. See Table 2 for a summary of data used to define fossil fuel commodities within CCM.

With over 95% of the population considered to have access in 2019, India has achieved one of the fasted electrification rates in history [68]. However, thresholds for a household having achieved electricity access are contested [84]. It is likely that when considerations of reliability and affordability are included, a lower share of households have access. Despite a large grid with ample capacity to generate power for the population, there is still a lack of distribution infrastructure to provide households with a stable supply, particularly in rural locations [85]. Hence rural homes receive approximately 6 h a day of stable electricity supply in comparison to 20 h per day for urban households [85,86]. The Indian electricity grid currently has an emissions factor of 415 ktCO_2e/PJ_{Elec} [81]. However, this factor is expected to reduce as the sector moves away from coal fired plants towards renewable options in the coming decade [68]. Using projections from the IEAs India Outlook on electricity generation and emissions [68] in the Stated Policy Scenario (SPS), emissions factors are derived every year of the time horizon. Currently the price of electricity is 0.077 USD/kWh and 0.116 USD/kWh for households and businesses respectively [87]. Three separate processes are used to differentiate electricity between urban, rural and commercial supplies, see Fig. 3 for a visualization. For simplification, it is assumed that commercial electricity has no limits on availability. Finally it is assumed that solar radiance has no costs, emissions or limits on production.

For charcoal production, earth mound charcoal kilns have no capital costs but do incur labour costs and efficiency losses. The activity costs of the kiln process are estimated assuming that 62 man-hours/month [88] are required to supervise a kiln producing roughly 5 t of charcoal per cycle, completing roughly 9 carbonization cycles a year [89]. The processes is assumed to have an emissions factor of 36.52 ktCO_2e/$PJ_{Charcoal}$ and an efficiency of 30% [81]. Charcoal is one of the solid fuels which becomes part of the TSF mix. As choice of solid fuel is based on several factors such as proximity to forestry and possession of livestock; factors which are not captured in detail within the model, it is assumed that the percentage share of each commodity within the TSF mix remains consistent though time, based on the breakdown of domestic cooking fuels reported in the 2011 Indian Census [77].

Table 3
Numerical data used to estimate the characteristics of fuel processing and distribution.

Parameter	Assumption	Unit	Ref
Cost of Labour (India)	0.57	USD/hr	[91]
HGV CO_2e Intensity	706	gCO_2e/km	[92]
HGV Oil Consumption	10.1	MJ/km	[92]
12 t HGV payload	5.5	t	[93]
Household Demand	11	MJ/day	[94]
Indian Population (2020)	1.366	billion	[95]
Annual population growth	1	%	[95]
Rupee to dollar exchange	0.0136	Rs/USD	[96]
Cost of fuel Oil	1.2	USD/L	[87]

The base year inputs for existing LPG infrastructure are based on India's existing 195 bottling facilities which have the combined capacity to process 20.3 mt of LPG per year [90]. The inputs for efficiency and fuel consumption are calculated assuming that the process is powered by electricity at a rate of 0.025 kWh/kg_{LPG} and incurs material losses of around 3.4% [88]. LPG is packaged in standard size 14.5 kg canisters, of gross weight of 29.5 kg, and a bulk transport network delivers to distributors who then disseminate to households [78].

In reality, bulk LPG transport occurs via a combination of Heavy Goods Vehicle (HGV), rail, and pipelines; however, as HGVs carry the majority of the weight, only this form of transport is represented by CCM. Currently 22,000 HGVs are on contract for packaged LPG transport in India [78]; for input to CCM this capacity is split between urban and rural transport based on the number of households primary depending on LPG in the base year. Therefore, the model has exactly enough capacity to supply LPG users 2020 but must invest in additional distribution capacity if more households are to be served later in the time horizon. The average distance travelled by LPG in India is estimated as 250 km [88]. Table 3 contains data points used to estimate the emissions and costs associated with HGV transport.

Natural gas use within the Indian residential sector is currently negligible [97], however, it is assumed that the LPG bottling and distribution network could be used to supply Compressed Natural Gas (CNG) if this commodity is selected by the model to meet future demands. Alternatively natural gas could be distributed via the, currently underdeveloped, Piped Natural Gas (PNG) grid [97]. To capture planned PNG network development, the activity of this process is limited to 4 million users in the base year and expanded linearly to the potential of 50% of urban demand by 2030.

Kerosene is processed in oil refineries and packaged in 210 l steel drums [88]. Kerosene processing has an emissions factor of 20.44 $ktCO_2e/PJ$ [81], consumes natural gas at a rate of 25.48 g/kg and has material losses of 1.2% [88]. The existing HGV distribution network for kerosene is assumed to be similar to the structure of the LPG network. The activity costs, capacity, emissions and efficiency parameters for the distribution of fossil fuel commodities are calculated on a case by case basis using the Eqs. (1), (2), (3), (4) and (5) given in Section 2.1.

As advanced bio-energy commodities, advanced biomass and biogas, are not currently in widespread use in India, the characteristics of their production and distribution processes are defined based case studies found in the literature. For commercial scale biomass pelleting, data from a techno-economic evaluation of biomass electricity generation for India [91] is used as a template. The annual production and costs per PJ output are based on a facility which outputs 1500 kg of pellets per hour, 300 days of the year, 20 h a day; requiring a man power of 5 for a lifetime of 10 years [91]. The up front cost of this facility is 25,999 USD and the annual repair and maintenance costs are estimated as 10% of the up front costs [91]. The facility is powered via electricity at a rate of 0.1 $\mathrm{kWh/kg}_{pellets}$.

The collection of crop residues for large scale pellet manufacture is partly based data from the techno-economic analysis [91] and partly on the energy intensity and emissions factors of a HGVs, see Table 3. The collection process assumes costs of 2.5 and 0.05 $\mathrm{USD}/t_{residue}$ for transport and materials respectively. It is assumed that the pelleting facility is located within 50 km of the feed stock source and HGV capacity is 3 t unprocessed biomass. For commercial advanced biomass distribution, it is assumed that the truck must travel 50 km to rural communities and 100 km to urban. Due to the increased mass density of pellets over raw biomass, each truck has a capacity of 5.5 t of packaged pellets [91].

Similarly, the collection process which deliver feed-stock materials to commercial biogas digesters is defined based on the same assumptions of cost, emissions, oil consumption and payload capacity of the HGVs. The techno-economic parameters of commercial biogas production is based on the Bowenpally, Hyderabad biogas facility [98]. This system has a capital cost of 400,000 USD and a fixed maintenance cost of 37,582 USD/year [98]. The facility can produce 75 $\mathrm{m}^3_{Biogas}/t_{feedstock}$ with a maximum processing capacity of 10 $t_{Feedstock}/\mathrm{day}$ [98]. The facility is assumed to have a lifetime of 30 years [99]. The transport requirements of large scale advanced bio-energy production are defined using Eqs. (1), (2), (3), (4) and (5) given in Section 2.1.

For small scale advanced biomass production, a machine capable of producing 100 $\mathrm{kg}_{Pellets}/\mathrm{hour}$ is considered at a unit cost of 9100 USD [97]. It is assumed that this system is run 360 days of the year operating 10 h a day; powered via diesel. The relative fuel consumption and costs are assumed similarly to the large scale system [91]. As small scale advanced biomass systems are operated by a single individual, producing pellets from locally sourced materials, no feed-stock or gathering costs are included in the data inputs and there is no subsequent distribution process. It is also assumed that the person running the system pays themselves a standard wage, see Table 3.

Home scale biogas digestion is modelled on a commercially available system [100] costing around 329 USD [101]. The home size unit produces around 1 $\mathrm{m}^3_{biogas}/2\mathrm{kg}_{OFMSW}$ per day and has lifetime of 10 years. Alternatively, moderately sized farm digestors produce roughly 10 $\mathrm{m}^3_{biogas}/24\mathrm{kg}_{dung}$ on a daily basis [101], costing 612 USD upfront and 50 USD/year for maintenance [99]. Although many are not in use, around 5 million farm size digestors are currently installed in India [99]. In addition farm scale biogas digestors can feed into biogas generators for small-scale off-grid electricity generation. Biogas generators typically operate at 33% conversion efficiency [69] and cost around 1355 USD [102].

Finally, an off-grid solar photo-voltaic system is defined within the model, linked exclusively to a pressure-cooker stove. The costs and technical attributes of the system are estimated based on a 2 kW commercially available setup [103]. The system has a peak load capacity of 2000 W and is available for a price of 96,000 Rs. The PV system has a battery pack of 150 Ah and is capable of running a load of 500 W for roughly 4 h. It is assumed that the system has a lifetime of 10 years with no operation or maintenance costs [103]. As the availability, cost and technical performance of cookstove vary by region, only data for cookstoves available within the region of India are used. The selection of urban cookstove are defined identically to their rural counterparts, with the exception that solar reflectors are not included as an option for urban households (see Table 4).

Cooking energy demands are estimated based a final energy requirement of 11 MJ per household per day, as determined by Indian household surveys [94]. Data from the 2011 census [77] is used to split the base year demands into urban and rural. Data from the World Bank on historic rates of population growth and urbanization [95] is used to project urban and rural demands over the 2020–2030 period.

The demands are further split into boil and flame cooking based on data from a life cycle analysis of Indian cooking fuel [88]. This data gives the average consumption of specific food stuffs for urban and rural regions, cooking times, culinary practices and the fuel consumption linked to each method. Rice, pulses, milk and tea all require boiling methods. Wheat, used to produce chapati flat-breads, requires a high heat intensity flame cooking method. Roughly 60% of vegetables are fried over a flame, where the remainder are boiled [76]. Portion of cooking energy demands required for boiling foods is calculated as 63% and 66% for rural and urban households respectively.

The final annual activity bound set on each cookstove unit is 4.015 PJ/mU for stoves capable of fulfilling both boiling and flame based demand; reduced to 2.65 and 2.53 PJ/mU for cookstoves only capable of fulfilling boiling demands for urban and rural regions respectively. The base year installed capacity of each cookstove type is determined from number of households reporting primary use in the 2011 Indian census [77], see Fig. 4.

2.3. Scenarios

Three scenarios are developed which focused towards the core research objective of examining the interaction between clean cooking access, sectoral CO_2e emissions and system cost. The base case scenario is constructed to reflect business as usual development, so that baseline costs, emissions and access rates can established. The clean cooking scenario exclusively targets the achievement of universal clean cooking access by 2030. Lastly, the clean-green scenario is developed to also achieve universal access goals but this time in the context of cooking sector CO_2e emissions reductions. The three scenarios are summarized below.

1. Base Case Scenario:

Premise: *Business as usual development assumptions, hence trends in clean cookstove uptake remain limited to historic patterns*

Constraints:

Table 4
Numerical data used to define all the cookstove options for the case study. **ND = Natural Draft, *FD = Forced Draft, †Estimated based on TCS efficiency and emissions data [81] compared with improved efficiency of ICS.

Cookstove	Efficiency		Unit cost		Life		Emissions	
	%	Ref	USD	Ref	Years	Ref	$ktCO_2$/ PJ	Ref
TCS	13	[5]	4	[5]	3	[5]	446	[81]
ICS	23	[5]	29	[5]	3	[5]	274†	–
ND** Gasifier	30	[6]	50	[6]	5	[6]	105	[81]
FD* Gasifier	48	[6]	65	[6]	10	[6]	105	[81]
ND** Rocket	35	[6]	25	[6]	7	[6]	105	[81]
LPG Burner	57	[45]	78	[45]	10	[45]	274	[81]
Gas Burner	60	[45]	60	[45]	10	[45]	147	[81]
Biogas Burner	55	[45]	36	[45]	15	[45]	1.33	[81]
Kerosene Wick	47	[45]	20	[45]	5	[45]	148	[81]
Induction Plate	67	[6]	80	[6]	15	[6]	0	–
Pressure Cooker	78	[104]	105	[104]	5	[104]	0	–
Solar Reflector	–		100	[6]	10	[6]	0	–

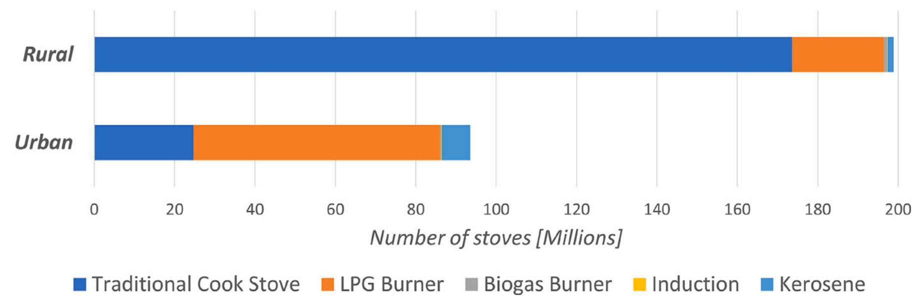

Fig. 4. Data from the 2011 Indian census [77] showing the proportion of cookstove types used in the base year across urban and rural populations.

- The total annual saturation of LPG burners, natural gas burners, biogas burners and all forms of advanced biomass cookstove are limited to historic patterns of uptake.
- No limits on the use of kerosene wicks, TCS or ICS options.

2. Clean Cooking Scenario
Premise: *Aspirational scenario where SDG7.1, universal access to clean cooking facilities, is achieved by the year 2030*
Constraints:

- Use of TCS and kerosene cookstoves are limited such that their maximum allowable saturation declines linearly over the time horizon such that they are completely phased out by the year 2030.
- The maximum allowable saturation of ICSs are limited from 2025 on-wards and completely phased out by the year 2030.
- Growth constraints are set on the uptake of advanced bio-energy fuels such that, if chosen, supply chains scale up linearly.

3. Clean-Green Scenario
Premise: *Dual aspirational scenario where both the SDG7.1 target and sectoral emissions reduction of 50% are achieved by 2030*
Constraints:

- Use of TCS and kerosene cookstoves are limited such that their maximum allowable saturation declines linearly over the time horizon such that they are completely phased out by the year 2030.
- The maximum allowable saturation of ICSs are limited from 2025 on-wards and completely phased out by the year 2030.
- Growth constraints are set on the uptake of advanced bio-energy fuels such that, if chosen, supply chains scale up linearly.
- Limits are set on the annual whole system emissions. The maximum allowable emissions decline annually to reach at least 50% reduction on base year emissions by 2030.

3. Results

Fig. 5 shows how the model chooses to meet the residential urban and rural cooking demand for all three scenarios. The base case scenario demonstrates business as usual dynamics with limited uptake of clean cooking options, especially in rural regions where progress is outstripped by population growth. In contrast, the clean cooking scenario sees use of TCSs decline in rural regions until completely phased out by the year 2030, as dictated by the scenario constraints. The model then replaces TCSs with ICSs as an intermediate solution for the years 2020–2025. From 2025, the ICSs are also phased out and replaced with advanced cookstoves which meet 100% of the rural demand by the year 2030. For urban regions, the clean cooking scenario sees TCS and LPG cooking displaced by small amounts of natural gas and ICS between 2020–2025, after which use of biogas scales up to meet 100% of urban demand by 2030. Finally, the clean-green scenario selects the same portfolio of cookstove technologies to replace TCSs and ICSs, but speeds up the rate of transition in order to meet the required CO_2e reductions.

The model estimates a whole system cost in the range of 70 billion USD for the base case scenario, see Fig. 6. For the clean cooking scenario the system cost is reduced to 62 billion USD, Fig. 6. This reduction is a result of the transition from LPG to options which utilize low cost waste products as primary resources, see Fig. 9. However, the system cost rises with the faster transition required by the clean-green scenario. The annual system costs per household for each scenario is shown in Fig. 7.

The base case emissions and costs remain consistent throughout the time horizon with both growing at a rate consistent with the projected rise in demand. The annual costs associated with the clean cooking scenario drop in the years immediately following the base year. This can be attributed to the switch from LPG burners and TCSs the higher efficiencies and lower fuel costs of ICS and natural gas burners, see Fig. 9. System costs begin to rise from 2025 onwards due to the infrastructure investments associated with producing advanced biomass and biogas as staple energy carriers. Visualized in Fig. 8, as the costs

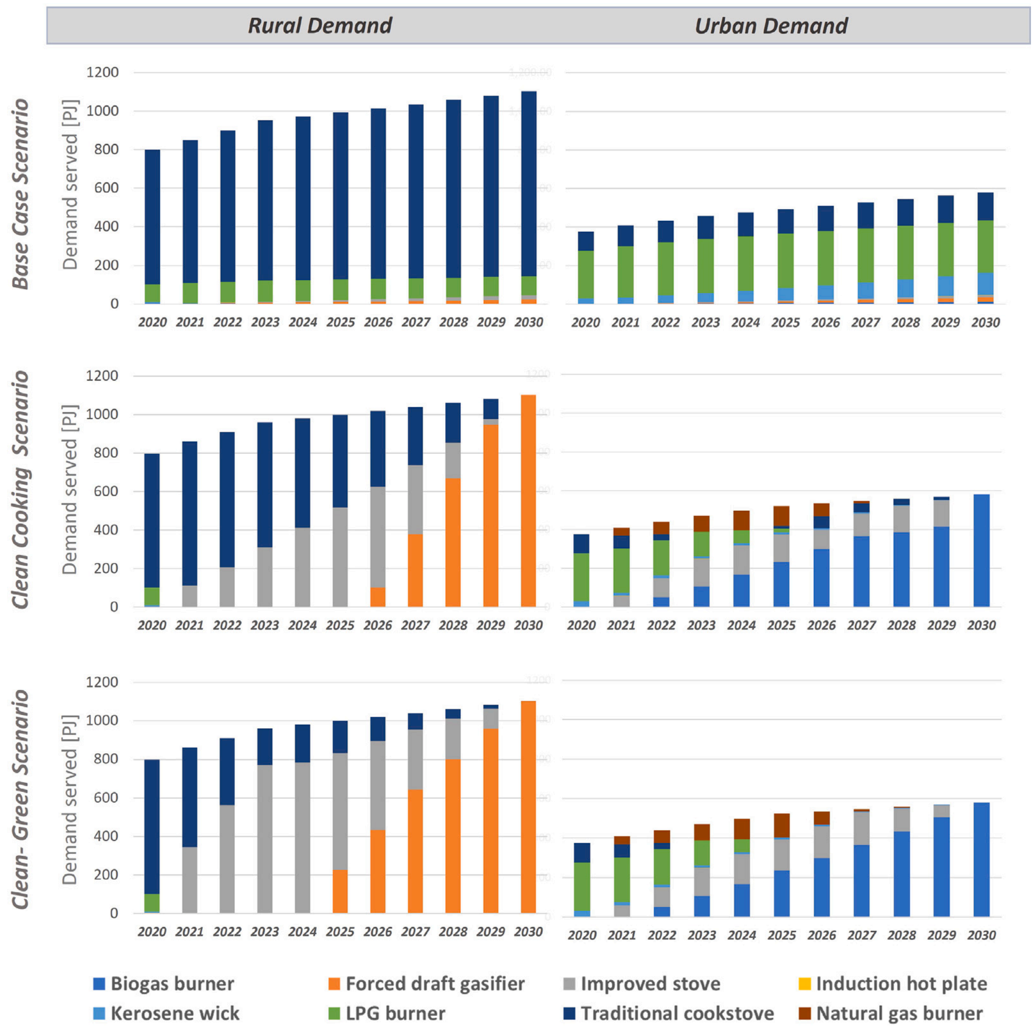

Fig. 5. Scenario analysis results showing the residential fuel transitions which occur under each of the scenario development assumptions. Each graph shows which portion of the residential cooking energy demand is met by each cookstove type in each year of the time horizon, segregated into urban and rural demands.

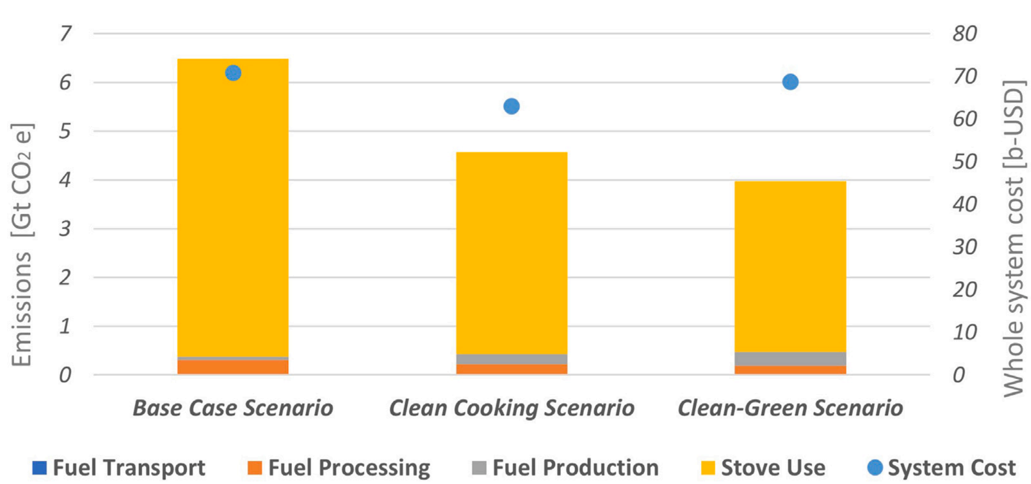

Fig. 6. Whole system emissions, broken down by activity, in comparison to whole system cost. All scenarios show that cookstoves use contributes the most to whole system emissions.

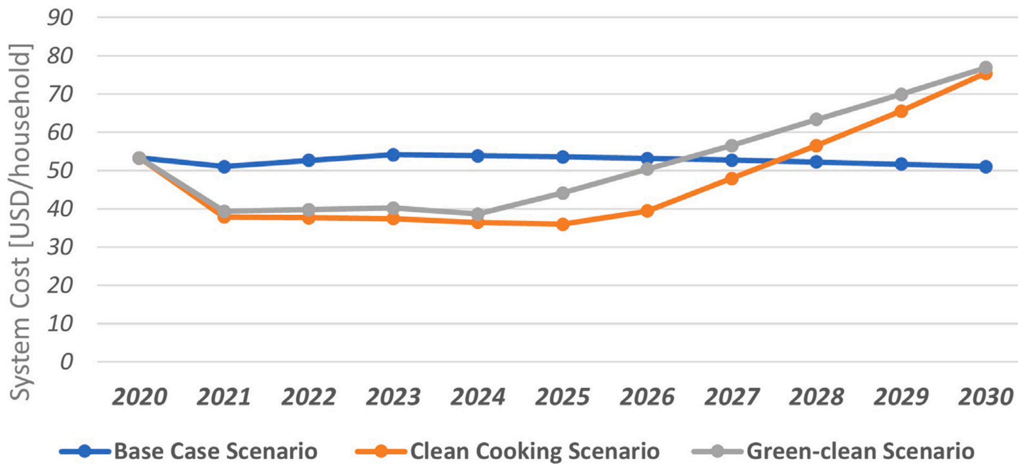

Fig. 7. The annual whole system cost, expressed at household scale.

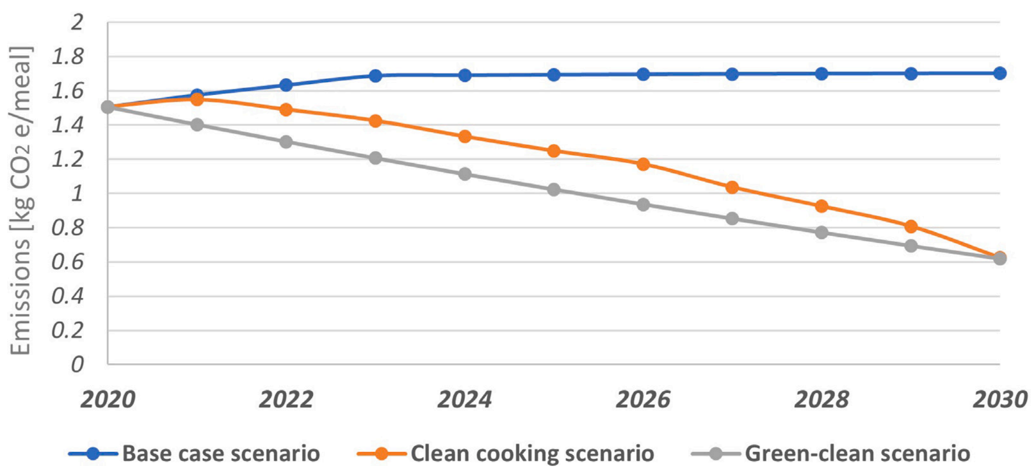

Fig. 8. Estimate of the average emissions generated per meal cooked assuming that each household requires 11 MJ/day of final energy to cook 3 meals per day.

rise the GHG emissions produced per meal reduce, reaching almost half of the base year emissions by 2030. A similar pattern is seen in the clean-green scenario, where costs initially drop but then begin to rise earlier and faster than in the clean-cooking scenario. A swifter and more consistent reduction in emissions is also noted in the clean-green scenario.

Fig. 9 gives a full breakdown of annual investments, showing the origin of system costs and the composition of fuel supply chains chosen by the model. System costs for all scenarios are dominated by fuel expenditure, followed by the cost of replacement cookstoves, with the remaining costs representing investments in fuel production infrastructure. Infrastructure investments are almost non-existent for the base case scenario as progression of past trends means that this scenario features high TSF consumption throughout the timeline; in addition the infrastructure required to supply LPG is already sufficient. For the clean-cooking and green-clean scenario, the model selects significant investment in commercial-scale biogas production facilities with a scale up in biogas transport infrastructure. To fulfil the demands for advanced biomass materials the model also invests in small-scale chipping and pelleting machines and a small amount of commercial-scale pelleting facilities with urban distribution.

The results provide insights regarding the application of specific technologies in a least cost approach to meeting SDG7.1, both with and without the presence of climate change mitigation goals. However, in the context of energy access policy development, the utility of the results are constrained by the limitations of the modelling approach. Discussion of the models strengths, utility of results, associated limitations and potential future work is expanded on in Section 4.

4. Discussion

This proof-of-concept demonstration of CCM, using India as a case study region, represents one of the first energy system optimization models to consider technically-granular solutions to energy access issues within an ESOM, in combination with a GHG emissions reduction target including fuel supply. This modelling approach allows for targeted investigation of SDG7 and SDG13, in order to derive cost optimal pathways reach both goals. A strength of the approach is the explicit representation of the fuel supply chain, including existing infrastructure and investments required for the transition. The CCM has the ability to allocate different solutions based on the differing demand, fuel supply and technology profiles of urban and rural regions. In particular, realism is added by expressing cooking demands and technologies by flame cooking and boiling methods, allowing the model to stack cookstoves if this is the cost-optimal pathway.

The results of the case study, presented in Section 3, suggest that for India, transitioning towards advanced bio-energy system is the least-cost way forward to achieving clean cooking access in parallel with emissions reductions. This result is far more ambitious than current plans for India to scale up bio-energy use in the residential cooking sector [97]. In addition, the model results suggest that ICS technology may have a valid place as a transitional solution, particularly for rural

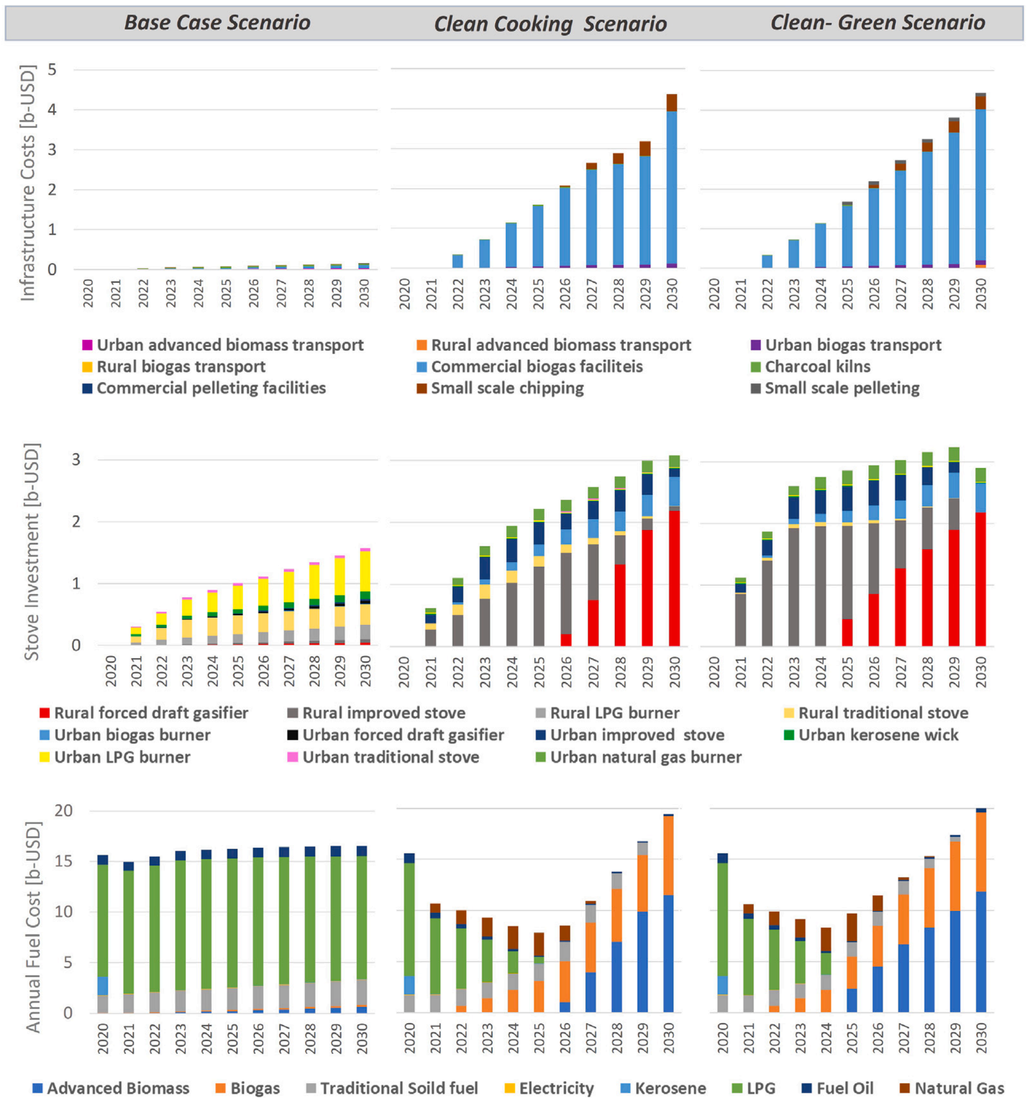

Fig. 9. Breakdown of annual system costs and investments for all three scenarios. The costs include annual activity and materials costs associated with fuel production, investments in new cookstoves and investment in new fuel supply infrastructure.

households. The whole system cost for this transition is around 62 billion USD, raising to approximately 68 billion USD if integrated with emissions reductions of 50% by technology the year 2030. These results are based on the data available at the time of analysis, their robustness could be improved by substituting for more up to date information as it becomes available. The results show very high base year system emissions, because of the high rate of unsustainable fuel-wood harvesting and the associated emission factor applied to this. Future model runs could apply variable assumptions of fuel-wood harvesting to determined the models sensitivity to this factor.

The value of the optimization approach is the calculation of an 'ideal' economic and environmental outcome. Hence, the TIMES framework is useful for examining the dynamics between energy access goals, costs and GHG emissions; as well as deriving cost-effective pathways towards reaching set goals. By not accounting for real-world features such as historic patterns of behaviour and preference, hierarchical cookstove switching or household finances, the model generates a solution under a theoretical ideal. A potential disadvantage of this approach is the tendency of the CCM to generate solutions which feature knife-edge stove-switching and infeasible rates of infrastructure development. For example, in the case study results, in both the clean-cooking and green-clean scenario LPG and TSF fuels are rapidly replaced with a combination of biogas, natural gas and advanced biomass cooking fuels. These features are a direct result of no limitations being applied to the uptake of new cookstoves or maximum capacity of new fuel supply chains. Future application of this model can add user-defined constraints to limit the speed of technology diffusion and the rate of change in household preferences and stove acceptability.

For policy makers and energy planners, the optimization approach can be applied to challenge or substantiate viewpoints regarding the solutions to energy access issues. For example, the case study CCM scenario analysis substantiates the transition towards natural gas use for urban regions but suggests that bio-energy may be a more cost-effective solution for rural areas over India's current plan to further promote LPG uptake [97]. However, the model results do not represent a step-by-step road-map to clean cooking access, but rather an exploration of solutions which result in desired environmental and economic outcomes. Moreover, although the CCM was not designed to capture household-level barriers to fuel-switching, scope does exist to pivot the model towards examining clean cooking access from this perspective. Similar to previous work in MESSAGE-Access [45,55], this type of development would involve splitting the end-use cooking demand by household income, the application of technology-specific discount rates for each income group and the internalization of time and household income as monetary flows. These changes would allow the demographic-specific impact of financial constraints, fuel subsidies and micro-financing schemes to be studied.

In reality, household fuel choice is dependent on factors such as geographic location and cooking environment [105,106]; features which are not captured in detail within CCM. Cookstove options such as gasifiers, rocket stoves, ICS and solar parabolic reflectors are only appropriate solutions for households where cooking takes place outside. Similarly, home-scale biogas digestors and solar Photovoltaic (PV) systems are only applicable in cases where the household has outside space to store the equipment. For inner cities and apartment residences, options like gas burners and electric stoves are more practical solutions. Similarly, the costs and logistics of supplying cooking fuels like LPG also vary by region depending on transportation and storage requirements [107,108]. It is possible to split the final energy demands by household type to better capture some of these nuances, but the structure of TIMES means that any further integration of these complexities is very challenging without linking to other models. This can be addressed in future research.

Additionally, the temporal availability of bio-energy resources may be incorporated into future iterations of the CCM. The CCM currently describes each bio-energy resource as a single commodity, when in reality, each type of resource has several sources, each with unique temporal availability and energy density profiles [71,72]. This is an important consideration in a bio-energy based cooking system, as deficits in security of cooking fuel supply quickly lead to fuel stacking and cookstove abandonment [109,110]. Bio-energy may be a less feasible solution if the seasonal variability of supply were represented within the model. Representation can be achieved through the extended use of time-slices and activity bounds where appropriate data exists. Similarly, the water requirements of the anaerobic digestion process are not included here. Although water consumption may be inconsequential for some regions; for rural locations experiencing water scarcity, biogas digestors may not be feasible [111]. Hence, future iterations of CCM could consider the flow and constraints of non-energy commodities through the system.

The application of CCM to the case study of India shows how this modelling approach can be used to determine least-cost pathways towards SDG 7.1 targets in the context of a regions specific cooking demand and energy resource profile. Hence, the CCM results would likely be very different if applied to a region with less robust LPG infrastructure, more limited bio-energy resources and a more reliable electricity supply. The case study results show that CCM can be applied to investigate a multitude of uncertainties regarding the achievement of regional cooking access goals. Furthermore, there is substantial scope for further development of the CCM, as discussed in this section.

5. Conclusions

This study addresses an important gap in energy systems modelling by developing a novel modelling methodology, CCM, which represents the transition required to meet integrated pathways to achieving climate mitigation and universal access to clean cooking, two critically important global goals. Achieving clean cooking targets as set out by SDG7.1 is essential for facilitating progress across several other global development indicators [5], playing an especially crucial role in improving health outcomes for many of the worlds most vulnerable populations. Moreover, many of these populations are likely to increasingly exposed to the adverse consequences of climate change, despite being the least responsible and the least able to mitigate the negative impact on their lives [14]. Hence, policies which progress both energy access and climate mitigation objectives have a part to play in the pursuit of improved global equity, the costs of which are far outweighed by the benefits. When it comes to informing energy transitions at a policy level, energy systems optimization models are a core tool, but to date have not explicitly represented technologically-granular pathways for achieving universal clean cooking access in parallel with climate change goals.

The CCM instance of TIMES demonstrates how clean cooking systems can be represented within optimization frameworks. CCM is a novel description of a cooking system which captures emissions, energy consumption and efficiency losses across all relevant fuel supply chains at a high level of technical granularity. The methodology was developed with a view to investigating whole system emissions from across the cooking sector in the context of achieving clean cooking targets as set out by SDG 7.1. The structure of the TIMES framework allows for mandated emissions reduction targets to be set for either the whole or a sub-set of the system. This feature allows for energy access objectives to be studied in the context of a regions specific climate mitigation policy or to understand the impact of climate policy on a least cost pathway towards universal energy access. The model is made freely available under a Creative Commons licence [59], allowing for its continued use and development.

The use of CCM can underpin energy access and climate mitigation policy and planning in developing countries, subject to available data and careful calibration. Further developments should focus on capturing the temporal availability of more disaggregated bio-resources; the inclusion of non-energy consumable resources, and non-cost variables impacting household decision making such as finance and preference.

CRediT authorship contribution statement

A.F. Hollands: Methodology, Data curation, Formal analysis, Investigation, Writing – original draft. **H. Daly:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Datasets related to this article can be found at https://doi.org/10.5281/zenodo.6334117, an open-source online data repository hosted by Zenodo [59].

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