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A general modeling framework to evaluate energy, economy, land-use and GHG emissions nexus for bioenergy exploitation

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Abstract

This paper presents a modeling framework to address the energy, economy, emissions and land use nexus when exploiting bioenergy in developing countries. The modeling framework combines a qualitative and a quantitative element. The qualitative element integrates two components: 1) technology roadmapping to identify long-term technology targets through expert judgment and 2) scenario analysis to investigate different future storylines. The quantitative element comprises four integrated tools, namely the energy system model (ESM), the land use and trade model (LUTM), an economic model, and an external climate model. An overview of the modeling framework, scenario analysis, structure of the models, modelling techniques, mathematical formulations and assumptions is presented and discussed. The modeling framework is applied to the particular context of Colombia, as a case study of a developing country with large bioenergy potential. In this study case, the impacts that an accelerated deployment of bioenergy technologies might cause on the energy demand and supply, emissions and land use until 2030 are evaluated. Results suggest that a plan to exploit bioenergy in Colombia should prioritize the deployment of technologies for biomethane production, power generation & CHP, which can reduce more GHG emissions and more emissions per incremental hectare of land than first-generation biofuels. Moreover, while the share of bioenergy in the primary energy demand decreases in all the analyzed scenarios, it is possible to envision significant increases in the share of bioenergy in road transport energy demand, power generation and natural gas supply for scenarios implementing roadmap goals. In addition, impacts of El Niño oscillation on the dependence of hydro for power generation can be partly mitigated by exploiting the complementarity of hydro and bioenergy, which might result in a reduction of up to 5-6% in the demand for fossil fuels used in power generation in dry years. However, despite the ambitious goals proposed here, bioenergy alone cannot significantly reduce emissions by 2030 (maximum 10% reduction relative to baseline) and effective climate change mitigation requires a portfolio of additional measures.

Keywords: energy policy, roadmap, scenario analysis, biomass, land use, emissions.

Nomenclature

Acronyms

BID	Inter-American Development Bank
BRICS	Brazil, Russia, India, China, South Africa
CHP	combined heat and power
CNG	compressed natural gas
COE	cost of electricity
DANE	National Administrative Department of Statistics, Colombia
DECC	Department of Energy & Climate Change
EIA	U.S. Energy Information Administration
ENSO	El Niño and La Niña southern oscillation
ESM	energy system model
FAO	Food and Agriculture Organization of the United Nations
FAPRI	Food and Agricultural Policy Research Institute
FFB	fresh fruit bunches (palm oil)
GCM	General Circulation Model
GDP	gross domestic product
GHG	greenhouse gas
IAM	Integrated assessed model
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis

IPCC Intergovernmental Panel on Climate Change
LCOE levelized cost of electricity
LEAP Long-range Energy Alternatives Planning System
LHV lower heating value
LPG liquefied petroleum gas
LULUCF land use, land-use change and forestry
LUTM land use and trade model
MME Ministry of Mines and Energy, Colombia
NEA Nuclear Energy Agency
NMVOC non-methane volatile organic compounds
NOx nitrogen oxides
PPP purchasing power parity
Toe ton of oil equivalent
UNEP United Nations Environment Programme
UPME Mining and Energy Planning Unit, Colombia

Symbols

A dummy variable to estimate vehicle ownership
AL activity level
BMV blend mandate of biofuels by volume
C installed power generation capacity
CC capacity credit
CK coefficient to evaluate the annual energy demand for cooking per household
Cov supply coverage
D population density
DC total discounted cost
DE decommissioning cost
Deg factor representing the change in a property (e.g. efficiency, emission) as a technology ages
E access to energy services (electricity and natural gas)
ECAa energy consumption for appliances
ECApa energy consumption for appliances per capita
ECCH energy consumption for cooking per household
ECCI energy consumption in agricultural industries
ECCp energy consumption for cooking per capita
ECF energy consumption by fuel for various sectors
ECL energy consumption for lighting
ECLH energy consumption for lighting per household
ECLp energy consumption for lighting per capita
ECP consumption of energy resources for power generation
ECV energy consumption for a vehicle
ECWp energy consumption for water heating per capita
EF emission factor
EI energy intensity
F fuel cost
FE fuel economy for a new vehicle
FS floor space per person
FSQ floor space quintile factor
GDP gross domestic product
GDPp gross domestic product per capita
GHG greenhouse gas emission
H number of households
HDD heating degree days
HH household expenditure
HHp household expenditure per person
I investment cost
IS income share for different regions or quintiles
LHF lighting hours factor coefficient
LHV lower heating value
M motorcycle ownership
MEF multiplying emission factor for biofuels
Mil mileage for a vehicle
OD annual number of days demanding hot water
OM operation & maintenance cost
OW appliance ownership
P population, e.g. number of inhabitants
PG power generation
PL peak load
Q quintile number, i.e. 1, 2, 3, 4 and 5
R dummy variable to estimate vehicle ownership
r discount rate
RM planning reserve margin
S household size

Sales	number of vehicle sales
SH	vehicle share
Stock	number of vehicles
Sur	survival rate of vehicles
T	temperature
t	year
U	urban fraction of population
UEC	unit energy consumption by type of appliance
V	vehicle ownership
VE85	percentage of vehicles able to run with E85
VEFF	percentage of vehicles that are flex fuel
W	unit energy consumption per light bulb
x	mass content
α	parameter of Gompertz function
β	parameter of Gompertz function
ψ	saturation level of Gompertz function
λ	negative constant of Gompertz function
φ	negative constant of Gompertz function
θ	speed of adjustment
ε	random error
k	cost exponent in logit function
$k_{1,2,\ldots n}$	constant of Gompertz function
γ	cost sensitivity coefficient in logit function
μ	fuel share
ϑ	coefficient that influence the unit energy consumption in appliances
ζ	coefficient that influence the unit energy consumption in appliances
ξ	coefficient that influence the energy consumption by fuel for various sectors
∇	gradient to model differences in access to energy services across quintiles

Subscripts

a	a-th type of appliance
bg	related to biogas
bio	related to biofuels
blend	related to blends of fossil fuels and blends
c	c-th type of vehicle
d	d-th time step, day
E	type of energy service, e.g. electricity, natural gas, heating, etc.
E20	related to the fuel program E20 (ethanol 20%v)
E85	related to the fuel program E85 (ethanol 85%v)
F	period of falling
f	f-th type of fuel
fossil	related to fossil fuels
g	g-th type of power generation technology
I	type of agricultural industry
lg	related to landfill gas
MAX	maximum
Other	related to other pollutants
p	p-th type of pollutant
Q	q-th quintile
R	period of rising
r	region, i.e. rural and urban
ru	related to rural regions
s	type of sector
t	t-th time step, year
u	related to urban regions
v	v-th year of production (vintage) of a certain type of vehicle or motorcycle

1. Introduction

In the 20th century, industrialization and population growth led to a rapid increase in world energy consumption. This trend has been followed in recent years by various emerging economies (e.g. BRICS) and it is likely or at least desirable that many other developing countries move along that path in the future. However, the need to meet a growing energy demand to sustain economic growth has resulted in serious negative impacts including climate change, deforestation, soil and water contamination, loss of biodiversity and concerns on water supply (UN, 2014a; IPCC, 2014; IEA, 2012c).

In the coming decades, energy, environment and sustainable development goals are expected to face serious challenges at national, regional and global levels (Rodriguez, Delgado, DeLaquil, & Sohns, 2013; UN, 2014b; IEA, 2012c; Hoff, 2011; WEF, 2011; Hanlon, Madel, Olson-Sawyer, Rabin, & Rose, 2013; IPCC, 2014; UN, 2014a; Bizikova, Roy, Swanson, Venema, & McCandless, 2013; Halstead, Kober, & van der Zwaan, 2014). Many of these challenges are interrelated. For example, energy, water and land are required to cultivate food crops, which are needed to support the world's growing population. Water is needed to generate most forms of energy (instead e.g. photovoltaic cells or wind energy do not require water), and energy is required for securing water supply. Population, water and energy infrastructure are needed for ensuring economic development. Land is not only required for food production but also for energy purposes and contributes significantly to greenhouse gas emissions. Energy, land use and economic development affect climate change in many ways, but are also affected by it. Various terminologies exist to refer to these relationships depending on the extent and number of linkages among the different sectors. Among others, this nexus can include water-energy (WE), water-energy-food (WEF), water-energy-land (WEL), climate-land-energy-water (CLEW) and climate-land-energy-water-development (CLEWD) (UN, 2014a).

The depth and intensity of linkages between climate, energy, water, land and development vary enormously among countries and regions (Arent, et al., 2014; IPCC, 2014; Hanlon, Madel, Olson-Sawyer, Rabin, & Rose, 2013). Some of these linkages pose significant problems at the national or regional level, but can be solvable as are relatively short-lived (Halstead, Kober, & van der Zwaan, 2014). Examples of such linkages include: the energy-water nexus (Halstead, Kober, & van der Zwaan, 2014), the energy-sustainable development nexus (WEF, 2011) and the energy- and water-land nexuses (UN, 2014a). In contrast, some other linkages are global and worsen the impact of national or regional linkages in many parts of the world (IPCC, 2014; UN, 2014a). These linkages are long lived and are not easily solvable, typically requiring global solutions (Halstead, Kober, & van der Zwaan, 2014). Examples of such linkages include the influence in both directions of climate change with energy, water, land and economic development (Halstead, Kober, & van der Zwaan, 2014; UN, 2014a).

While challenges associated with these sectors have been mostly addressed and studied independently, a multidisciplinary approach to investigate the nexus can lead to a more efficient use of resources as well as cross-sectorial consistence (Halstead, Kober, & van der Zwaan, 2014). In the last few decades, integrated approaches to investigate the above-mentioned interrelations have been promoted with moderate success. Today, multidisciplinary integrated approaches addressing these nexuses are uncommon, although certain exceptions exist (UN, 2014a).

Interrelations between sectors at a global or regional scale (e.g. focusing on climate change and its linkages) have been addressed by a limited number of multi-sectorial integrated assessed models (IAM) (UN, 2014a). IAMs are commonly used to investigate climate change and related global environmental problems by describing relevant parts of the energy-economy-climate system (UNEP, 2013; IPCC, 2014). IAMs describe in a simplified manner the interaction between multiple components of the overall system, for instance energy supply and demand, land use, the carbon cycle, atmospheric chemistry and climate system (UNEP, 2013). Examples of IAMs addressing three or more linkages at global or regional scale include: IMAGE, ASF, ICLIPS, IGSM, MERGE, GCAM, and Second Generation Model (Pollitt, et al., 2010).

At a national level, a moderate number of approaches have addressed the mentioned nexus. Methods and characteristics vary largely across different approaches. Approaches can be classified according to various criteria: 1) type of analysis, 2) level of comprehensiveness, 3) extent of analysis, 4) type of entry point, 5) type of targeted country, 6) level of accessibility and 7) flexibility to be applied to different contexts and countries. Regarding the type of analysis, most of the tools are purely quantitative, while only a few incorporate qualitative elements (Ferroukhi, et al., 2015). Regarding the level of comprehensiveness, most of the tools have complex frameworks, while there is a lack for relatively simple tools that can provide preliminary assessments

(Ferroukhi, et al., 2015). Various approaches are “entry points” (i.e. one sector influences others), while a reduced number are “fully integrated” (i.e. relationships between sectors exist in all directions) (Ferroukhi, et al., 2015). Regarding the extent of analysis, most studies investigate less than three sectorial linkages (e.g. (Masson, et al., 2014; Suttles, Tyner, Shively, Sands, & Sohngen, 2014; Di Leo, Pietrapertosa, Loperte, Salvia, & Cosmi, 2015; Viebahn, Vallentin, & Höller, 2014; Senger & Spataru, 2015; Bryan, Crossman, King, & Meyer, 2011; Edmonds, Clarke, Dooley, Kim, & Smith, 2004)), while only a few studies have investigated more than three (details in (UN, 2014a; Ferroukhi, et al., 2015)). Regarding the type of entry point, approaches have used either food or energy as entry point. Ferroukhi et al. point out that while various simple tools using food as entry point exist, there is a lack for such tools using energy as the entry point. Regarding the type of country targeted, most approaches focus on industrialized countries and a few emerging economies, while only a few studies have addressed non-OECD developing countries. Notable examples include (Hermann, et al., 2012; Morrison, 2012; Welsch, et al., 2014; Wattana, 2013; Omar, Almoustafa, & Al-Din, 2013; Daher & Mohtar, 2013; Swierinski, 2012). From studies in non-OECD countries, only five have addressed the topic of biomass and bioenergy and its interrelations with other sectors. Regarding the level of accessibility, most of the tools appear accessible to a large number of users and allow for policy making.

Hence, on the basis of the literature survey presented above, there is a gap for relatively simple tools addressing the nexus challenge that satisfy the following criteria: 1) provide preliminary assessment, 2) use energy as the entry point, 3) combine quantitative and qualitative methodologies, 4) address the topic of biomass and bioenergy and its interrelations with other sectors and 5) be applicable to developing countries.

This paper aims at filling this gap. For this purpose, an approach combining a quantitative and a qualitative element is proposed. The quantitative element comprises four separate tools, namely the energy system model (ESM), the land use and trade model (LUTM), an economic model, and an external climate model. Given that energy is the entry point, the development of an energy model as comprehensive as possible is proposed. In contrast, simple models for analyzing land use, trade, economy and climate are proposed. For the land use and trade, it is proposed to use a resource-focused statistical model, which is non-spatially explicit analysis and thus easy to implement and inexpensive. The economic model aims at describing in a simple way economic growth, population growth, prices of energy resources and commodities, as well capital costs of technologies. For climate, projections from external models are taken and uses as drivers for the ESM and the LUTM models. This combination of models ensures a high level of accuracy for the entry point (i.e. energy) and a relatively simple approach that can provide preliminary assessment for the nexus between energy, land use, emissions and economy. On the other hand, the qualitative element combines two components: a) technology roadmapping to identify long-term technology targets through expert judgment and b) scenario analysis to investigate different future storylines. In order to develop the above-mentioned tools, the use of state-of-the-art modeling techniques and well-known and generic platforms is proposed. This may increase the level of accessibility and reproducibility, particularly in developing countries. Finally, addressing multiple bioenergy technology areas and its linkages to other sectors is proposed.

The modeling framework described above is applied to the case study of Colombia. In particular, it is used to estimate the impacts of an accelerated deployment of bioenergy technologies in Colombia for the period 2015-2030, which has been formulated as a technology roadmap by authors in (Gonzalez-Salazar, et al., 2014c).

This paper is structured as follows. Section 2 discusses the proposed method; Section 3 describes the details of the Energy System Model (ESM); Section 4 reports the detailed assumptions made for applying the modeling framework to Colombia. Section 5 presents results for the energy demand and supply obtained from models. Section 6 presents the impacts on the land use and trade, while Section 7 shows the impacts on GHG emissions. Finally, conclusions are presented in Section 8.

2. Method

2.1. Criteria to develop the method

Recommendations from prior art are used as guidelines to define a set of criteria to develop a research method that addresses the challenges described above.

Regarding modeling energy systems and their linkages with the economy and the environment, various recent studies recommend best practices to design research methods. For example, (DeCarolis, Hunter, & Sreepathi, 2012) recommend to make source code and model data publicly available, make transparency a design goal, utilize free software tools, develop test systems for verification exercises and work towards interoperability among models. (Pfenninger, Hawkes, & Keirstead, 2014) recommend energy modelers to design methods and analyses that are more transparent and reproducible. Similarly, (AfDB-OECD-UN-World Bank, 2013) recommend the following good practices: 1) be flexible, transparent and adaptable to context, 2) provide explicit justification for preferred options, 3) establish clear goals, 4) analyze potential effects, risks and alternatives against a framework of sustainability criteria, 5) involve key stakeholders and encourage public involvement.

Regarding the additional complexities found in developing countries, (Urban, Benders, & Moll, 2007) discuss how research methods need to ensure an adequate representation of these complexities. According to Urban et al., as much top-down as bottom-up approaches found in literature offer a sub-optimal characterization of energy systems in developing countries. They suggest to develop new simulation or toolbox models featuring a better description of the power sector, access to modern energy services, investment decisions and subsidies, preferably following a bottom-up or hybrid approach. To be consistent with these guidelines, the following criteria to develop the research method are defined:

1) It should be transparent, easy to implement, generic and replicable.
2) It should be low priced to adapt to constrained R&D budgets.
3) It should be built in well-known and generic platforms in order to increase the level of accessibility.
4) It should follow robust and state-of-the-art approaches (preferably bottom-up) to address the gaps in knowledge described above.

2.2. Proposed method

While the approach of most nexus tools found in literature is purely quantitative, the method proposed in this paper combines quantitative and qualitative elements. There is a key advantage associated with this combination. While quantitative approaches (i.e. analytical modeling) are essential for assessing (separately and jointly) energy, economy, emissions and land use, they alone are typically insufficient to identify potential solutions on the long-term. On the other hand, qualitative approaches are well-accepted methods to identify long-term solutions and to describe how and why they should be used (IEA, 2010). However, qualitative methods alone are also insufficient to evaluate the impact of long-term solutions on different sectors. Thus, combining qualitative and quantitative elements offers the possibility of identifying potential long-term solutions and quantifying associated impacts. In the proposed modeling framework (see Figure 1), the qualitative element combines two components: technology roadmapping and scenario analysis. Technology roadmapping is primarily used to identify long-term technology targets, milestones and policies through expert judgment; scenario analysis is employed to define and investigate different future storylines. On the other hand, the quantitative element comprise four separate tools, namely the energy system model (ESM), the land use and trade model (LUTM), an external climate model and an economic model. These tools are employed to evaluate the impacts of implementing the long-term technology targets on the energy system, the land use and the GHG emissions. Qualitative and quantitative elements influence each other. While the influence of qualitative methods (e.g. technology roadmapping and scenario analysis) on the quantitative analysis is explicit, the opposite influence is less obvious but equally important. Results obtained from quantitative analysis must be used in a feedback loop to calibrate and update the technology roadmapping process. In this way, it can be ensured that the qualitative element incorporates the best available technologies and strategies (see also Figure 2). However, a problem arises when producing a first-time technology roadmap, as quantitative analyses might not yet available. In this case, the proposed framework relies on the experts' knowledge from prior art and would be inevitably affected by their potential biases. This challenge is nonetheless reduced once a continuous technology roadmapping with quantitative analysis is put in place. More details of both elements are presented in following sections.

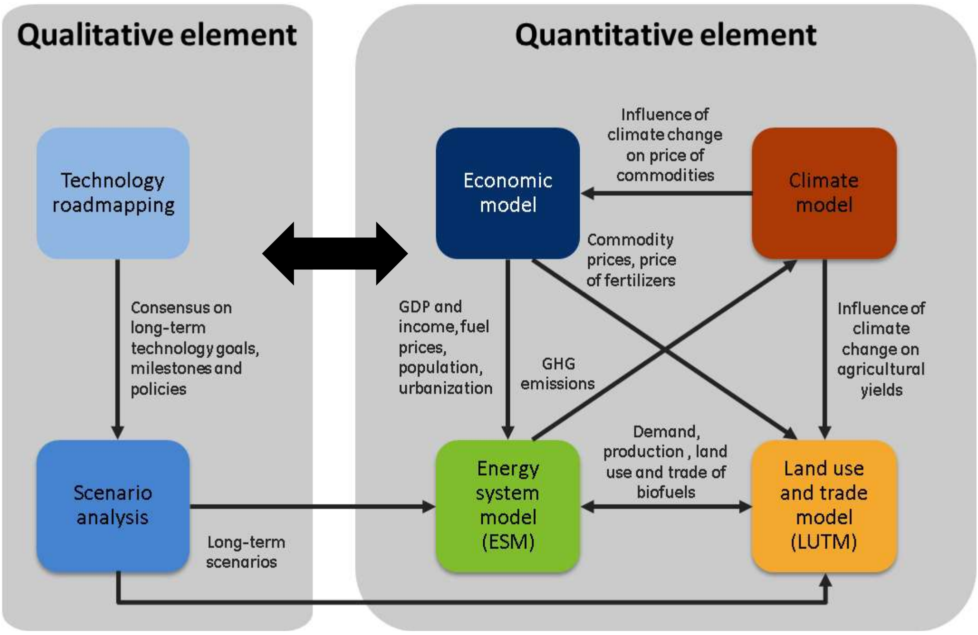

Figure 1. *Modeling framework*

2.3. Qualitative element

Long-term and strategic planning of energy resources offers multiple benefits: a) it enables a nation to prepare for the future in an orderly and systematic way, b) it provides a basis for building consensus on needs and for measuring progress and impact and c) it turns consensus and analytical work into systematic actions. In this study, a qualitative element combining technology roadmapping with scenario analysis to address the challenge of long term and strategic planning of energy resources is proposed.

2.3.1. Technology roadmapping

Technology roadmapping is a tool used in strategic planning, which offers the key advantage of providing information to organizations or nations to make better technology investment decisions (Garcia & Bray, 1997; Phaal, Farrukh, & Probert, 2001; IEA, 2010). Technology roadmapping does this by: a) engaging diverse stakeholders in finding consensus on common goals (e.g. needs, solutions, etc.), b) identify critical needs that drive technology selection and decisions, c) identify technologies that satisfy critical needs and d) develop and implement a plan to deploy selected technology alternatives. Technology roadmapping is particularly important when the investment decision is not straight forward, because of uncertainty in which alternative to pursue, or because a need to a coordinated deployment of multiple technologies exists (Garcia & Bray, 1997).

In this paper, the guide to development and implementation of energy technology roadmaps developed by IEA (IEA, 2010) has been taken as a model and further adapted to the conditions of developing countries. This is a very detailed and robust method that relies on expert judgment and analytical modeling to identify long-term technology strategies and plans. It consists of four phases: i) planning, where scope, boundaries and approach are defined; ii) visioning, where opinion of experts on long-term goals, technologies and policies is collected through workshops and surveys; iii) development, where the roadmap document is created; iv) implementation and revision, where the roadmap is implemented and monitored. While this method can be applied to any country, its structure is best adapted to OECD countries. For developing countries, it can be challenging to implement the full method, which requires various detailed and lengthy processes and involve multiple working groups. In developing countries, resources and experts often lack or should focus on fulfilling needs that are more urgent. Thus, the original IEA method has been here simplified (see Figure 2). The number of process steps and feedback loops has been reduced, while at the same a more prominent role to analytical modeling has been given, which in the IEA methodology is optional. Another improvement over prior art is the use of a new strategy to build consensus based on the Delphi method via two surveys and a workshop. In this strategy, the opinion of individual experts about long-term technology strategies is influenced by the opinion of the group of experts, which facilitates reaching consensus. More details of this strategy are presented by authors in (Gonzalez-Salazar, et al., 2014c).

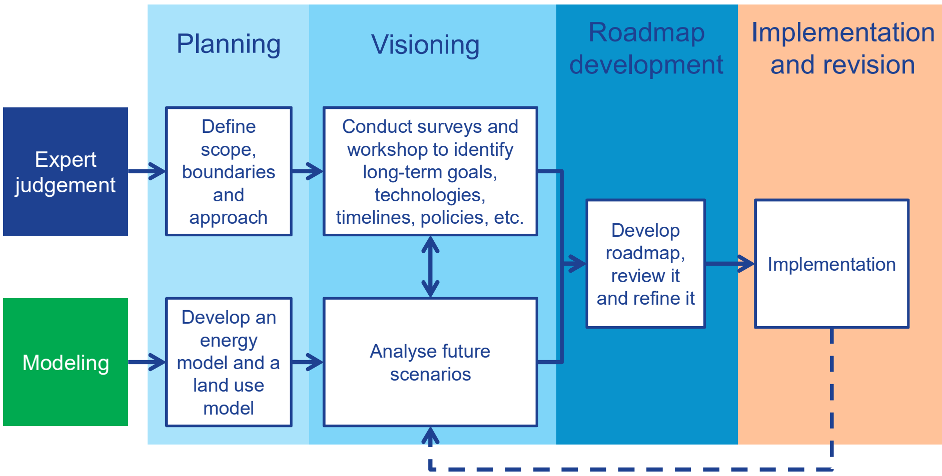

Figure 2. *Qualitative element of the modeling method*

2.3.2. Scenario analysis

In some cases, consensus cannot be built among experts to find solutions. In this case, the IEA recommends either: 1) choosing one position, 2) presenting the opposing views if one of those is the minority, or 3) attempting to create consensus between the two sides. In this study, it is rather proposed to analyze multiple differing views through scenario analysis. Key advantages of scenario analysis include: a) it offers the possibility to address the uncertainty caused by unpredictability of future events, b) it allows considering various future storylines when consensus cannot be built and c) it allows policy analysis. By identifying the most effective policy measures, scenario analysis might contribute to increase the chances of implementing a technology roadmap.

2.4. Quantitative element

A combination of four separate tools, namely the energy system model (ESM), the land use and trade model (LUTM), an external climate model and an economic model (see Figure 3) is proposed. These tools are employed to evaluate the impacts of implementing the long-term technology targets on the energy system, the land use and the GHG emissions.

While in this framework relations exist between the four separate tools, these relations do not occur in all directions. Thus, this framework can be described as one using energy as entry point. Given that energy is the entry point, the development of an energy model as comprehensive as possible is proposed. The ESM model is a scenario-based, demand-driven model that combines various modeling techniques to replicate the behavior of the country's energy system and the associated emissions. The ESM model is built on the Long-range Energy Alternatives Planning System (LEAP), a platform widely used to report energy policy analysis and greenhouse gas (GHG) mitigation assessments that is free for users in developing countries (Connolly, Lund, Mathiesen, & Leahy, 2010). Given the extension of the EMS model, a full section is dedicated to explain this model (see Section 3). In contrast, relatively simple models for analyzing land use, trade, economy and climate are proposed. For the land use and trade, it is proposed to use a simple resource-focused statistical model (LUTM), which is non-spatially explicit analysis and thus easy to implement and inexpensive. It estimates land use as well as production and trade of 18 agricultural and forestry commodities and is built in Microsoft Excel. The ESM and the LUTM models employ various state-of-the-art modeling techniques designed or adapted from prior art (see Sections 3 and 2.5, respectively), which satisfy the premises of being transparent and replicable. In addition, the two models are built on well-known and generic platforms, such as LEAP and Microsoft Excel, which makes them relatively inexpensive and easy to replicate.

2.4.1. Linkages between tools

The four tools of the quantitative element are interrelated. Firstly, the scenarios defined in the qualitative element influence the ESM and the LUTM models. Long-term goals, policies and assumptions of the different scenarios are used as inputs for these two models. The ESM model is influenced by the LUTM model as well as by the economic and climate models. The demand for energy resources by the different sectors of the economy is influenced by multiple economic drivers including the GDP & household expenditure, population, energy prices and access to energy services (e.g. electricity, natural gas and biofuels).

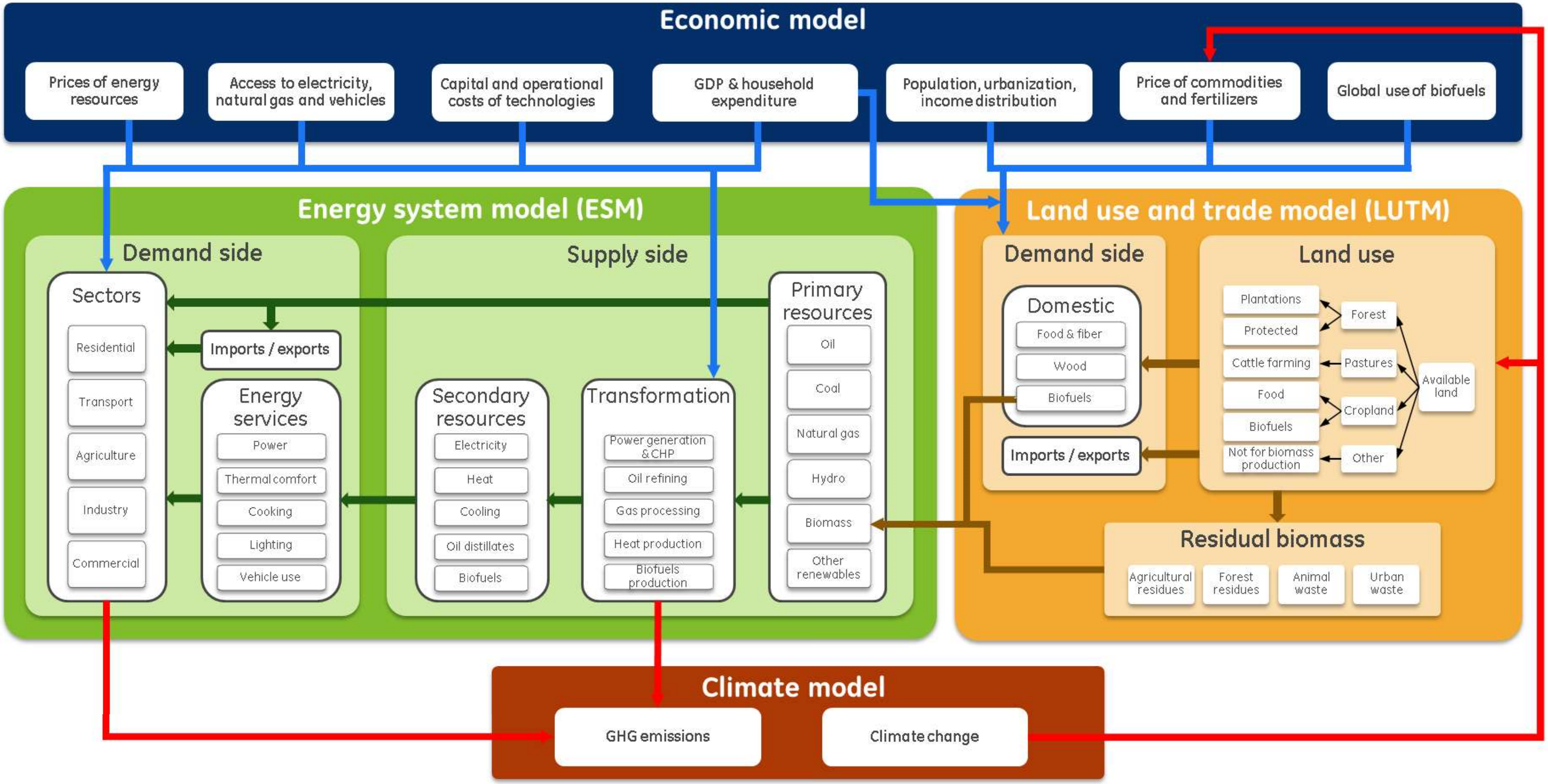

Figure 3. *Quantitative element of the modeling framework*

The deployment and performance of technologies for transforming primary energy resources into secondary energy carriers is influenced by capital and operational costs and in some cases by climate conditions (e.g. hydro power, wind power, etc.). The demand for biomass resources estimated in the ESM model is then exported to the LUTM model. The LUTM model optimizes the production and trade of biofuels, woodfuel and other commodities and estimate feedstocks and required land. Outputs of the LUTM model are then used as inputs in the ESM model to estimate the conversion of residual biomass into energy. In addition to the link with the ESM model, the LUTM model is also linked with the economic and climate models. GDP, population, price of commodities and global use of biofuels are the main economic drivers to estimate the demand for agricultural and forestry commodities in the LUTM model. The LUTM optimizes the land use and allocates production for supplying local demand and exports. Climate change influences this optimization, as agricultural yields and price of commodities depend to certain extent on climate change conditions. Finally, GHG emissions produced on the demand and supply sides of the ESM model influence the climate change model. While emissions associated with the land use in the LUTM model also influence the climate change model, this link is not covered in the present study.

2.4.2. Climate model

Rather than formulating a new climate model, the use of projections of an external climate model is here proposed. Projections of the general circulation model (GCM) developed by Fischer et al. at IIASA (Fischer, 2011) are used. Projections of this model used in the present study include: a) influence of climate change on agricultural yields and b) influence of climate change on price of commodities. Details of the mentioned projections can be found in (Fischer, 2011). Additionally, climate conditions influence the performance (i.e. efficiency and capacity factor) of some renewable energy technologies, such as hydro power, wind, solar, biomass, etc. Thus, the use of external climate models to link the performance of some renewable energy technologies to climate data is proposed. For this purpose, projections of the GCM model developed by IIASA can also be used (Fischer, 2011).

2.4.3. Economic model

Similarly to the climate model, the economic model also relies on projections or approaches by external models. Projections taken from external models are divided into seven categories: 1) GDP and household expenditure, 2) Population, urbanization and income distribution, 3) capital and operational cost of technologies, 4) access to electricity, natural gas and vehicle use, 5) prices of energy resources, 6) price of commodities (agricultural and forest) and 7) global use of biofuels.

2.4.3.1. GDP and household expenditure

Projections of GDP for individual countries can be taken either from the World Bank (World Bank, 2015), FAPRI-ISU (FAPRI, 2011), or from official projects by governments. Household expenditure (*HH*) is the final expenditure per household in PPP (US$2005) and is taken from (World Bank, 2013). It varies widely across the different segments of the income distribution. Therefore, the future household expenditure is further disaggregated into income quintiles and expressed as household expenditure per person (expenditure by quintile divided by the quintile population, i.e. 20% of the total population), following the method suggested by (Daioglou, 2010):

Eq. 1 $HHp_{r,Q} = IS_r \cdot IS_Q \cdot HH/(P_r/5)$

Where $HHp_{r,Q}$ is the household expenditure per person by region and quintile (US$2005/person), P_r is the population by region, IS_Q is the income share by quintile and IS_r is the income share by region. IS_Q and IS_r are derived following the method suggested by Daioglou and are shown in (Gonzalez-Salazar, et al., 2014c).

2.4.3.2. Population, urbanization and household size

Projections on population (*P*) and urbanization (*U*) are taken from the World Bank (World Bank, 2013). Urbanization (*U*) is defined as the fraction of urban to total population. The number of households in a country (*H*) is typically quantified in national census. The household size (*S)* is then estimated as:

Eq. 2 $S = H/P$

The household size represents the number of inhabitants per household, which varies significantly by region (rural vs. urban) and by household income. Allocation of household size by region (i.e. rural and urban) is estimated using the correlation proposed by (Daioglou, 2010):

Eq. 3 $S_u/S = 0.174078 \cdot (P_u/P) + 0.82592$

Where the subscript u represents the urban fraction. Next, the allocation of household sizes across quintiles is defined using the approach defined in (Daioglou, 2010). The floor size per person (*FS*) it is determined using a Gompertz curve defined by these equations (Daioglou, 2010):

Eq. 4 $$FS = \varphi \cdot e^{-1.341 \cdot e^{\left(\frac{-0.125}{1000}\right) \cdot HHp}}$$

Eq. 5 $$FS_{u,Q} = (0.28925 \cdot (P_u/P) + 0.71705) \cdot FS \cdot \left(1 + \left(0.131 \cdot (Q - 3)\right)\right)$$

Eq. 6 $$FS_{ru,Q} = \left[\frac{FS - \left((P_u/P) \cdot (0.28925 \cdot (P_u/P) + 0.71705) \cdot FS\right)}{1 - (P_u/P)}\right] \cdot \left(1 + \left(0.131 \cdot (Q - 3)\right)\right)$$

Eq. 7 $$\varphi = (-2.964 \cdot ln(D) + 60.577) \cdot \left(1 + \frac{0.125 * HHp}{35000}\right)$$

Where FS is the average floor space (m^2/person), $FS_{U,Q}$ and $FS_{ru,Q}$ are the urban and rural floor spaces by quintile, P is the population, D is the population density, *Q* is the quintile number, φ is a parameter of the Gompertz curve and subscripts *u, ru* and *Q* represent urban, rural and quintile, respectively.

2.4.3.3. Access to electricity, natural gas and biofuels

The access to electricity, natural gas and biofuels follows an evolutionary trend over the years that might be described by a Gompertz curve:

Eq. 8 $$E_{E,r,t} = \kappa_1 \cdot e^{-\kappa_2 \cdot e^{-\kappa_3 \cdot (t-1973)}}$$

Where $E_{E,r,t}$ is the access to energy services disaggregated by type of energy *E* (i.e. electricity, natural gas, biofuels) and by region *r* in year *t* and $\kappa_1, \kappa_2, \kappa_3$ are parameters of the Gompertz function. The parameters of the Gompertz function are estimated through a regression analysis. Disaggregation of the regional access to energy services by quintile in year *t* ($E_{E,r,t,Q}$) is estimated using the following equations, as suggested by (Daioglou, 2010):

Eq. 9 $$E_{E,r,t,Q} = E_{E,r,t} \cdot \left[1 + \nabla_{E,r,t} \cdot (Q - 3)\right]$$

Eq. 10 $$\nabla_{E,r,t} = 0.307 \cdot \left(\frac{E_{E,r,t}}{100} - 1\right)$$

Where *Q* are the different quintiles (i.e. 1, 2, 3, 4, 5), and $\nabla_{E,r,t}$ is a gradient to model the differences in access to energy services across quintiles. Note that when quintile is 3, the access to energy services $E_{E,r,t,3}$ is equal to the value $E_{E,r,t}$. For quintiles with higher expenditure than Q3 (i.e. Q>3), the expected access to energy services is $E_{E,r,t,Q} \geq E_{E,r,t}$. Likewise, for quintiles with lower expenditure than Q3 (i.e. Q<3), the expected access to energy services is $E_{E,r,t,Q} \leq E_{E,r,t}$.

2.4.3.4. Capital and operational cost of technologies

Current and projected capital and operational cost of technologies are taken from various sources including among others: the U.S. Energy Information Administration –EIA– (Morrison, 2012), the International Energy Agency –IEA– (IEA, 2012a), the Nuclear Energy Agency –NEA– (IEA-NEA, 2010) as well as process simulation tools (Thermoflow, 2011).

2.4.3.5. Prices of energy resources

Projections on prices of energy resources are also taken from a variety of sources including: EIA (EIA, 2011), IEA (IEA, 2012c) and the UK Department of Energy & Climate Change (DECC, 2011).

2.4.3.6. Price of commodities (agricultural and forest)

Price of commodities are taken from FAO/IIASA (Fischer, 2011), the World Bank (World Bank, 2012) and FAPRI-ISU (FAPRI, 2011).

2.4.3.7. Global use of biofuels

Projections on global use of biofuels and their influence on agricultural prices, production and demand are taken from FAO/IIASA (Fischer, 2011).

2.5. Land Use and Trade Model (LUTM)

A land use and trade model (LUTM) was developed to estimate the land requirements necessary to accomplish long-term targets identified in technology roadmapping. The modeling method used in the LUTM model is shown in Figure 4, details can be found in (Gonzalez-Salazar, et al., 2014b). For the sake of brevity, the LUTM model is not discussed in this paper. This model estimates land allocation as well as production, imports and exports of 18 agricultural and forestry commodities during the period 2015-2030. The model is built under the assumption that the fundamental driver of land use and trade is the maximization of the profit perceived by local actors (i.e. local producers and importers). Competition is considered at three levels: food vs. biofuels, residues for energy vs. other uses and local production vs. imports. Main inputs of the model include the assumptions from scenarios, demand for agricultural commodities, local biofuel polices, yields, local and international prices and macroeconomic variables. The LUTM model is built in Microsoft Excel and uses the Generalized Reduced Gradient (GRG) nonlinear algorithm to perform the optimization.

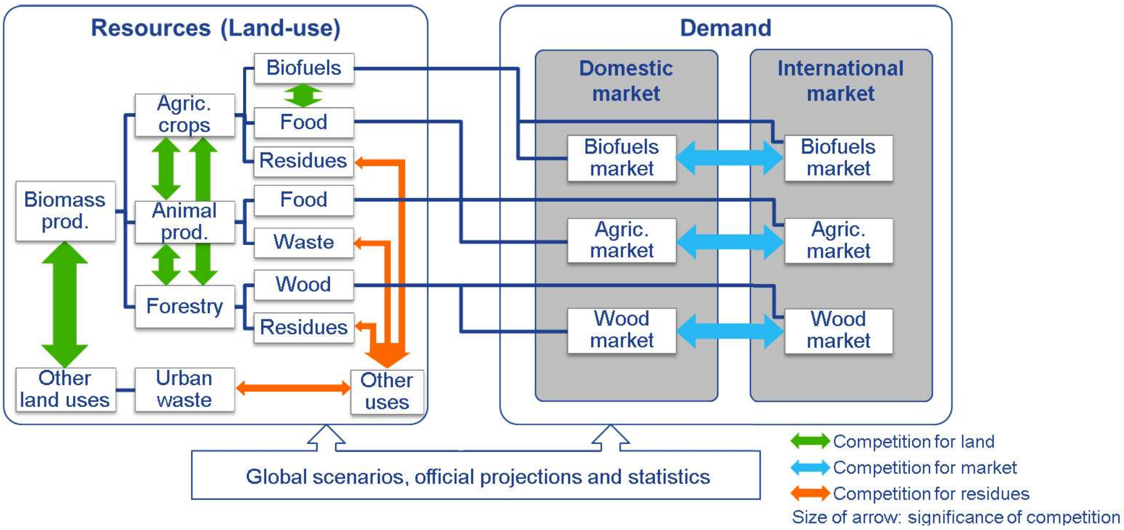

Figure 4. *Modeling method of the LUTM model*

The ESM and the LUTM models influence each other and work in parallel in a process of 3 steps. In a first step, the local demand for biofuels (e.g. bioethanol, biodiesel, renewable diesel, etc.) and other biomass resources (biogas, biomethane, wood, etc.) is estimated in the ESM model and then exported to the LUTM model. In a second step, the LUTM model optimizes the production and trade of biofuels, woodfuel and other commodities and estimate feedstocks and required land. In a third step, the outputs of the LUTM model are used as a feedback loop in the ESM model to estimate the conversion of residual biomass into energy.

2.6. Limitations

The proposed framework presents some limitations that are acknowledged. It focuses only on the quantification and analysis of the impacts that implementing various bioenergy policies might cause on the energy supply and demand, energy-related GHG emissions and land use at a country level. A complete analysis of the social (i.e. job creation, improvement of the Human Development Index, etc.), environmental (i.e. life cycle GHG emissions, water footprint, impact on biodiversity, etc.) and economic impacts of implementing such policies is not covered in this paper and is recommended for further investigation.

3. Energy System Model (ESM)

The energy system model (ESM) is a data-intensive, scenario-based, demand-driven model that combines various techniques to comprehensively replicate the behavior of the energy system at a country level. Since one of the premises to build the model was to have the highest possible accuracy in estimations, bottom-up approaches are employed as much as possible, accordingly to guidelines from earlier references (Bhattacharyya, 2011; Connolly, Lund, Mathiesen, & Leahy, 2010). The model has been built on the Long-range Energy Alternatives Planning System (LEAP) (Heaps, 2012), a platform is widely used to report energy policy analysis and GHG mitigation assessments and free for users in developing countries (Connolly, Lund, Mathiesen, & Leahy, 2010). Two main sides represent the energy system in the model: 1) the demand side, in which the country's economy is divided into sectors (e.g. residential, industrial, transport, etc.) and 2) the supply side, in which conversion technologies and losses are considered (see Figure 5). For each side, the model calculates energy flows, required capacities, emissions and costs.

3.1. General assumptions

While different sectors on the demand side are modeled with different approaches, they are connected on the macroeconomic scale. Assumptions on future population, growth in domestic product (GDP), energy prices, climate conditions and availability of land, do not change across scenarios and are exogenously added. GHG emissions associated with the direct combustion of fuels in each branch of the demand and the supply sides of the model are accounted using IPCC guidelines included in LEAP. Indirect emissions associated with transport, exposure, dose/response effects, but also land-use change, cultivation, irrigation, etc. are not considered. According to IPCC guidelines, biogenic CO_2 emissions (produced by burning biomass resources) are estimated but not accounted as emissions of the 'energy sector', because they are considered emissions of the 'land use, land-use change and forestry' (LULUCF) sector.

3.2. Modeling techniques

The ESM model, sketched in Figure 6, is demand-driven, i.e. the demand for energy is firstly calculated on the demand side and then estimated on the supply side. Thus, a stronger focus has been given in this paper to describe how the energy demand is estimated. In this regard, bottom-up techniques are considered for the residential, road transport and agricultural sectors, where typically bioenergy is mostly used. Bottom-up techniques combine the use of economic variables (e.g. GDP, population, energy prices, income, etc.) and engineering variables (e.g. technologies, efficiencies, specific energy consumption, etc.) to estimate final energy demand. Bottom-up techniques used on the demand side include a comprehensive dynamic engineering-economy module of the residential sector, a stock-turnover-economic analysis of the road transport sector and an engineering module of the agriculture sector. In contrast, a less sophisticated top-down technique is used for other sectors not strongly linked to bioenergy such as commercial, industrial, non-road transport, etc. This top-down approach relies on econometrics to estimate the aggregate final demand by fuel and by sector as a function of key economic drivers (e.g. GDP, energy prices, etc.). The main advantage of using bottom-up techniques for sectors strongly linked to bioenergy and top-down techniques for other sectors is its simplicity. However, it is important to note that this approach reduces the degree of accuracy in estimation for sectors not strongly linked to bioenergy. There are two main reasons for this (Bhattacharyya, 2011): a) econometrics are not able to link the demand to the technology, policy or consumer habits and b) econometrics rely heavily on past trends to determine future demand, which might lead to poor forecasts. On the supply side, a techno-economic approach was used to calculate energy production, capacity requirements by technology, losses and demand for resources. Efficiencies and cost of conversion technologies were collected from several sources available in the literature and incorporated into the model. The competition between multiple technologies is simulated with an optimization approach.

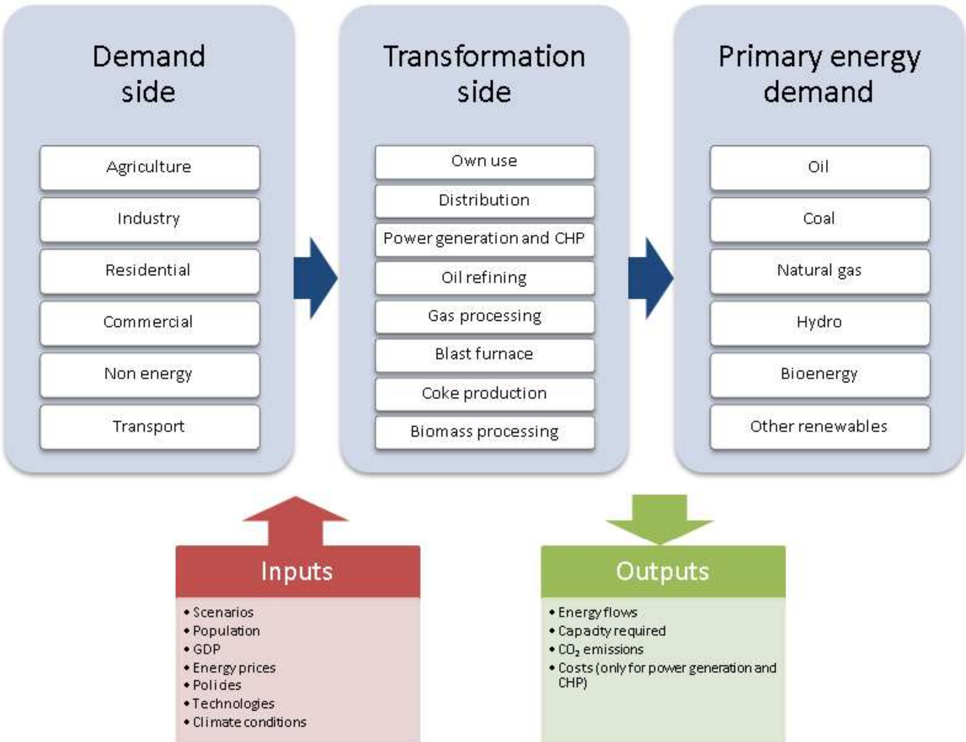

Figure 5. *Outlook of the energy system model (ESM)*

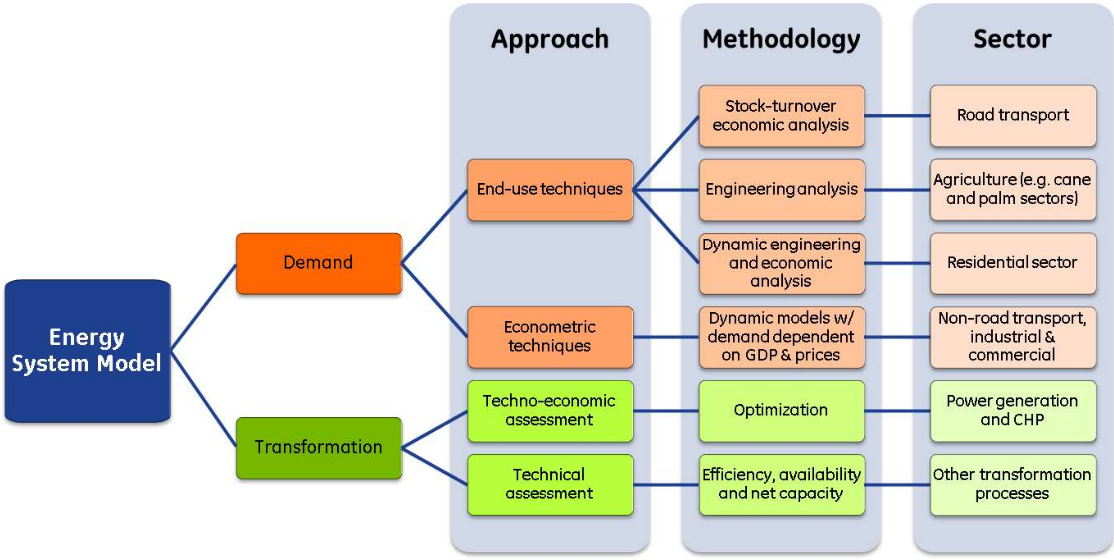

Figure 6. *Summary of the employed modeling techniques in the ESM model*

3.3. Model of the demand side

The model of the demand side is divided into four main sub-models: 1) road transport, 2) agricultural industries, 3) residential sector and 4) non-road transport, industrial and commercial sectors. A more detailed description of these sub-models is presented as follows.

3.3.1. Road transport

The energy demand of road transport and its associated emissions are estimated using a stock-turnover economic analysis consisting of four steps, as shown in Figure 7.

3.3.1.1. First step: estimate vehicle ownership

Models representing the future vehicle ownership as a function of economic and social data are defined. For vehicles with at least four wheels, the model proposed by (Dargay, Gately, & Sommer, 2007), which relates the future vehicle ownership to historical data, GDP per capita, density and urbanization is used. This model is a long-term dynamic S-shaped curve (Gompertz function), in which vehicle ownership growth is slow at the lowest income, then it rapidly increases as income rises and then it reaches a saturation level. The model is defined by next equation:

Eq. 11 $V_t = (\psi_{MAX} + \lambda D_t + \varphi U_t) \cdot (\theta_R R_t + \theta_F A_t) \cdot e^{\alpha e^{\beta GDPp_t}} + (1 - \theta_R R_t + \theta_F A_t) \cdot V_{t-1} + \varepsilon_t$

Where V_t is the actual vehicle ownership (vehicles per 1000 people), $GDPp_t$ is the gross domestic product per capita (in purchasing power parity), ψ_{MAX} is the saturation level, D_t is the population density, U_t is the urban franction of population, λ and φ are negative constants, R_t and A_t are dummy variables, θ_R and θ_F are speeds of adjustment for periods of rising and falling income ($0 \leq \theta \leq 1$), α and β are parameters of the Gompertz function, subscript t represents the year and ε_t its random error term.

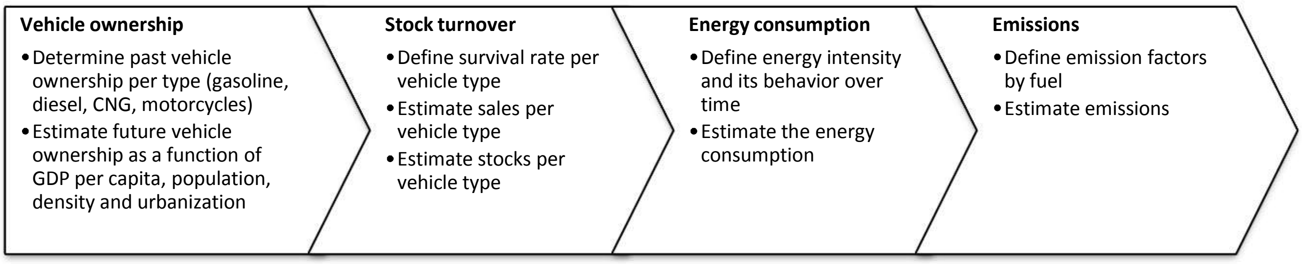

Figure 7. *Process to estimate energy demand of road transport*

While this model describes ownership for at least four-wheeled vehicles, it does not further disaggregate data by vehicle type (e.g. trucks, vans, sport utility vehicles, light vehicles, etc.). Therefore, a logit function is used to estimate the share of each vehicle type per year as shown in the following equation:

Eq. 12 $SH_{c,t} = \frac{\left[{}^{1}/_{k_c F_{c,t}}\right]^{\gamma}}{\sum_c \left[{}^{1}/_{k_c F_{c,t}}\right]^{\gamma}} \cdot \theta + (1-\theta) \cdot SH_{c,t-1}$

Eq. 13 $\sum_c SH_{c,t} = 1$

In this equation, $SH_{c,t}$ is the share of each vehicle type per year ($0 \leq SH_{c,t} \leq 1$), $F_{c,t}$ is the fuel cost required for each vehicle type to drive 100 km (US$2005/100 km), k_c is a cost exponent, γ is the cost sensitivity coefficient, θ is the speed of adjustment ($0 \leq \theta \leq 1$), and subscripts *c* and *t* are respectively vehicle type and year. $F_{c,t}$ is estimated as the fuel cost per year (US$2005/MJ) for the different vehicle types multiplied by the fuel economy (MJ/100 km, see Table 5).

For motorcycles, a simplified version of the model proposed by (Dargay, Gately, & Sommer, 2007) is used. This model is a long-term dynamic S-shaped curve, in which future ownership is a function of historical ownership and GDP per capita:

Eq. 14 $M_t = \psi_{MAX} \cdot \theta e^{\alpha e^{\beta GDPp_t}} + (1-\theta) \cdot M_{t-1}$

Where M_t is the actual motorcycle ownership (motorcycles per 1000 people) in year *t* and the other parameters have been defined above. These parameters are estimated using a regression analysis to best fit the historical data and are shown in Table 4.

3.3.1.2. Second step: estimate stock turnover

In a second step, a detailed stock turnover analysis is performed. For this purpose, the stock analysis in LEAP is employed to estimate the retired, legacy and new vehicles for the different types of vehicles (gasoline, diesel, motorcycles, etc.) by year (Heaps, 2012):

Eq. 15 $Stock_t = V_t \cdot P_t = \sum_c Stock_{c,t}$

Eq. 16 $Stock_{c,t} = Sales_{c,t} + \sum_v Stock_{c,t,v}$

Eq. 17 $Stock_{c,t,v} = Sales_{c,v} \cdot Sur_{c,t-v}$

In these equations, $Stock_t$ is the actual number of vehicles in year *t*, which is equal to the actual vehicle ownership V_t times the population P_t. $Stock_t$ is also equivalent to the sum of vehicles of the different types *c* in year *t* ($Stock_{c,t}$). $Stock_{c,t}$ is then estimated as the sum of the sales of vehicles of type *c* in year *t* ($Sales_{c,t}$) and the summation of the number of legacy vehicles of the same type *c* produced in different years *v* and surviving in year *t* ($Stock_{c,t,v}$). In turn, $Stock_{c,t,v}$ is estimated as the multiplication of the sales of vehicles of type *c* produced in year *v* by the rate of these vehicles still surviving in year *t* ($Sur_{c,t-v}$).

3.3.1.3. Third step: estimate energy consumption

In a third step the overall energy consumption per vehicle type are estimated using the following equation:

Eq. 18 $ECV_{c,t,f} = \mu_{c,t,f} \cdot \sum_v \left(Stock_{c,t,v} \cdot FE_{c,v} \cdot Deg_{c,t-v} \cdot Mil_{c,t,v}\right)$

Where $ECV_{c,t,f}$ is the energy consumption per vehicle type per year disaggregated by type of fuel; $FE_{c,v}$ (MJ/100 km) is the fuel economy per vehicle type for a new vehicle; $Deg_{c,t-v}$ is a degradation factor representing the change in fuel economy as a vehicle ages; $Mil_{c,t,v}$ is the mileage (km/vehicle); $EC_{c,t,f}$ (MJ) is the energy consumption per vehicle type per year disaggregated by type of fuel and $\mu_{c,t,f}$ is the share of the energy consumption by fuel type.

It is assumed that the fuel economy is proportional to the fuel's lower heating value (MJ/l) and that biofuels do not affect it. While biofuels might offer certain advantages than counterparts (e.g. higher octane rating for bioethanol and higher lubricity and cetane number for biodiesel), significant modifications of the engine are required to exploit these advantages. As technologies for modifying the engine are not considered in this study, it is assumed that biofuels do not impact fuel economy. Finally, the share of the energy consumption by fuel type $\mu_{c,t,f}$ is calculated. The fuel shares associated with the two types of fuels that can be used in vehicles, e.g. biofuels and fossil fuels, are here treated as $\mu_{c,t,bio}$ and $\mu_{c,t,fossil}$ respectively. The fuel share of biofuel in a type of vehicle *c* in year *t* ($\mu_{c,t,bio}$) is calculated as a function of the blend mandate ($BMV_{c,t,bio}$), the lower heating value of the biofuel in MJ/liter (LHV_{bio}), the lower heating value of the counterpart fossil fuel in MJ/liter (LHV_{fossil}) and the supply coverage of biofuel at a national level ($Cov_{t,bio}$).

Eq. 19 $\mu_{c,t,bio} = \left(BMV_{c,t,bio} \cdot \frac{LHV_{bio}}{LHV_{t,blend}}\right) \cdot Cov_{t,bio}$

Eq. 20 $LHV_{t,blend} = \left(BMV_{c,t,bio} \cdot LHV_{bio}\right) + \left(1 - BMV_{c,t,bio}\right) \cdot LHV_{fossil}$

Eq. 21 $\mu_{c,t,fossil} = 1 - \mu_{c,t,bio}$

3.3.1.4. Fourth step: estimate emissions

The fourth step is estimating the greenhouse gas emissions through the following equation:

Eq. 22 $GHG_{c,t,v,p} = EC_{c,t,v} \cdot EF_{c,t,p} \cdot Deg_{c,t-v,p}$

Where $GHG_{c,t,v,p}$ (ton CO_2-eq.) are the emissions by pollutant for the different vehicle types, vintage and year, $EF_{c,t,p}$ is the emission factor by pollutant (kg/TJ) and $Deg_{c,t-v,p}$ is a degradation factor representing the change in emissions as a vehicle ages. Pollutants analyzed in this study include CO_2, CO, CH_4, NMVOC, NOx, N_2O and SO_2.

For combustion of biofuels, emission factors are estimated using the following equation (TNO, 2009):

Eq. 23 $EF_{bio,p} = EF_{fossil,p} \cdot MEF_{bio,p}$

Where $EF_{bio,p}$ is the emission factor for biofuels by pollutant, $EF_{fossil,p}$ is the emission factor for counterpart fossil fuel and $MEF_{bio,p}$ is a multiplying emission factor for biofuels. $MEF_{bio,p}$ for vehicles using 100% biofuels is shown in Table 1. Then, for biofuel blends the emissions are proportional to the biofuel energy content in the blend. Further, it is assumed that the CO_2 emissions produced during combustion of biofuels are biogenic (EPA, 2008).

Table 1. *Multiplying emission factors for biofuels (TNO, 2009)*

Pollutant	Gasoline vehicles and motorcycles using 100% bioethanol	Diesel vehicles using 100% biodiesel
NOx	1.28	1.3
PM	1.35	0.43
HC	1	0.46
CO	1	0.81

3.3.2. Residential sector

The energy demand of the residential sector and its associated emissions are estimated using a bottom-up dynamic model consisting of four steps (see Figure 8), partly based on the method proposed in (Daioglou, 2010). It uses five exogenous primary drivers (e.g. population, household expenditure, population density, household size and ambient temperature) to determine five energy demand uses (e.g. cooking, appliances, water heating, space heating/cooling and lighting).

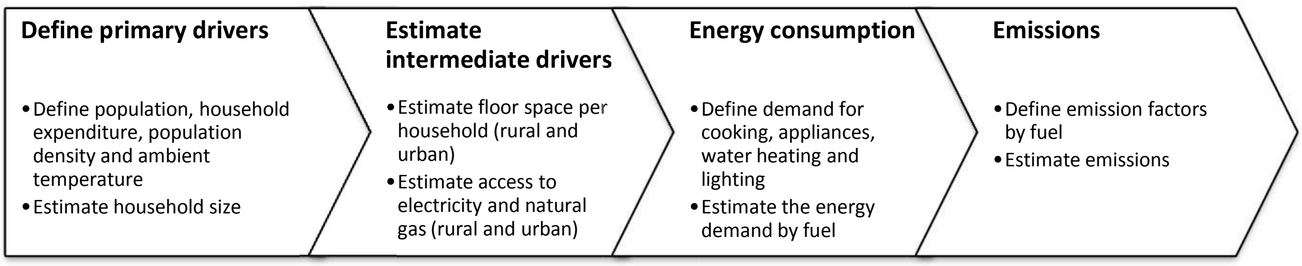

Figure 8. *Method process to estimate energy demand of residential sector*

3.3.2.1. First step: define primary drivers

Primary drivers include: population (*P*), population density (*PD*), ambient temperature (*T*), household expenditure (*HH*) and household size (*S*). Population, population density, household expenditure and household size are defined in the economic model (see Section 2.4.3). Finally, the ambient temperature is expressed in average heating degree days (HDD).

3.3.2.2. Second step: estimate intermediate drivers

In a second step, intermediate drivers are estimated. Intermediate drivers include floor space per person (*FS*) and access to electricity and natural gas (*E*). Both drivers are taken from the economic model shown in Section 2.4.3.

3.3.2.3. Third step: estimate energy consumption

In a third step, the demand for cooking, appliances, water heating, space cooling and lighting as well as the energy demand by fuel are estimated.

Water heating: it is modeled as a Gompertz curve dependent on income, following the method developed by Daioglou. For the particular case of water heating, the demand is not disaggregated by region and quintile and is rather estimated for the entire country.

Eq. 24 $ECWp = (0.003 \cdot HDD + 2.756) \cdot OD \cdot e^{-\kappa_4 \cdot e^{-\kappa_5 \cdot HHp}}$

Where *ECWp* is the energy consumption for water heating per capita (MJ_{UE}/person/year), *HDD* is the heating degree days, HHp is the household expenditure per capita (US$2005/person), *OD* are the annual number of days demanding hot water and κ_4, κ_5 are parameters of the Gompertz function.

Appliances: Demand for energy associated with appliances is modeled for three categories: refrigeration, air conditioning and other appliances. Models are based on ownership and energy use per appliance. The appliance ownership is defined by the general equation:

Eq. 25 $OW_{a,r,Q} = \psi_a \cdot e^{-\kappa_6 \cdot e^{-(\kappa_7/1000) \cdot HHp_r}}$

Where $OW_{a,r,Q}$ is the ownership by appliance, region and quintile (units/household), ψ_a is the saturation level by appliance (units/household), HHp_r is the household expenditure per capita by region (US$2005/person), κ_6, κ_7 are parameters of the Gompertz function and the subscript *a* represents the type of appliance. The unit energy consumption of appliances is defined by the general equation:

Eq. 26 $UEC_a = \vartheta_a \cdot \zeta_a^{(t-1971)} + UEC_{MAX,a}$

Where UEC_a is the unit energy consumption by type of appliance (kWh/year), $UEC_{MAX,a}$ is an assumed limit to UEC_a and ϑ_a, ζ_a are coefficients that influence the unit energy consumption over the years. Finally, the overall energy consumption for appliances (ECA_a) and the overall energy consumption for appliances per capita ($ECAp_a$) are estimated through the following equations:

Eq. 27 $ECA_a = \sum_r \sum_Q \left(OW_{a,r,Q} \cdot UEC_a \cdot H_{r,Q}\right)$
Eq. 28 $ECAp_a = \frac{1}{P} \cdot \left(\sum_r \sum_Q \left(OW_{a,r,Q} \cdot UEC_a \cdot H_{r,Q}\right)\right)$

Details on the application of this method to the categories of refrigeration, air conditioning and other appliances generally follow the guidelines provided by (Daioglou, 2010) but for the sake of brevity are not shown here.

Lighting: Energy demand for lighting is modeled through the following equation proposed by Daioglou:

Eq. 29 $ECLH_{r,Q} = 0.68 \cdot FS_{r,Q} \cdot W \cdot LHF_r$

Where $ECLH_{r,Q}$ is the annual energy consumption of lighting per household by region and quintile (kWh/household), $FS_{r,Q}$ is the floor space per person, W is the unit energy consumption per light bulb and LHF_r is a lighting hours factor coefficient. In addition, the overall annual energy consumption for lighting (ECL) and the annual energy consumption for lighting per capita ($ECLp$) are estimated through the following equations:

Eq. 30 $ECL = \sum_r \sum_Q \left(ECLH_{r,Q} \cdot H_{r,Q} \cdot E_{El,r,Q}\right)$
Eq. 31 $ECLp = \frac{1}{P} \cdot \left(\sum_r \sum_Q \left(ECLH_{r,Q} \cdot H_{r,Q} \cdot E_{El,r,Q}\right)\right)$

Where $E_{El,r,Q}$ is the access to electricity by region and quintile and $H_{r,Q}$ is the number of households by region and quintile.

__Cooking:__ The energy demand per capita for cooking is assumed to be 3 MJ of useful energy per person per day, which is the suggested value in (Daioglou, 2010).

3.3.2.4. Fourth step: estimate emissions

The fourth step relates to the definition of emission factor and the estimation of total emissions. Generally, the method to estimate emissions is the same as that used for road transport. The emission factors by pollutant are taken from the LEAP database. Further, it is assumed that the CO_2 emissions produced during combustion of biomass resources are biogenic.

3.3.3. Agricultural industries

Demand for energy in agricultural industries is estimated as the product of the activity level by sector and the annual energy intensity by sector:

Eq. 32 $ECCI_{I,E,t} = AL_{I,t} \cdot EI_E$

Where $ECCI_{I,E,t}$ is demand for type of energy *E* (i.e. electricity and heat) in industry *I* (e.g. cane and palm industries) in year *t*; $AL_{I,t}$ is the activity level in industry *I* in year *t*, i.e. the total amount of locally produced commodities (e.g. sugar, palm oil and jaggery). The local production of these commodities is estimated through the LUTM model. On the other hand, EI_E is the energy intensity by type of energy, i.e. the demand of energy per unit of activity.

3.3.4. Non-road transport, industrial and commercial sectors

Econometric methods were used to estimate the aggregate final energy demand by fuel as a function of key drivers (e.g. sectorial GDP, energy prices, etc.) in non-road transport, industrial and commercial sectors. Econometric methods were used mainly because data was not readily available and not substantially affected by changes in bioenergy technologies. The final energy demand by fuel is estimated using the following equation:

Eq. 33 $ECF_{f,t,s} = e^{\left[\theta\cdot\left(\xi_1\cdot ln\left(F_{f,t}\right)+\xi_2\cdot ln\left(GDP_{t,s}\right)\right)+\left((1-\theta)\cdot ECF_{f,t-1,s}\right)\right]}$

Where $ECF_{f,t,s}$ is the energy consumption of fuel *f* by sector *s* in year *t*, ξ_1 and ξ_2 are coefficients of the equation, $F_{f,t}$ is fuel cost, $GDP_{t,s}$ is the sectorial gross domestic in year *t* (billion US$2005, PPP) and θ is the speed of adjustment. Coefficients ξ_1 and ξ_2 and speed of adjustment θ are calibrated through regression analysis to best fit historical data.

3.4. Model of the supply side

The model of energy transformation processes is divided into two main sub-models: 1) power generation and 2) other energy transformation processes.

3.4.1. Power generation

Power generation is modeled through an optimization algorithm which orders dispatch and capacity addition to minimize the net present value of lifetime total costs of the system (i.e. capital costs, operating costs, fuel costs, decommissioning, etc.). Optionally, the optimization algorithm can be configured to meet a renewable power target. The method to analyze power generation consists of four steps (see Figure 9).

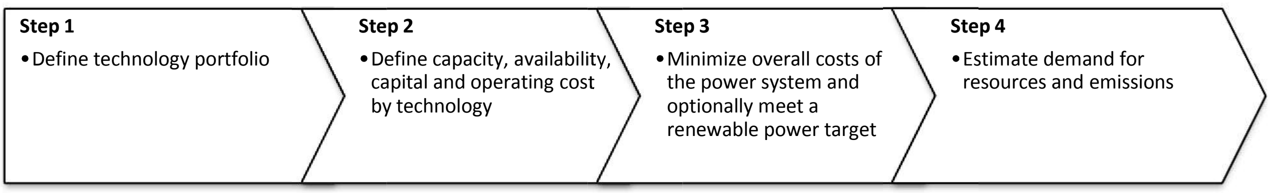

Figure 9. *Method to analyze power generation*

3.4.1.1. First step: define technology portfolio

In a first step, a technology portfolio is defined. The technology portfolio consists of two main groups: traditional technologies and new technologies. Traditional technologies are those used today (e.g. hydropower, gas turbines, coal power plants, etc.), while new technologies are those expected to become available in the future in a particular country.

3.4.1.2. Second step: define performance characteristics and costs

In a second step the capacity, availability, efficiency, capital and operating cost and other characteristics of the different technologies are collected from several sources (IEA-NEA, 2010; Thermoflow, 2011; IEA, 2012a; EIA, 2014), among others.

3.4.1.3. Third step: perform optimization

In a third step, an optimization algorithm calculates the least cost capacity expansion and dispatch required to meet a minimum planning reserve margin and optionally a renewable power target. The optimization algorithm minimizes the net present value of the lifetime total costs of the system. For this purpose the Open Source Energy Modeling System (OSeMOSYS) algorithm incorporated into LEAP is used. The total costs of the system include capital, operation & maintenance, fuel and decommissioning costs. The objective function, taken from (Howells, 2009), is defined as:

Eq. 34 $Min\ DC = \sum_t \sum_g \left[\left(I_{g,t} + OM_{g,t} + F_{g,t} + DE_{g,t} \right) \cdot (1+r)^{-t} \right]$

Where $I_{g,t}$ is the investment cost for technology type *g* in year *t* (US\$2009/kW), $OM_{g,t}$ is the operation and maintenance costs (US\$2009/kW), $F_{g,t}$ is the fuel cost (US\$2009/MMBtu), $DE_{g,t}$ is the cost for decommissioning a power plant and *r* is the discount rate. A mandatory constraint and an optional constraint are associated with this optimization problem. The mandatory constraint ensures that a minimum planning reserve margin (*RM*) is met. The optional constraint ensures that for particular scenarios an optional renewable power target is met. The planning reserve margin is defined as:

Eq. 35 $RM_t = \frac{(\sum_g C_{g,t} \cdot CC_{g,t}) - PL_t}{PL_t}$

Where RM_t is the planning reserve margin in year *t*, $C_{g,t}$ is the installed capacity by technology (MW) in year *t*, $CC_{g,t}$ is the capacity credit by technology, i.e. the amount of firm conventional generation capacity that can be replaced by renewable power ($0 \leq CC_{g,t} \leq 100\%$) and PL_t is the power peak demand throughout the year (IEA, 2012b).

Additional variables required to perform the optimization include a) exogenous capacity additions and b) maximum annual capacity and capacity addition by technology. Exogenous capacity additions reflect planned capacity additions and retirements and are exogenously entered into LEAP. The maximum annual capacity addition is estimated on a technology by technology basis and is also exogenously entered into LEAP.

3.4.1.4. Fourth step: estimate emissions

In a fourth step, the demand for energy resources and the generated emissions by technology are estimated. The demand for resources is estimated through the following equations:

Eq. 36 $ECP_{g,f,t} = \sum_{d=0}^{365} \frac{PG_{g,f,t,d}}{\eta_{g,f,t,d}}$

Where $ECP_{g,f,t}$ is the annual demand for fuel *f* by technology *g* in year *t*, $PG_{g,f,t,d}$ and $\eta_{g,f,t,d}$ are the power generated and the efficiency of technology *g* in day *d* of year *t*, respectively. Efficiency is assumed to be constant over the days and the years ($\eta_{g,f,t,d} = \eta_g$). Finally, the greenhouse gas emissions are calculated using this equation:

Eq. 37 $GHG_{g,f,t,p} = PG_{g,f,t} \cdot EF_{g,f,t,p}$

Where $GHG_{g,f,t,p}$ (Tons of CO_2 equivalent) are the annual emissions of pollutant *p* in year *t* created by power technology *g* by combusting fuel *f*. $EF_{g,f,t,p}$ is the emission factor by pollutant associated with combustion of fuel *f* in power technology *g* (kg/TJ) and $PG_{g,f,t}$ is the annual power generation by technology disaggregated by fuel and year. Pollutants analyzed in power generation include CO_2, CO, CH_4 and NOx. The emission factors by pollutant are taken from the LEAP database. Detailed characteristics of all fuels used in the power generation module are shown in (IEA, 2012b). It is assumed that the CO_2 emissions produced during combustion of biomass resources in power generation are biogenic. It is also assumed that no GHG emissions are generated by wind and hydro power technologies.

Further, it is assumed that there are four effects by burning landfill gas or biogas, see following equations:

Eq. 38 $GHG_{(lg,bg),p} = GHG_{(lg,bg),CO2a} + GHG_{(lg,bg),CO2b} + GHG_{(lg,bg),CH4} + GHG_{(lg,bg),Other}$

Eq. 39 $GHG_{(lg,bg),CO2a} = x_{(lg,bg),CO2} \cdot 1\ kg_{(lg,bg)}$

Eq. 40 $GHG_{(lg,bg),CO2b} = EF_{(lg,bg),CO2} \cdot PG_{(1kg:\ lg,bg)}$

Eq. 41 $GHG_{(lg,bg),CH4} = -x_{(lg,bg),CH4} \cdot 1\ kg_{(lg,bg)}$

Eq. 42 $GHG_{(lg,bg),Other} = \sum_{Other}\left(EF_{(lg,bg),Other} \cdot PG_{(1\ kg:\ lg,bg)}\right)$

Where $GHG_{(lg,bg),p}$ are the greenhouse gas emissions associated with burning 1 kg of landfill gas or biogas for power generation. The first effect relates to the emission of biogenic CO_2 not produced during the combustion of landfill gas or biogas ($GHG_{(lg,bg),CO2a}$). CO_2 already contained in these fuels is not produced during combustion and is subsequently emitted. This first effect is calculated as the mass content of CO_2 in landfill gas or biogas ($x_{(lg,bg),CO2}$) per kilogram of landfill gas or biogas combusted ($1\ kg_{(lg,bg)}$). The second effect relates to the emission of biogenic CO_2 by burning the combustible material, e.g. hydrogen, hydrocarbons, CO, etc., contained in landfill gas or biogas ($GHG_{(lg,bg),CO2b}$). The second effect is calculated as the emission factor of CO_2 for power generation ($EF_{(lg,bg),CO2}$) multiplied by the power generated with 1 kg of landfill gas or biogas ($PG_{(1kg:\ lg,bg)}$). The third effect relates to the reduction in methane emissions that otherwise would be released into the atmosphere by not using these resources ($GHG_{(lg,bg),CH4}$). This reduction is calculated as the mass content of methane in the landfill gas or biogas per kilogram of landfill gas or biogas combusted. The avoidance of methane emission is therefore treated here as a credit, i.e. a 'negative' emission following the method suggested in (den Boer, den Boer, & Jager, 2005). The fourth effect relates to the emission of other pollutants, e.g. CO and NOx, by burning the landfill gas or biogas ($GHG_{(lg,bg),Other}$). The fourth effect is calculated as the summation of the individual emissions of other pollutants. These individual emissions are calculated as the emission factors of these pollutants for power generation ($EF_{(lg,bg),Other}$) multiplied by the power generated with 1 kg of landfill gas or biogas ($PG_{(1kg:\ lg,bg)}$). In summary, burning biogas or landfill gas in power plants would: a) generate biogenic CO_2 emissions proportional to carbon content in the fuel, b) generate biogenic CO_2 emissions as well as NOx and CO by burning the fuels and c) avoid methane emissions proportional to the CH_4 content, which for accounting purposes are treated as negative methane emissions.

3.4.2. Other conversion processes

Other conversion processes are modeled on a case-by-case basis. Some conversion processes are not modeled in depth and are rather calculated and calibrated using general official data (e.g. natural gas works, reinjection and flaring, oil refining, coke factories, blast furnace, charcoal production, own use and energy distribution). For the sake of brevity this data is not included in this paper. Some other processes are analyzed in more detail using data from technical reports and various sources: palm oil mill and production of biodiesel, biomass gasification, wood pelletization, production of renewable diesel, biomethane production and heat production in biomass boilers.

3.4.2.1. Cane mill, sugar and bioethanol production

In the sugar cane mill, the cane is crushed and cane juice, bagasse, tops and leaves are extracted. Tops and leaves are actually left on the field for soil replenishment. The mill is mechanically driven by steam turbines fed with steam produced in bagasse-fuelled boilers. Three independent routes are considered for the co-production of sugar and bioethanol from cane juice. In the first route only sugar is produced from molasses in a sugar factory. In the second route, sugar and bioethanol are co-produced in a sugar factory with an annexed distillery. In the third route, only bioethanol is produced by directly converting cane juice into bioethanol via fermentation, distillation and dehydration, but without co-producing sugar. The fraction of cane juice allocated to each of the three routes is estimated through the LUTM model.

3.4.2.2. Palm oil mill and biodiesel production plant

In the palm oil extraction mill, the fresh fruit bunches of the palm are crushed producing palm oil and residues. Part of the residues (e.g. fiber, stone) is commonly used as fuel in steam boilers to provide heating, while other part of the residues (e.g. rachis) is commonly returned to the field for soil replenishment. The process to convert palm oil into biodiesel consists of oil refining, transesterification and biodiesel purification steps. Similarly to the case of bioethanol, the production, imports and exports of biodiesel are estimated through the LUTM model.

3.4.2.3. Gasification of wood and biomass residues

Biomass gasification is a thermochemical process to convert biomass resources into a gas mixture called syngas and containing H_2, CO_2 and CO. Syngas is used in other conversion processes, including syngas co-firing in gas turbine simple and combined cycles, heat production in boilers and biomethane production. Two gasification processes are considered, one using wood and other using other biomass residues (e.g. rice husk, cane leaves and tops, bagasse and palm residues, etc.) as feedstocks. For wood gasification it is considered a MILENA gasifier, a twin-bed gasifier with a circulating fluidized bed as gasifier and bubbling fluidized bed as combustor (Morrison, 2012). For gasification of biomass residues it is considered a SilvaGas gasifier, a commercially available technology proven on large scale (up to 40 MW) consisting of two circulating fluidized beds with sand as heat carrier (Risø DTU, 2010). This gasifier can also be fed with a wide variety of feedstocks, which makes it appropriate for gasification of biomass residues. Technical assumptions for both gasifiers are shown in (Gonzalez-Salazar, et al., 2014c).

3.4.2.4. Wood pelletization (as pre-treatment in co-firing with coal)

Wood pelletization is a process to convert wood into pellets via milling and mechanical compression. It is a process that demands electricity and that is required for other processes such as biomass co-firing in a coal power plant. Wood pellets have higher energy content than wood and are easier to handle, which facilitates its use in coal power plants. Technical characteristics of the wood pelletization process are shown in (Gonzalez-Salazar, et al., 2014c).

3.4.2.5. Renewable diesel production

Renewable diesel is produced by hydrotreating of vegetable oils using palm oil as feedstock. In this process, hydrogen is used to remove oxygen from the triglyceride vegetable oil molecules and to split them into three separate chains, which are similar to diesel fuel components (NESTE OIL, 2014). The process consumes palm oil, electricity, heat and natural gas and produces renewable diesel, renewable gasoline and renewable propane. Emissions associated with the renewable diesel conversion process include biogenic CO_2 (1.0884 Ton/TJ-renewable diesel), non-biogenic CO_2, CO, CH_4, NMVOC and NOx for burning natural gas as well as avoided non-biogenic emissions (emission credits) by substituting renewable fuel products (i.e. renewable diesel, renewable gasoline and renewable LPG) for fossil fuels. Characteristics of the process are summarized in (Gonzalez-Salazar, et al., 2014c).

3.4.2.6. Biomethane production

Biomethane is produced through two different conversion processes: methanation and biogas gas upgrading. Methanation is a catalyst-based exothermic process in which syngas is converted into a gas stream containing mainly methane. It is chemically described by the balance $CO + 3H_2 \rightarrow CH_4 + H_2O$. If syngas from wood is used (using a MILENA gasifier), it is then converted into biomethane in a HaldorTopsøe's TREMP® methanation process. The TREMP® methanation process is a custom-made commercially available technology using three step reactors with heat recovery from exothermic reactions. If syngas from biomass residues is used (using a SilvaGas gasifier), it is then converted into biomethane in a PSI/CTU methanation system. This is an isothermal fluidized bed methanation technology with internal regeneration of the catalyst, which is on the demonstration phase. On the other hand, biomethane production through biogas gas upgrading is a process to increase the methane content of the biogas gas in order to achieve quality characteristics to natural gas. In this process various components are removed from the biogas gas (mainly CO_2, H_2O and H_2S) through a pressure swing adsorption (PSA) process, pre-purification and dehydration systems. This is a commercial and mature technology. Technical assumptions for the different biomethane production processes are shown in (Gonzalez-Salazar, et al., 2014c). Emissions from producing and using biomethane are estimated in a similar way to those from power generation using landfill gas and biogas, but not shown in detail here. There are four effects associated with the production and use of biomethane: a) emission of biogenic CO_2 contained in biogas, b) emission of biogenic CO_2 by burning biomethane, c) avoidance of methane release (den Boer, den Boer, & Jager, 2005) and d) emission of other pollutants, e.g. CO and NOx, by burning biomethane. Details are presented in (Gonzalez-Salazar, et al., 2014c)

3.4.2.7. Heat production in biomass-based boilers

Heat production in biomass-based boilers is mostly used to provide supplementary heat to various. Two commercially available technologies are considered, viz. residues-fuelled boiler at small-scale and wood boiler at small scale able to burn coal if necessary.

4. Application of the modeling framework to Colombia

The modeling framework is applied in this paper to the case study of Colombia. Thus, this analysis represents an extension of the work presented by authors in separate papers (Gonzalez-Salazar, et al., 2014a; Gonzalez-Salazar, et al., 2014b; Gonzalez-Salazar, et al., 2014c; Gonzalez-Salazar, Venturini, Poganietz, Finkenrath, & Spina, 2016a). The following sections present specific assumptions used to apply the modeling framework to Colombia.

4.1. Motivation

Colombia is contemplating peace agreements after a 50-year armed conflict, which would open up the possibility of modernizing agriculture, improving living standards in rural areas and exploiting the vast bioenergy potential (i.e. Colombia is one of the seven countries in the world where more than half of the potentially available global arable land is concentrated (FAO, 2011)). However, Colombia does not yet seem prepared for such ambitious reforms. While today bioenergy is the second largest renewable energy resource (3.8 million tons of oil equivalent –Mtoe–) after hydro power (4.2 Mtoe) (UPME, 2011b), only a limited number of studies have previously explored its further deployment (MRI-UNC-NUMARK, 2010; Mora Alvarez, 2012) and the magnitude of its impact has not been investigated in detail. More importantly, no official plans exist today for exploiting it in the long-term at a national level.

4.2. General assumptions for Colombia

The selected base year is 2009, which is the year with the most recent statistics available. The last calculated year is 2030. A particularly important assumption is that renewable energy technologies are heavily influenced by El Niño and La Niña Southern Oscillation (ENSO) and their performance is simulated using data from the last 15 years taken from (XM, 2013). All general assumptions are taken from multiple sources and are not included here for the sake of brevity; details can be found in (Gonzalez-Salazar, et al., 2014c).

4.3. Technology roadmapping and scenario analysis

Recognizing the importance of biomass in Colombia and the lack of long-term strategic planning to exploit it, a technology roadmap envisioning an accelerated deployment of bioenergy until 2030 was proposed by authors (Gonzalez-Salazar, et al., 2014c). In this roadmap, expert judgment from over 30 contributors from the government, academia, industry and non-governmental organizations (NGO's) is consolidated regarding long-term vision, goals, and milestones for deploying bioenergy. Experts identify five key bioenergy areas: 1) bioethanol, 2) biodiesel, 3) renewable diesel, 4) biomethane and 5) biomass-based power generation & CHP. While there was consensus among experts on the future of biomethane and biomass-based power generation & CHP, there were opposing views on the future of first generation transport biofuels. While some experts advocated a significant growth in blend mandates of first generation biofuels, others were in favor of fixing the current blend mandates to avoid worsening the conflicts of land use and food vs. biofuels. Scenario analysis is then employed to evaluate separately these two visions. Four scenarios primarily differentiated by their underlying assumptions on government policies are defined:

Baseline scenario

Firstly, a baseline scenario assuming no future change in policies or technologies was created and calibrated using the national energy balances (UPME, 2011b). It allows a description of how the energy system would unfold if policy measures, patterns of supply and demand and deployment of technologies remain unchanged.

Scenario I

Scenario I targets the deployment of biomethane production, biomass-based power generation & CHP and maintains unchanged the current blend mandate of first-generation biofuels, i.e. E10 (10 v% bioethanol, 90 v% gasoline) and B10 (10 v% biodiesel, 90 v% diesel fuel). This scenario aims at deploying efficient technologies in terms of environmental performance and land use, while maintaining the current deployment of first generation transport biofuels. Its long-term goals by sector include:

- Biomethane: use 5% of biomass residues and 1% of biogas from animal waste resources nationwide to produce biomethane for injection into the natural gas network by 2030.
- Power generation & CHP: achieve a renewable power generation target of 10% by 2025 by deploying biomass combustion in steam turbine CHP power plants, co-firing wood pellets in coal power plants and biogas/landfill gas combustion in reciprocating engines. Small-hydro and wind are also considered, but large-hydro is excluded. Additionally, it targets the nationwide use of 5% of the biogas from animal waste and municipal water treatment plants, 100% of the methane produced in the palm oil industry and 10% of the municipal landfill gas for power generation & CHP by 2030.

Scenario II

Scenario II targets a combined deployment of biomethane production, biomass-based power generation & CHP with further growth of first-generation biofuels (e.g. bioethanol, biodiesel and renewable diesel). Its long-term goals for biomethane and power generation are the same as for Scenario I, while its long-term goals for biofuels include:

- Biodiesel (palm oil based): increase the quota mandate to B20 in 2020 and B30 in 2030.
- Bioethanol (cane based): 1) increase the quota mandate to E20 in 2025 and 2) implement an E85 fuel program in 2030.
- Renewable diesel (palm oil based): achieve a 10% energy contribution of renewable diesel to the total diesel fuel production in 2030.

Scenario III

Scenario III shares targets with Scenario II but considering an enlargement in cultivation land of sugar cane on a large-scale beyond the Valley of the Cauca River (currently the only large-scale cultivated area), which is not examined in the other scenarios.

4.4. Assumptions of the ESM model

4.4.1. General assumptions

The national energy balances (UPME, 2011b) developed by the Mining and Energy Planning Unit (UPME), an agency affiliated to the Ministry of Mines and Energy, have been used as the primary source of information to build the ESM model for Colombia. However, often data and statistics for various branches of the energy system are not readily available. In these cases, official data from other governmental agencies was used. Data has been particularly scarce regarding technologies costs. Hence, in this study, technology costs have been only considered for the power generation and CHP module. A full economic analysis of other bioenergy technologies remains to be investigated.

4.4.2. Assumptions of the road transport sector

Available data disaggregates the number of vehicles in four types (Ciudad Humana, 2012; MinTransporte-CEPAL, 2010; UPME, 2010; ACP, 2012): a) motorcycles, b) gasoline road vehicles with at least 4 wheels, c) diesel road vehicles with at least 4 wheels (including trucks) and d) CNG-fuelled vehicles. The number of vehicles is then divided by the population (taken from (World Bank, 2013)) to obtain the vehicle ownership per type. In the original study by (Dargay, Gately, & Sommer, 2007) the relationship between vehicle ownership and income growth was estimated for 45 countries for the period 1960-2002. Colombia was excluded from this study due to the lack of consistency in data. In this study, the model is re-evaluated using more recent statistics and parameters are calibrated using regression analysis. A comparison of the model parameters of (Dargay, Gately, & Sommer, 2007) and this study is shown in Table 2. The improved parameters are therefore used to estimate the future ownership of vehicles with at least four wheels until 2030 in Colombia.

Table 2. *Comparison of model parameters for the vehicle ownership model*

Model parameters	Dargay et al.	This study
Parameter α	-5.8970	-4.8400
Parameter β	-0.1169	-0.0925
Maximum saturation ψ_{MAX}	852	827
Constant λ	-0.000388	-0.000388
Constant φ	-0-007765	-0-007765
Speed of adjustment θ_R	0.095	0.095
Speed of adjustment θ_F	0.084	0.084
Coefficient of determination R^2	99.3%	99.6%

The parameters of the logit function used to estimate share of vehicles with at least four wheels is shown in Table 3. These parameters are obtained through a regression analysis to best fit historical data. More details are shown in (Gonzalez-Salazar, et al., 2014c). Parameters to evaluate the motorcycle ownership in Colombia are presented in Table 4 and are obtained through regression analysis to best fit historical data.

Table 3. *Parameters of the logit function to estimate vehicle shares*

Model parameters	Gasoline vehicles	Diesel vehicles	CNG vehicles
Parameter k_c	0.2104	0.0999	50
Parameter γ	50	50	50
Speed of adjustment θ	0.015	0.0076	1
Coefficient of determination R^2	88.25%	85.35%	80.41%

Table 4. *Model parameters of the motorcycle ownership model*

Model parameters	Value
Parameter α	-25
Parameter β	-0.3602
Maximum saturation ψ_{MAX}	200
Speed of adjustment θ	0.4874
Coefficient of determination R^2	93.6%

Regarding age distribution, information disaggregated by vehicle type is available in (ACP, 2012; Ciudad Humana, 2012; MinTransporte-CEPAL, 2010; UPME, 2010), details are shown in (Gonzalez-Salazar, et al., 2014c). The survival rate per vehicle type is also available in the literature. While survival rates for motorcycles and 4 wheeled vehicles are found in (UPME, 2010), further disaggregation by vehicle type is not available. It is therefore assumed that the survival for 4 wheeled vehicles is the same for diesel, gasoline and CNG vehicles, details are found in (Gonzalez-Salazar, et al., 2014c). Data on fuel economy per vehicle type is only available as an average and not disaggregated by vintage (Econometria - UPME, 2010). Reported data for base year (2009) is summarized in Table 5. The degradation factor is not available and it is therefore assumed that the average fuel economy remains constant for the different vintages (i.e. $FE_{c,t,v} = FE_{c,v}$). The future fuel economy is estimated using the fuel economy by vehicle for the base year and future projections for decline. An annual projected rate of decline of -0.7% in fuel economy for all vehicle types in Latin America until 2030 is taken from (OPEC, 2004; Dargay, Gately, & Sommer, 2007).

The supply coverage of biofuels ($Cov_{t,bio}$) is a variable that describes the effect of having a limited availability of biofuels nationwide (particularly in remote and border regions). The supply coverage of the different biofuels is here modeled through a Gompertz functions with a maximum value of 85%, see details in (Gonzalez-Salazar, et al., 2014c). Next, the mileage is estimated. Mileage is the annual distance traveled per vehicle (km/vehicle). For the base year mileage is calculated using the overall energy consumed by vehicle taken from (UPME, 2011a) as well as the number of stocks and the fuel economy shown in Table 5.

Table 5. *Energy intensity by vehicle type in year 2009*

	Motorcycles [A]	**Gasoline vehicles** [A]	**Diesel vehicles** [A]	**CNG vehicles** [B]
Vehicles (thousand)	2669[1]	2243[2]	793[2]	297[3]
Fuel type	Gasoline	Gasoline	Diesel fuel	CNG
Fuel LHV (MJ/l)	32.87[4]	32.87[4]	36.71[4]	0.04[5]
Fuel density (kg/liter)[6]	0.740	0.740	0.837	0.185
Average fuel economy $FE_{c,2009}$ (A: km/l, B: km/m^3)[7]	40.89	8.17	3.80	28.10
Average fuel economy $FE_{c,2009}$ (MJ/100km)[8]	80.39	402.33	964.95	140.62
Average mileage (km/vehicle)[9]	12426	11773	18908	65349

[1] (Ciudad Humana, 2012)
[2] (MinTransporte-CEPAL, 2010; UPME, 2010)
[3] (ACP, 2012)
[4] (UPME, 2010)
[5] It is taken the average of natural gas produced in the Cusiana field and the Guajira region according to data from (UPME, 2010)
[6] Data taken from (MIT, 2010). The density of CNG is at a pressure of 200 bar.
[7] (Econometria - UPME, 2010)
[8] Calculated using the fuel economy published by Econometria and the assumed fuel LHV
[9] Mileage is calculated as: energy consumed by fuel/ (Stocks · fuel economy). The energy consumed by fuel is taken from (UPME, 2011b)

While it is desirable to include a mileage degradation factor that considers the reduction in travelled distance as a vehicle ages, this data is not readily available. Thus, it is assumed that the mileage by vintage is constant. Future mileage is estimated using available projections. A 0.4% annual growth for gasoline vehicles and motorcycles and a 0.5% annual growth for diesel vehicles and CNG vehicles are taken from (E4tech, 2013).

Competition of E85 with gasohol in gasoline vehicles occurring by launching the E85 program is modeled through the following equations:

Eq. 43 $VE85_t = VEFF_t \cdot Cov_{E85,t}$

Eq. 44 $\mu_{E85,t} = \frac{\left[{}^{1}/_{F_{E85,t}}\right]^{\gamma}}{\left[{}^{1}/_{F_{E20,t}}\right]^{\gamma} + \left[{}^{1}/_{F_{E85,t}}\right]^{\gamma}}$

Eq. 45 $\mu_{E20,t} = 1 - \mu_{E85,t}$

In Eq. 43 $VE85_t$ is the percentage of vehicles in year *t* that are able to run with E85 and have access to it, $VEFF_t$ is the percentage of vehicles that are flex fuel (assumed to enter into the market in 2015 and further calculated by LEAP considering the survival rate and new acquisitions), Cov_{E85} is the supply coverage of E85 by year. On the other hand, in Eq. 44 $\mu_{E85,t}$ is the energy share of E85 used in flex fuel vehicles, which is modeled as a function of the cost of E20 ($F_{E20,t}$ in US\$2005/MMBtu), the cost of E85 ($F_{E85,t}$ in US\$2005/MMBtu) and the cost sensitivity coefficient γ (assumed to be 2). This low degree of sensitivity implies that in the first year of implementation (i.e. 2030) the substitution of E20 for E85 is not likely to happen easily even if major price changes occur (Argonne National Laboratory, 2007).

Finally, the emission factors by pollutant are taken from the LEAP database, which refers to Tier 1 emissions factors suggested by IPCC in 2006 (Heaps, 2012). $Deg_{c,t-v,p}$ factors for NOx, NMVOC, N_2O, CO and CH_4 by vehicle are taken from (Toro Gómez, et al., 2012). For the sake of brevity these degradation profiles are not included in this study.

4.4.3. Assumptions of the residential sector

Assumptions on future urban and rural populations are taken from various sources (DANE, 2005; World Bank, 2013). Historical household final consumption expenditure in PPP (US$2005) is taken from (World Bank, 2013). Ambient temperature is expressed in heating degree days (HDD), which in average for Colombia is 677 (ChartsBin, 2014). For household expenditure, it is found that the historical household expenditure is linearly correlated with the GDP in the following form (coefficient of determination R^2 = 99.53%):

Eq. 46 $HH = 0.5327 \cdot GDP + 2.3E10$
Eq. 47 $HHp = HH/P$

Future household expenditure is estimated by using this correlation and the assumed future GDP (billion US$2005, PPP, taken from (Gonzalez-Salazar, et al., 2014c).

Regarding household size, the historical average household size is taken from available statistics for years 1973, 1985, 1993 and 2005 (DANE, 2006), which have decreased over the years. A correlation between household size *S* and the year *t* is obtained with a coefficient of determination R^2 of 99.15% and used to estimate household size in the future:

Eq. 48 $S = 6.2324E10 \cdot e^{-0.01173 \cdot t}$

Regarding access to electricity and natural gas, historical data disaggregated by region for various years is collected from several sources (Coronado Arango & Uribe Botero, 2005; Fresneda, Gonzalez, Cárdenas, & Sarmiento, 2009; DANE, 2010; DANE, 2011; Parra Torrado, 2011). Parameters, coefficients of determination of the Gompertz model describing the access to electricity and natural gas as well as results and historical data are discussed and reported in detail in (Gonzalez-Salazar, et al., 2014c).

For water heating, the historical data, fuel shares and obtained Gompertz function are shown in more detail in (Gonzalez-Salazar, et al., 2014c). Similarly, for appliances and lighting data and results can be found in (Gonzalez-Salazar, et al., 2014c).

The energy demand for cooking is estimated separately for rural and urban regions. For urban regions, the energy demand for cooking per capita is assumed to be a constant and is estimated as the average for the period 1975-2009 using historical data available in (UPME, 2011b). The obtained value is 1.8225 MJ_{UE}/person/day (standard deviation = 0.1722). For rural regions, the energy demand for cooking is estimated through the following equations:

Eq. 49 $ECCH_{Q,ru} = CK1 \cdot CK2^{t-1970} + CK3$
Eq. 50 $ECCp_{ru} = \frac{1}{P} \cdot \left(\sum_Q ECCH_{Q,ru} \cdot H_{Q,ru} \right)$

Where $ECCH_{Q,ru}$ is the daily energy consumption for cooking per household in rural areas dissagregated by quintile (MJ_{UE}/household/day), $ECCp_{ru}$ is the daily energy consumption for cooking per person in rural areas (MJ_{UE}/person/day), $H_{Q,ru}$ is the number of households in rural areas and $CK1$, $CK2$ and $CK3$ are function coefficients. Obtained parameters, results for the model and fuel shares are shown in (Gonzalez-Salazar, et al., 2014c).

4.4.4. Assumptions of agricultural industries

For the cases of sugar, palm oil and jaggery the demand of electricity and heat per unit of activity is summarized in Table 6.

4.4.5. Assumptions of non-road transport, industrial and commercial sectors

Coefficients ξ_1 and ξ_2 and speed of adjustment θ are calibrated through regression analysis to best fit historical data available in (UPME, 2011b). The price of fuel by year, sectorial GDP and results of the regression analysis of the energy demand by sector and fuel are presented in (Gonzalez-Salazar, et al., 2014c).

Table 6. *Energy intensity for palm and cane industries*

Commodity	Electricity (MJ/ ton)	Heat (MJ/ ton)	Reference
Sugar	450[1]	9625[1]	(Macedo, Leal, & Da Silva, 2004)[2]
Palm oil	533	11,481	(Panapanaan, et al., 2009)
Jaggery	-	12051[3]	(Velásquez, Chejne, & Agudelo, 2004) (UPME, 2011b)

[1] It is assumed that the yield of sugar is 12 ton per ton of sugar cane without leaves.
[2] The demand of electricity is 54 MJ/ton-cane and the demand of heat is 1155 MJ/ton-cane, taken from (Macedo, Leal, & Da Silva, 2004)
[3] Evaluated using efficiency published in (Velásquez, Chejne, & Agudelo, 2004) and energy demand published in (UPME, 2011b)

4.4.6. Assumptions of the power generation model

Traditional technologies include large and small hydro power plants (<10 MWe), simple and combined cycle gas turbines, coal power plants, diesel and gas reciprocating engines, wind turbines, bagasse-fuelled steam CHP power plants, palm residues-fuelled steam CHP power plants and small power generation units burning a wide range of fuels (UPME, 2011b). From these technologies only bagasse- and palm residues-fuelled steam CHP power plants are able to co-produce combined heat and power (CHP). New technologies include: biomass co-firing in coal power plants, syngas co-firing in gas turbine simple and combined cycles, biomass-fuelled CHP power plants at small scale (up to 10 MWe), biogas- and landfill gas-fuelled reciprocating engines. New technologies able to co-produce heat and power, include biomass-fuelled CHP power plants at small scale, biogas- and landfill gas-fuelled reciprocating engines.

Assumptions on performance, investment, operational, maintenance and fuel costs of traditional and new technologies are presented in (Gonzalez-Salazar, et al., 2014c). Other general assumptions include:

- A discount rate of 10% is assumed. A wide variation was found in the literature regarding the appropriate discount rate to be used in Colombia. Values between 5% and 18% were found (UPME, 2005; Correa Restrepo, 2008). This is certainly one important source of uncertainty. It is assumed a discount rate of 10%, which is in between the limits mentioned above, but which is also close to the discount rate of 9-12% described in (UPME, 2005) for energy projects in the country.
- A decommissioning cost of 5% of capital cost is assumed (IEA-NEA, 2010).
- Investment cost includes owner's costs but exclude interest during construction (IEA, 2012a).

Capacity credit by technology is shown in (Gonzalez-Salazar, et al., 2014c). The assumed minimum planning reserve margin is 40%, which has been the average value between 1998 and 2010 in Colombia (UPME, 2011a). This value is significantly higher than in other countries, where typically ranges between 15 and 25% (IEA, 2007; NERC, 2012; EIA, 2014). The annual electricity loads are divided into daily slices, for which a load shape is assigned. The load shape is taken from the state-owned transmission firm Interconexión Eléctrica S.A. for year 2009 (XM, 2013). When compared to data of 1996 the load shape of 2009 has virtually no differences and therefore it has been decided to keep the load shape constant until 2030.

A renewable power target is the share of electricity generated by renewable energy technologies. For Scenarios I and II a renewable power target is imposed and linearly increases from 0% in 2015 to 10% in 2025 and remains at this level afterwards. Technologies that qualify as renewable energy to meet the renewable power target include: wind power, small hydro (< 10 MWe), biomass fuelled CHP plants, biomass co-firing in coal power plants, syngas co-firing in gas turbine simple and combined cycles, biomass-fuelled CHP power plants at small scale (up to 10 MWe), biogas-fuelled reciprocating engines and landfill gas fuelled reciprocating engines.

Capacity additions by technology until 2019 are taken from various sources (IFC, 2008; UPME, 2009; Portafolio, 2012; Portafolio, 2013; Sector Electricidad, 2012; BNamericas, 2013; El Colombiano, 2013) and presented in (Gonzalez-Salazar, et al., 2014c) and sum in total 7.53 GW. Technologies planned to be added include large hydro (5.6 GW), small hydro (0.15 GW), coal (0.57 GW), natural gas turbines (1.1 GW) and diesel engines (0.12 GW). Full details are shown in (Gonzalez-Salazar, et al., 2014c) In addition to that, further capacity is exogenously added for Scenarios I and II to comply with the following long-term targets: a) reciprocating engine fuelled with biogas from animal waste and municipal water treatment plants to comply with the 5% target to exploit it by 2030, b) reciprocating engine fuelled with biogas from biodiesel production plants to comply with the 100% target to exploit it by 2030 and c) reciprocating engine fuelled with landfill gas to comply with the 10% target to exploit it by 2030

The maximum annual capacity addition is estimated on a technology by technology basis. The maximum annual capacity addition for those technologies that are already planned to be added (e.g. large and small hydro, coal, natural gas simple cycle gas turbines and diesel reciprocating engines) is assumed to be the maximum observed planned addition during the period 2009-2019. Based on discussion with experts a maximum annual capacity addition of 100 MWe is assumed for gas turbines at small-scale, coal power plants at small-scale and natural gas reciprocating engines, while 50 MWe is assumed for wind power given its slow-paced deployment. For biomass-based power generation technologies, the maximum annual capacity addition is related to the future technical biomass energy potential described in detail in (Gonzalez-Salazar, et al., 2014a; Gonzalez-Salazar, et al., 2014b). More details on this estimation can be found in (Gonzalez-Salazar, et al., 2014c).

4.4.7. Assumptions of other conversion processes

4.4.7.1. Cane mill, sugar and bioethanol production

In the first route, only sugar is produced from molasses in a sugar factory assuming a constant yield of 0.12 tons of sugar per ton of sugar cane (without leaves), taken from (BID-MME, Consorcio CUE, 2012). In the second route, sugar and bioethanol are co-produced in a sugar factory with an annexed distillery. In this route, sugar is produced in a similar fashion as in Route 1, but molasses are converted into bioethanol via microbial fermentation, distillation and dehydration. For Route 2, constant yields of 0.093 tons of sugar and 0.019 tons of bioethanol per ton of sugar cane (without leaves) are assumed, taken from (BID-MME, Consorcio CUE, 2012). In the third route, only bioethanol is produced by directly converting cane juice into bioethanol via fermentation, distillation and dehydration, but without co-producing sugar. This route is also known as autonomous distillery. It is assumed a constant yield of 80 liters of ethanol per ton of cane (without leaves), taken from (Ferreira-Leitao, et al., 2010; Gonzalez-Salazar & Willinger, 2007). The fraction of cane juice allocated to each of the three routes is estimated through the LUTM model.

4.4.7.2. Palm oil mill and biodiesel production plant

Regarding emissions, methane produced in wastewater as by-product of the biodiesel conversion processes is assumed to be 1.03 Ton-CH_4/Ton-FFB as published in (BID-MME, Consorcio CUE, 2012), which according to the source is released to the atmosphere. Other assumptions are shown in (Gonzalez-Salazar, et al., 2014c).

4.4.7.3. Heat production in biomass-based boilers

The assumed efficiency for these technologies is 30% for bagasse boilers (Velásquez, Chejne, & Agudelo, 2004), and 60% for wood boilers (Thermoflow, 2011). The availability of a bagasse boiler is assumed to be variable according to the influence of the El Niño phenomenon, whereas the availability of a wood boiler is assumed to be 55%. For the operation of the system, a merit order based on the fuel price is set. Thus, first bagasse is burned, followed by wood and then coal. Regarding emissions, it is assumed that the CO_2 emissions produced during combustion of biomass resources in heat production are biogenic. See details in (Gonzalez-Salazar, et al., 2014c).

4.5. Validation of the ESM model

The ESM model is calibrated and validated for the case study of Colombia by using data published in the national energy balances (UPME, 2011b). An acknowledged source of uncertainty relates to the fact that the latest available national energy balances correspond to year 2009 and predate five years the present study. The model is validated at different levels and results are shown in detail in (Gonzalez-Salazar, et al., 2014c), while they are just briefly addressed in this paper for the sake of brevity. At a first level, the demand for primary and secondary energy is validated by fuel and branch. At a second level, the overall GHG emissions by branch are validated. Results of the ESM model are in agreement with national energy balances and coefficients of determination of 99.2% and 88% are estimated for primary energy demand and emissions, respectively. Results of the EMS model for emissions are 3% to 13% higher than statistics, mainly because emissions of various transformation processes not estimated in the national energy balances have been accounted (e.g. oil refining, heat production, bioethanol and biodiesel production, blast furnace, charcoal factories, etc.). However, given the variability of the data, a deviation of 3-13% is considered acceptable.

5. Impacts on the energy demand and supply

5.1. Primary energy demand and influence of GDP

The primary energy demand in the country is found to be somewhat proportional to the Gross Domestic Product (GDP) and describes a trend that is consistent with historical data (see Figure 10). In the past, the primary energy demand grew moderately as a result of a modest increase in GDP. In contrast, a substantial increase in primary energy demand is expected when the future GDP growth predicted by the government is considered. In fact, an increase of 139% in the primary energy demand is expected between 2009 and 2030 for the baseline scenario, as a consequence of the assumed growth in GDP of 156%. This represents an increase from 39.39 to 94.16 MToe by 2030. On the other hand, the primary energy demand for Scenarios I and II follows a similar path to that of the baseline and reaches 94.18 and 89.18 MToe in 2030 respectively.

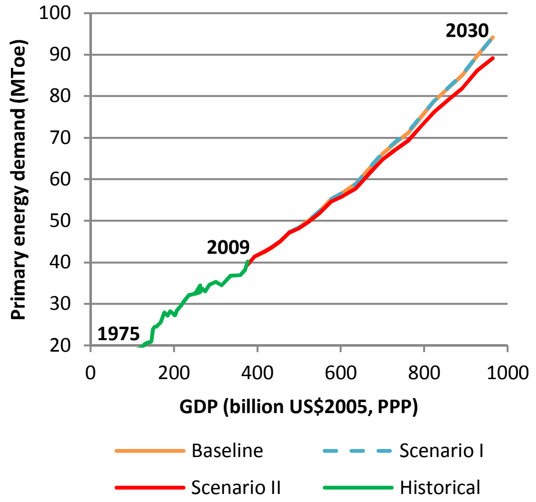

Figure 10. *Primary energy demand vs. GDP*

5.2. Impacts on road transport, electricity generation and natural gas supply

In the baseline scenario, a significant growth in primary energy demand (from 41 to 94 Mtoe), road transport demand (from 8 to 27 Mtoe), electricity generation (from 5 to 11 Mtoe) and natural gas supply (from 4 to 14 Mtoe) between 2010 and 2030 is estimated (Figure 11a). In this period, the share of fossil fuels in the primary energy demand increases from 75% to 85%, while in power generation it increases from 29% to 50% (Figure 11a). In contrast, the share of bioenergy during the same period reduces from 15% to 8% in the primary energy demand and from 3% to 1.6% in power generation (Figure 11b). This result is a consequence of a combination of factors including increasing urbanization, greater access to electricity and natural gas services, rapid growth of road vehicle ownership and increased deployment of gas- and coal-fired power plants. New policies on biomethane and power generation in Scenarios I and II can increase the share of bioenergy to ~6% in these sectors by 2030, while further deployment of first-generation biofuels in Scenario II can boost the share in road transport to 24%. Increased shares of bioenergy allow savings in fossil fuels in 2030 ranging from 2% (1.9 Mtoe) in Scenario I, to 6% (4.6 Mtoe) in Scenario II, and to 7% (5.4 Mtoe) in Scenario III (Figure 12). Despite this, the share of bioenergy in primary energy demand still declines to ~10% in all scenarios. This suggests that the energy demand grows more quickly than the bioenergy supply in the scenarios considered here, resulting in increased demand for fossil fuels.

5.3. Impacts on power generation

5.3.1. Electricity supply

In the baseline, electricity supply is expected to double between 2009 and 2030 (from 5.1 to 10.9 MToe, see Figure 13, left). The observed yearly fluctuations are explained by the varying availability of hydro resources caused by El Niño oscillation. In this period, hydro power increases from 3.5 to 5.3 MToe and its average share is 68%. Of this amount, small hydro contributes to 18 kToe in 2009 and 243 kToe in 2030 (0.4% and 2.2% of overall shares). Hydro's share starts growing in 2010 and reaches 85% in 2020, but it decreases to 50% by 2030. The increase between 2010 and 2020 is caused by a significant capacity expansion that has been officially planned (5.7 GW). However, between 2020 and 2030 hydro power is displaced by electricity generated in natural-gas fired power plants, due partly to their lower cost of electricity (see Table 7). It is important to note that the contribution of the different technologies to power generation does not only depend on the levelized cost of electricity. It also depends on the availability of energy resources and on officially planned capacity additions and retirements (exogenously added in LEAP).

Hydro power is followed by natural gas, coal and to a smaller extent by bioenergy, oil and other renewables. Between 2009 and 2030, natural gas-based power generation grows from 0.9 to 4.4 MToe (18-40% shares) and coal grows from 0.5 to 1 MToe (~10% share). In this period, biomass-based power generation grows from 130 to 170 kToe, although its contribution reduces from 2.5% to 1.6%. Power generation from oil and other renewables is marginal (<1% share).

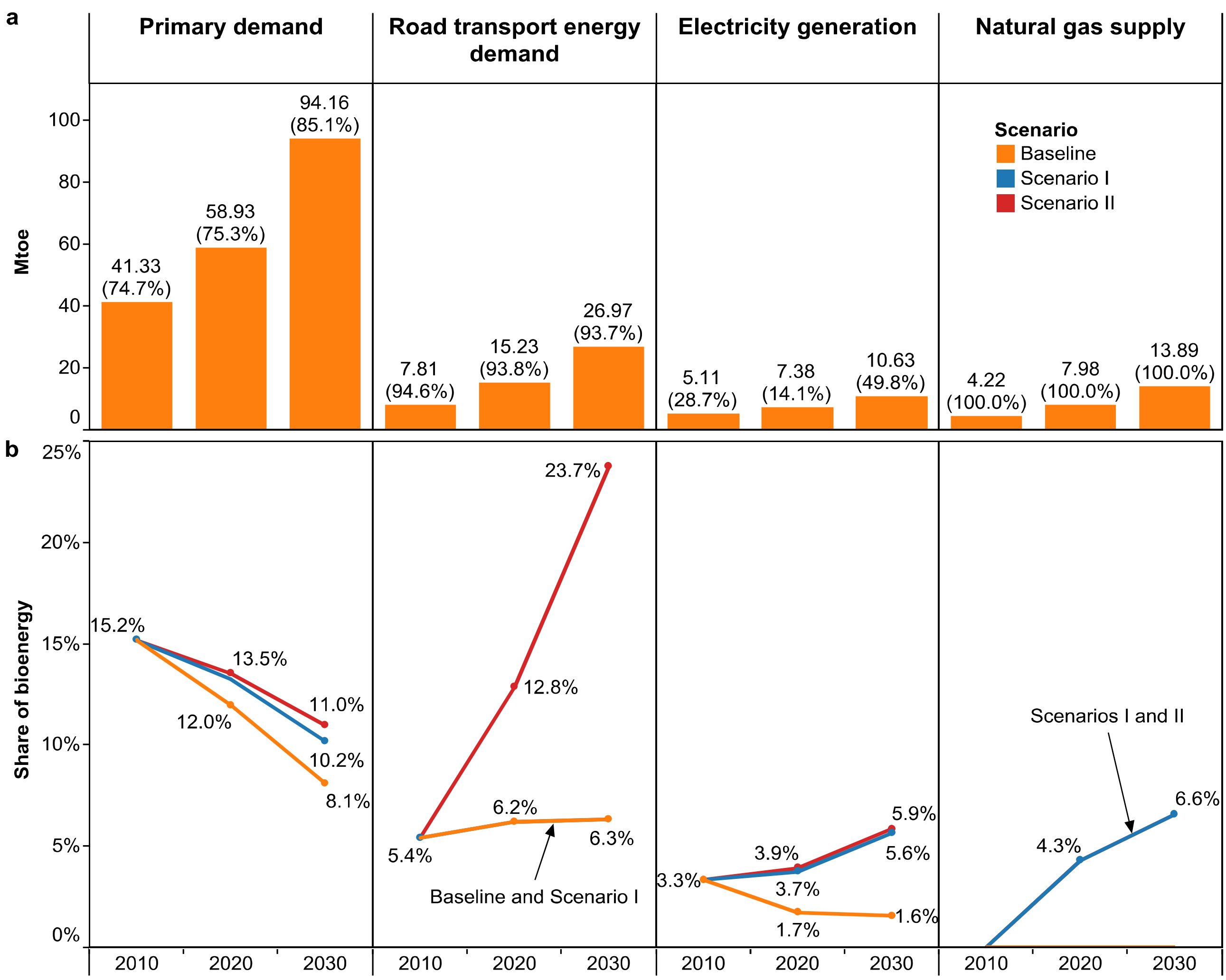

Figure 11. *Energy demand and shares for selected sectors. a, energy demand in million tons of oil equivalent (Mtoe) for selected sectors, share of fossil fuels is shown in brackets. b, shares of bioenergy in selected sectors are shown for the different scenarios. Data for Scenario III is equal to data for Scenario II*

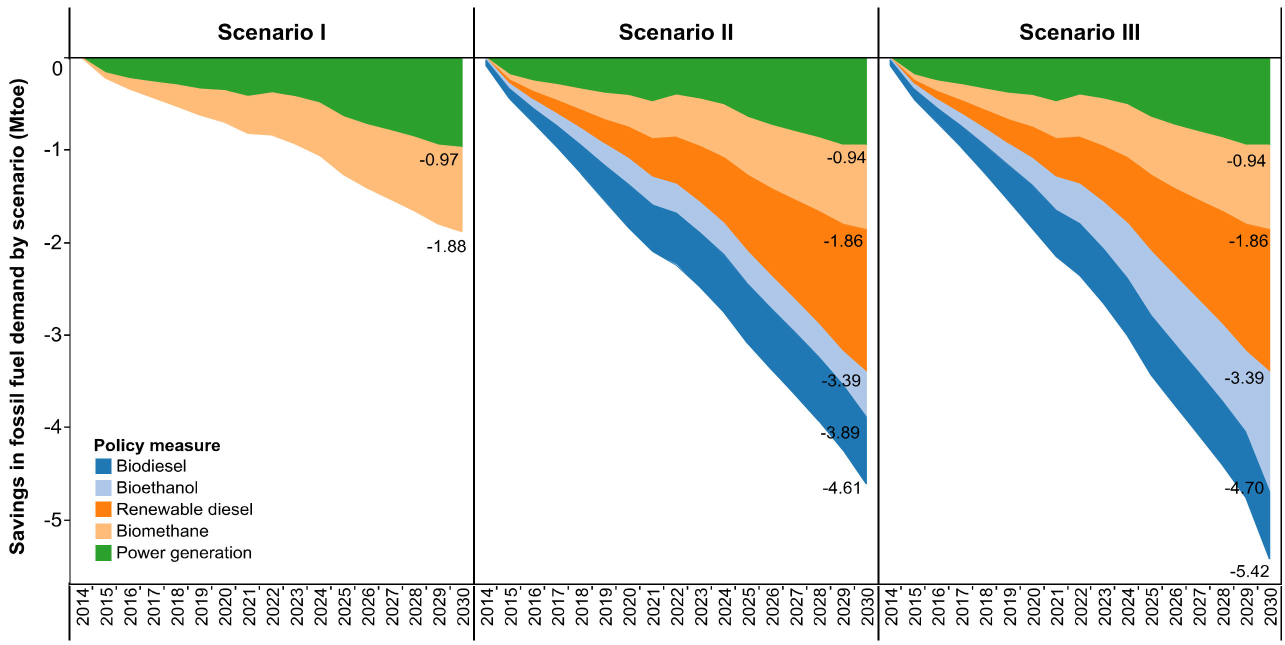

Figure 12. *Savings in fossil fuel demand in million tons of oil equivalent (Mtoe) by scenario. Labels indicate aggregated savings for the different policy measures*

Table 7. *Levelized cost of electricity (LCOE) by technology*[1]

US$2009/MWh	Levelized cost of electricity (LCOE)		
	2009	**2020**	**2030**
Natural gas combined cycle	67.5	66.9	66.9
Natural gas reciprocating engine	73.0	72.6	72.6
Wind power turbine	85.3	77.8	77.0
Natural gas simple cycle – Large (> 50 MW)	86.0	85.7	85.7
Natural gas simple cycle – Small (≤ 50 MW)	86.0	85.7	85.7
Coal power plant – Large (> 50 MW)	92.6	92.9	92.9
Coal power plant – Small (≤ 50 MW)	104.7	104.5	104.5
Hydro power plant – Large (> 10 MW)	128.8	128.7	137.9
Biomass CHP – Medium (>5 MW, ≤ 25 MW)	131.4	123.2	117.2
Fuel oil fuelled gas turbine – Small (≤ 50 MW)	151.2	150.9	150.9
Hydro power plant – Small (≤ 10 MW)	191.1	188.4	188.7
Diesel reciprocating engine	196.9	196.6	196.6
Diesel fuelled gas turbine – Small (≤ 50 MW)	244.9	244.6	244.6

Differences in power generation between Scenario I and the baseline are shown in Figure 13 (right). In Scenario I, power generation continues being mostly dominated by hydro (average share 68.3%), although there is an increased participation of other renewables replacing gas-based power generation. This is a result of implementing the power generation & CHP targets between 2015 and 2030. In this period, an increase in share from 2.5% to 5.6% is expected for bioenergy, and from 0.3% to 2% for wind. In contrast, the share of small hydro is expected to remain unchanged compared to the baseline (2-3% share). The aggregated contribution of renewables (including small hydro) grows from 3.2% in 2009 to 10% in 2030. Simultaneously, the share of gas in power generation in 2030 reduces from 40% in the baseline to 34% in Scenario I. Power generation in Scenarios II and III present nearly the same behavior as that in Scenario I with almost negligible modifications. For the sake of brevity, these differences are not shown here but can be found in (Gonzalez-Salazar, et al., 2014c).

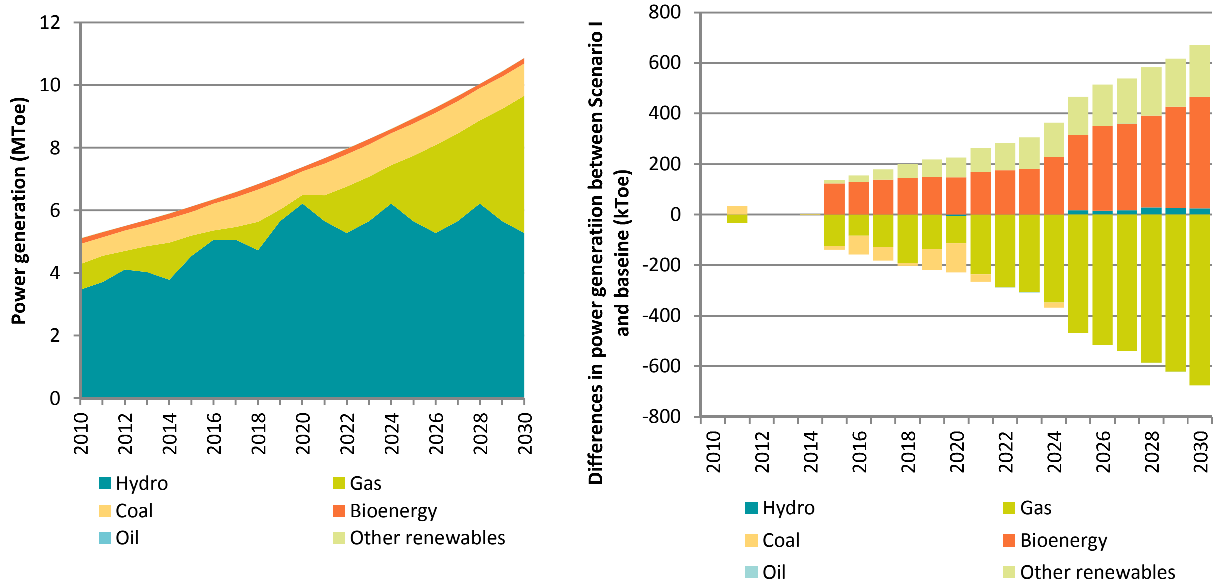

Figure 13. *Power generation by source for the baseline scenario (left), differences in power generation by source for Scenario I vs. baseline (right)*

5.3.2. Capacity

The power generation capacity is expected to grow from 13.5 to 26.4 GW between 2009 and 2030 (see Figure 14, left). The bulk of the capacity additions by 2030 comes from natural gas, hydro, coal and oil. Of the 13.2 GW of capacity additions, 6.8 GW correspond to gas-fired power plants (49% simple cycles, 51% combined cycles), 5.75 GW correspond to hydro power plants, 0.57 GW to coal-fired power plants and 0.12 GW to oil-fired power plants. About 46% of the expected capacity additions between 2009 and 2030 are already in construction or planned (6 GW), while

[1] Estimated as $LCOE = \frac{\sum_t (Investment_t + O\&M_t + Fuel_t + Decommissioning_t)\cdot(1+r)^{-t}}{\sum_t (Electricity_t)\cdot(1+r)^{-t}}$, according to the equation proposed by (IEA-NEA, 2010)

the remaining 54% are expected after 2019. After the planned expansion of 5.75 GW of hydro between 2009 and 2019, no further capacity is added between 2020 and 2030. This is most likely a consequence of the higher production cost of hydro relative to other technologies (particularly gas), according to the assumptions. Differences in installed capacity between Scenario I and the baseline scenario are shown in Figure 14 (right). Two important trends are observed. Firstly, additional capacity is required for renewables to comply with the power generation & CHP targets as of 2015. Secondly, an increase in installed capacity of renewables causes a less rapid growth of gas-fired power plants until 2030. Installed power generation capacity in Scenarios II and III presents nearly the same structure as that in Scenario I with almost negligible modifications. For the sake of brevity, these differences are not shown here but can be found in (Gonzalez-Salazar, et al., 2014c).

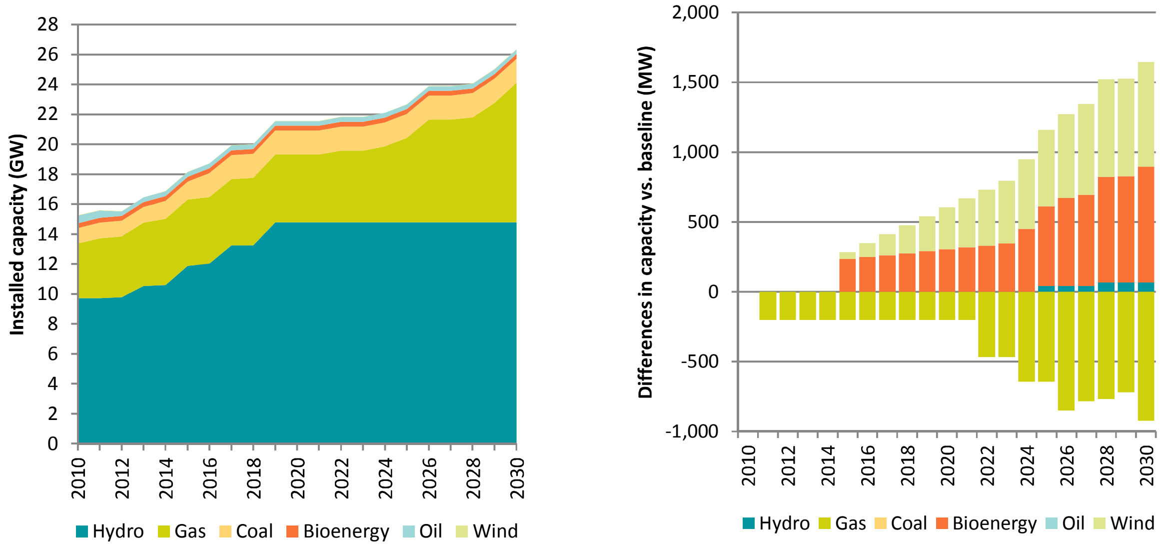

Figure 14. *Installed power generation capacity by source for baseline scenario (left), differences in installed power generation capacity between Scenario I and baseline (right)*

5.3.3. Complementarity of hydro and bioenergy

In the last 15 years, the availability of hydro and biomass-based power generation has been somewhat complementary (XM, 2013). This complementarity relates to the fact that the highest availability of hydro power occurs in years with low solar radiance, when the availability of biomass-based power is lowest (see details in (Gonzalez-Salazar, et al., 2014c)). This complementarity, however, has not been fully exploited. Assumptions on this complementarity have been included into models to evaluate the extent at which it can be used to mitigate the effects of the El Niño oscillation. Scenarios I and II attempt to exploit this complementarity, assuming that it will continue in the future. A reduction in fossil-fuel based power generation is expected for Scenarios I and II relative to the baseline. This reduction is maximal in wet years when hydro can deliver more power, but it is actually critical in dry years when hydro becomes less available. Figure 15 shows the aggregated contribution of hydro and bioenergy to the overall power generation for the baseline and Scenario I.

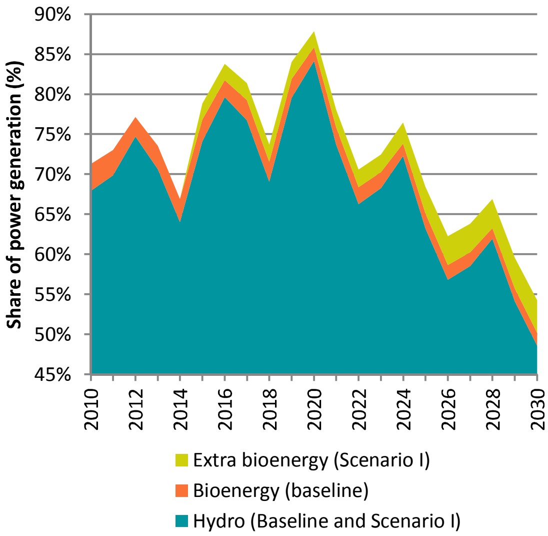

Figure 15. *Contribution of hydro and bioenergy to power generation in baseline scenario and Scenario I*

Results show that in Scenario I the share of biomass in power generation could grow up to 5.6% in dry years and up to wet years up to 4-5% in wet years, with a proportional reduction in demand for fossil fuels.

6. Impacts on the land use and trade

Results show that in order to accomplish the proposed targets, the land for producing woodfuel and feedstocks for biofuels (i.e. sugar cane and palm oil) should grow (Figure 16). Between 2010 and 2030, the forestland for producing woodfuel in plantations grows in all scenarios from 0.32 to 0.5 Mha (from 0.29 to 0.45% of land coverage). In the same period, the cropland for cultivating feedstocks for biofuels grows from 0.11 to 0.66 Mha (from 0.1 to 0.6% coverage) in the baseline and Scenario I, to 0.81 Mha in Scenario II (0.7% coverage) and to 1.33 Mha in Scenario III (1.2% coverage). The bulk of this cropland is used to produce feedstocks for biofuels that are locally consumed. Cropland for food production and natural forestland (via deforestation) transform into pastures for cattle farming, forest plantations and cropland for producing feedstocks for biofuels. In all scenarios the coverage of pastures is expected to increase from 34.4 to 36% (from 38.18 to 40.18 Mha) between 2010 and 2030, while the coverage of natural forestland is predicted to reduce from 54.53 to 52.73% (from 60.5 to 58.5 Mha). Moreover, the coverage of cropland for food production is expected to reduce from 3.75% (4.16 Mha) in 2010 to 2.96% (3.28 Mha) in 2030 in the baseline and Scenario I and to 2.65% (2.94 Mha) in Scenario III. The coverage of cropland for food production is expected to reduce in all scenarios because of three factors. Firstly and most importantly, cropland for food production is transformed into pastures for cattle farming as a result of the higher cost competitiveness of cattle products (i.e. meat and milk) compared to other agricultural products. Secondly, the assumed international prices for key export commodities (e.g. coffee) decrease in the long term and cause a significant reduction in harvested area. Thirdly, more cost-competitive duty-free imports from the U.S., available as of 2012, cause a further reduction in harvested area for some crops (e.g. rice and corn). Increases in cropland for producing feedstocks for biofuels, are however, insufficient to accomplish long-term goals and imports of biofuels are expected in all scenarios (Figure 17). In Scenario II, imports of bioethanol might account for 76% of the demand by 2030, while imports of biodiesel might reach 60% of the demand. Imports can even account for 36% of the demand in Scenario III, which suggests that expanding the cultivation land of sugar cane beyond the Valley of the Cauca River might also be insufficient to accomplish the targets. However, importing biofuels raise additional concerns as a definitive solution, because it transfers both positive and negative impacts to other countries. While importing biofuels might contribute to reducing GHG emissions, it does not enhance domestic rural development, it does not generate local employment, R&D and expertise, it requires additional energy to be transported from abroad and it transfers potential social and environmental negative impacts to other countries.

7. Impacts on GHG emissions

For all scenarios, GHG emissions in the energy sector are expected to increase until 2030 (Figure 18a). In the baseline scenario, GHG emissions increase significantly from 76 to 223 million tons of CO_2 equivalent ($MtCO_2$-eq) between 2010 and 2030. Combustion of oil and gas in road transport, power generation and the industry sector causes 76% of this increase. Emission reductions by deploying bioenergy range from 11.4 $MtCO_2$-eq by 2030 in Scenario I, to 20.3 in Scenario II and 22.6 in Scenario III, which represent abatements of 5%, 9% and 10% relative to the baseline, respectively. Figure 19 shows emission reductions disaggregated by policy measures. The bulk of the reduction in emissions for Scenario I comes from implementing new policy measures on power generation & CHP (74%), followed by new policy measures on biomethane (26%). 76% of the reduction in power generation & CHP comes from avoiding methane release in landfill gas and biogas from animal waste and wastewater, through combustion in reciprocating engines. The remaining 24% reduction comes from the replacement of gas- by biomass-based power generation. Similarly, in Scenarios II and III, the bulk of the reduction in emissions comes from implementing new policy measures on power generation & CHP (52% and 50% respectively), followed by new policies on renewable diesel (17-16%), biomethane (15-14%), bioethanol (8-13%) and biodiesel (~8%). This indicates that emission reductions caused by further deploying first generation biofuels (e.g. bioethanol, biodiesel and renewable diesel) in Scenarios II and III can equal the emission reductions caused by deploying biomethane and power generation & CHP in Scenario I. Thus, emission reductions in Scenarios II and III almost double reductions in Scenario I. It is important to note that emission reductions by avoiding methane release in Scenarios II and III are slightly higher than in Scenario I. The reason is that an augmented production of biodiesel in Scenarios II and III relative to Scenario I causes an increased generation of methane in wastewater facilities and in the corresponding avoidance by using it for power generation & CHP. Finally, the emission reduction per incremental land was estimated as the difference in emissions between scenarios and baseline per year divided by the difference in required cultivation land between scenarios and baseline. Scenario I offers the highest emission reduction per additional hectare of land used to cultivate biomass resources, i.e. ~150 tCO_2-eq per additional ha, while Scenarios II and II with expansion achieve 40 and 30, respectively (see Figure 18b). This suggests that despite Scenarios II and II with expansion achieving higher emission reductions than Scenario I, they are less effective in reducing emissions per additional hectare of land use.

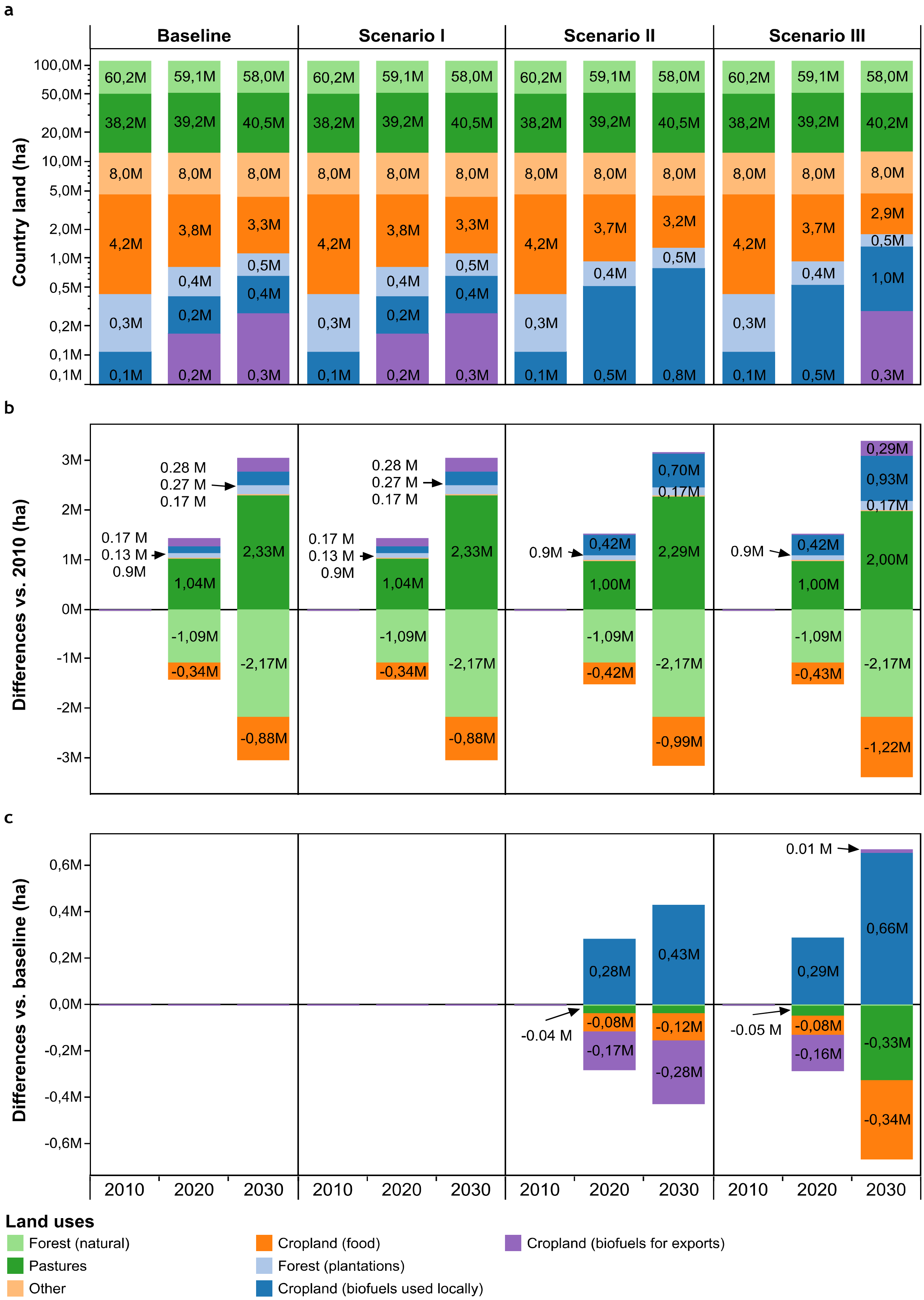

Figure 16. *Selected land uses by scenario. a, land uses in millions of hectares for 2010, 2020 and 2030 shown in logarithmic scale (the overall country land sums 110.95 Mha). b, land-use change in millions of hectares for years 2020 and 2030 relative to 2010 disaggregated by scenario and category. c, land-use change in millions of hectares relative to the baseline scenario disaggregated by scenario and category*

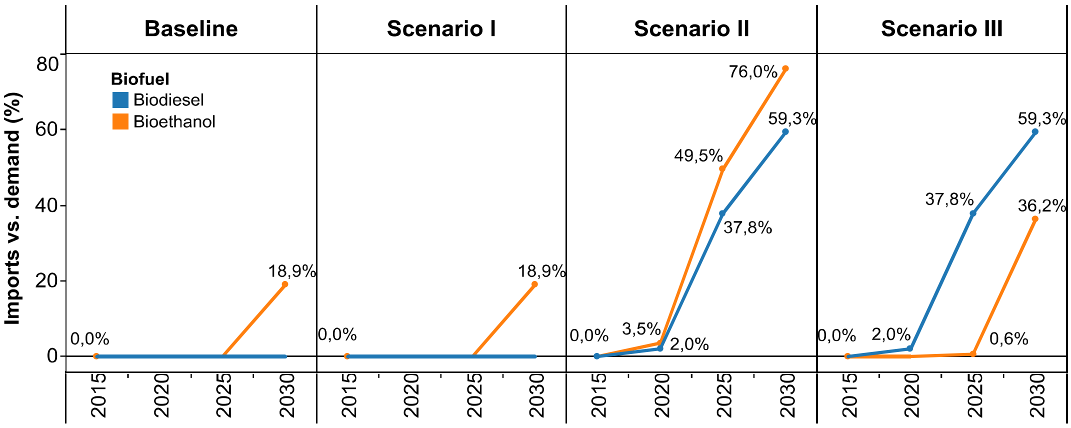

Figure 17. *Imports vs. demand for biofuels by scenario*

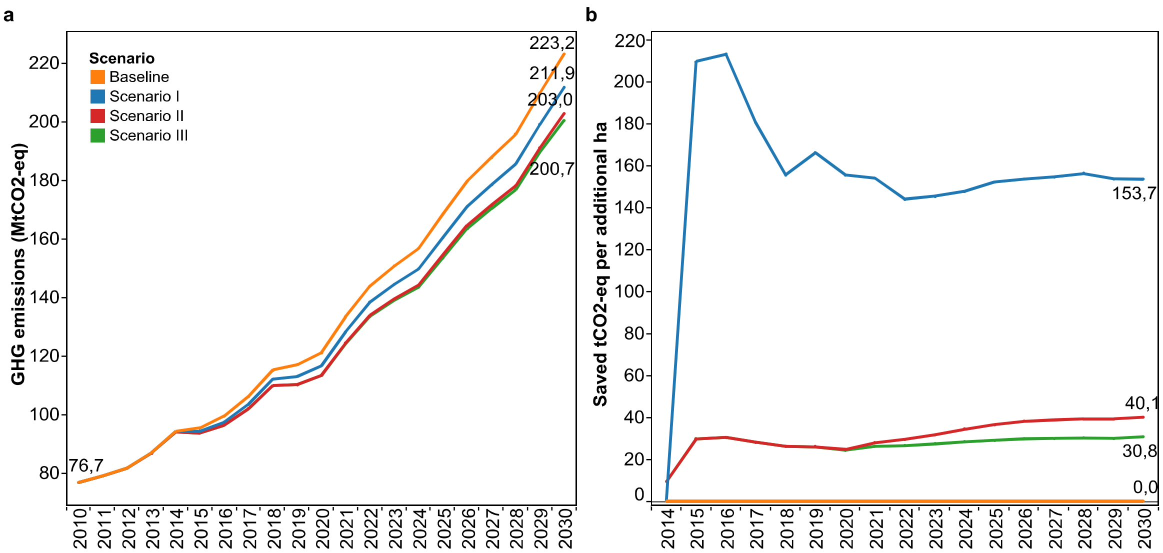

Figure 18. *GHG emissions by scenario. a, greenhouse gas emissions by scenario in MtCO$_2$-eq. b, Emission reductions per incremental land in saved tons of CO$_2$ equivalent per additional hectare of land to cultivate biomass resources*

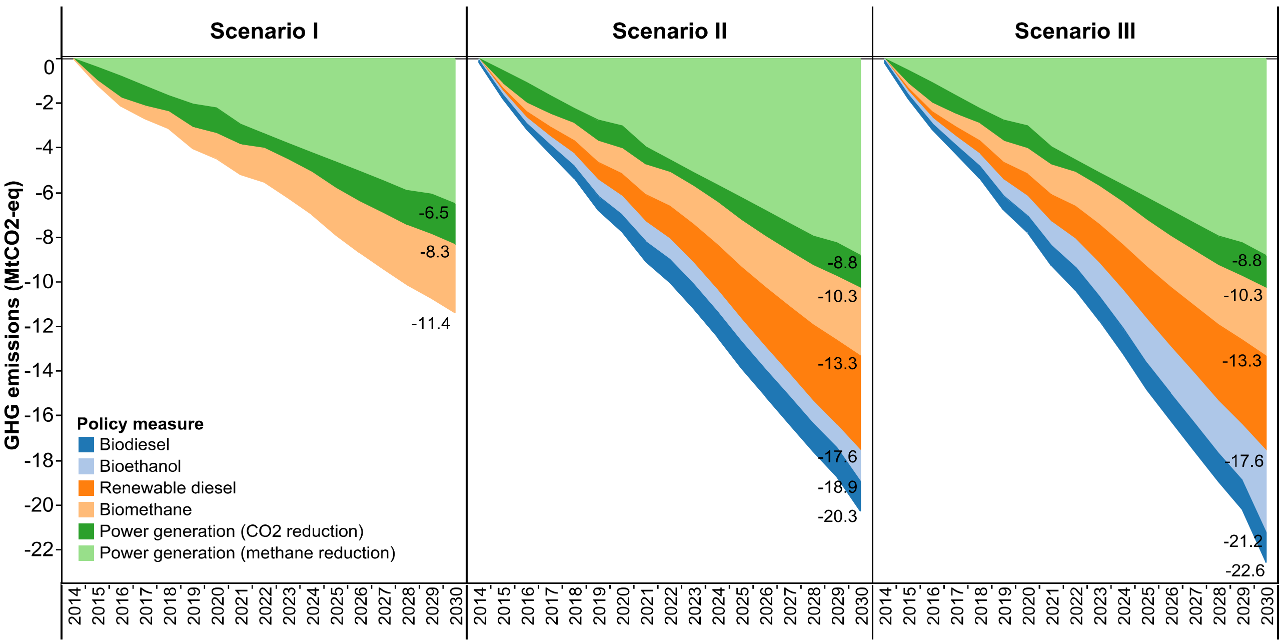

Figure 19. *Reduction in GHG emissions in MtCO$_2$-eq by scenario and policy measure. Labels indicate aggregated reductions for the different policy measures. For power generation the effects of reducing methane and CO$_2$ emissions are further disaggregated*

8. Conclusions

This paper presented a modeling framework to address the energy, economy, land use and GHG emissions nexus when exploiting bioenergy in developing countries. The novelty of the proposed framework can be explained as follows. Firstly, the proposed framework combines qualitative and quantitative methods to investigate long-term deployment of bioenergy and its associated impacts, whereas prior art concentrate in one or the other. Secondly, the proposed framework offers a comprehensive approach to investigate the energy sector and a relatively simple approach to investigate the economy, land use and climate linkages. This allows the possibility to provide preliminary assessments. In contrast, most prior art is characterized by having complex frameworks that do not allow preliminary estimations. The proposed framework offers various advantages: 1) it uses various state-of-the-art modeling techniques that are robust and acknowledged in the scientific community, 2) it uses well-known platforms (i.e. LEAP and Microsoft Excel), which are relatively inexpensive and easy to replicate, 3) it employs scenario analysis to consider possible alternative future storylines and to allow policy analysis and 4) it is calibrated and fully supported by official data. The generic character and flexibility of the method allows the possibility of implementing alternative scenarios or testing new technologies, and more importantly, of being adapted to other countries. However, these implementations are data intensive, which is actually a disadvantage of the proposed method. Moreover, the proposed modeling framework involves some limitations. These include: a) the ESM does not estimate lifecycle emissions and does not perform sophisticated modeling of branches not substantially affected by bioenergy, b) the impacts on rural development, living standards of rural communities, generation of employment, water demand and supply has been considered out of scope and c) for the particular case of power generation, results are obtained through a cost minimization approach, which does not necessarily take into consideration other drivers, such as the influence of politics, future energy and environmental regulations, sudden depletion of energy reserves, etc.

This modeling method was applied to evaluate the impacts that an accelerated deployment of bioenergy technologies in Colombia might cause on the energy demand and supply, emissions and land use until 2030. Results suggest that a plan to exploit bioenergy in Colombia should prioritize the deployment of technologies for biomethane production, power generation & CHP (in particular, landfill gas- and biogas-fuelled power plants), which can reduce more GHG emissions and more emissions per incremental hectare of land than first-generation biofuels. The advantage over biofuels is threefold: 1) avoiding methane release (a gas with 21 times more impact on GHG emissions than CO_2) in landfills and biogas from animal waste and wastewater, 2) contributing to the reduction of CO_2 emissions by replacing fossil fuels in gas or electricity supplies and 3) not requiring additional dedicated land. This result is not obvious in Colombia, given that currently power generation is mostly renewable (68% hydro-based in 2010) and road transport is ~95% fossil fuel-based. However, the results are consistent since power generation and transport only contribute to 20% of the national GHG emissions in 2004, while animal waste and residues (responsible for most methane emissions) contribute to 25% (IDEAM, 2009), similarly to other Latin American countries (De la Torre, Fajnzylber, & Nash, 2010). Moreover, these results agree with conclusions from earlier studies conducted for other countries (Cherubini & Stromman, 2011; Cherubini, et al., 2009; Gerssen-Gondelach, Saygin, Wicke, Patel, & Faaij, 2014). In addition, results show that the impacts of El Niño oscillation on the dependence of hydro for power generation can be partly mitigated by exploiting the complementarity of hydro and bioenergy, particularly in dry years. This complementarity might result in a reduction of up to 5-6% in the demand for fossil fuels used in power generation in dry years, when availability of hydro is limited.

Regarding biofuels, it is recommended to pursue policy measures for renewable diesel, which proved to be attainable and effective in reducing emissions. It is recommended to re-evaluate the policy measures proposed in this study for bioethanol and biodiesel. The proposed long-term goals for these technologies could not be attained under current land conditions and imports are needed in all scenarios. Additionally, bioethanol and biodiesel appeared less effective for reducing emissions and emissions per additional hectare of land use than other options. Despite the ambitious goals proposed in this study, bioenergy alone cannot significantly reduce emissions by 2030 (maximum 10% reduction relative to baseline) and effective climate change mitigation requires a portfolio of additional measures. These results are novel for Colombia and might be helpful to policymakers evaluating the role of bioenergy in a post-conflict context and to other countries with significant bioenergy potential and similar compositions of national GHG emissions. Recommendations for further studies include: a) investigate the life cycle GHG emissions of different bioenergy technologies under the specific conditions of Colombia, b) perform detailed economic analyses of different bioenergy routes and c) identify modeling frameworks, tools and methodologies to evaluate the impacts of implementing different bioenergy technologies on rural development, water supply, biodiversity, etc..

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