UvA-DARE (Digital Academic Repository)

A cross-sectoral integrated assessment of alternatives for climate mitigation in Madagascar

Nogueira, L.P.; Dalla Longa, F.; van der Zwaan, B.

DOI

[10.1080/14693062.2020.1791030](https://doi.org/10.1080/14693062.2020.1791030)

Publication date

2020

Document Version

Final published version

Published in

Climate Policy

License

Article 25fa Dutch Copyright Act

[Link to publication](#)

Citation for published version (APA):

Nogueira, L. P., Dalla Longa, F., & van der Zwaan, B. (2020). A cross-sectoral integrated assessment of alternatives for climate mitigation in Madagascar. *Climate Policy*, 20(10), 1257-1273. <https://doi.org/10.1080/14693062.2020.1791030>

General rights

It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations

If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: <https://uba.uva.nl/en/contact>, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.

UvA-DARE is a service provided by the library of the University of Amsterdam (<https://dare.uva.nl>)

RESEARCH ARTICLE

A cross-sectoral integrated assessment of alternatives for climate mitigation in Madagascar

Larissa P. Nogueira ^a, Francesco Dalla Longa^a and Bob van der Zwaan^{a,b,c}

^aEnergy Transition department, TNO, Amsterdam, The Netherlands; ^bFaculty of Science (HIMS and IAS), University of Amsterdam, Amsterdam, The Netherlands; ^cSchool of Advanced International Studies (SAIS), Johns Hopkins University, Bologna, Italy

ABSTRACT

Using the integrated assessment model TIAM-ECN, we analyze how Madagascar's nationally determined contribution (NDC) to the Paris Agreement can be implemented in both the energy and non-energy sectors. We explore how the country's national climate goal for 2030 can be reached under two different cost levels for climate change mitigation through land-use change. We find that land use is the main sector in which large greenhouse gas (GHG) emission reductions must be achieved, but there are opportunities to also exploit the country's abundant domestic low-carbon energy resources. We explore the options for such a transformation of Madagascar's energy system, which today largely relies on the use of biomass. If GHG emissions reduction in land use is hard or too costly to implement, e.g. as a result of land property rights or forest logging practices, total final energy use needs to be almost entirely renewable by 2050. The power sector needs to rely on 100% renewables already by 2030. In our scenario runs, biomass, hydropower, solar and wind energy account for the vast majority of electricity generation in Madagascar from 2030 onwards. Electrification is introduced in the residential sector – notably for cooking. Cumulative additional undiscounted investment requirements may be as high as US\$ 8 billion up to 2050.

Key policy insights

- Madagascar could reach its 14% GHG emission reduction target relative to 2030 business-as-usual levels through the land use sector only. However, given the potential higher mitigation costs in land use and its links with the energy system, overlooking mitigation options in the energy sector could be a missed opportunity to exploit abundant domestic low-carbon energy resources.
- Biomass may well remain the most important energy resource in Madagascar until 2050, mainly driven by residential cooking demand. Solid biomass stoves with efficient combustion should be promoted hand-in-hand with alternative fuels, e.g. electricity and bioethanol.
- Promoting GHG mitigation in both AFOLU and energy sectors maximizes co-benefits, which enables achieving a higher number of sustainable development goals (SDGs).
- Providing electricity for household services is an important part of climate change mitigation. Investments in power distribution infrastructure and decentralized electricity generation are needed to achieve electrification of rural households.

ARTICLE HISTORY

Received 17 November 2019
Accepted 30 June 2020

KEYWORDS

Madagascar; NDC; climate change; energy; land use; IAM

1. Introduction

All countries that are parties to the Paris Agreement are required to contribute to limiting the global average atmospheric temperature increase to 'well below' 2°C, and preferably less (UNFCCC, 2015). In this paper we

focus on Madagascar and thereby connect to work that has recently been done for Africa in the domain of assessments of regional contributions to global climate change mitigation goals (see, for example, IEA, 2014, 2019; Lucas et al., 2015; Sweerts et al., 2019; van der Zwaan et al., 2018b).

Madagascar is the fifth largest island in the world, located in the Indian Ocean east of the southern African continent. Its population was around 26 million in 2017 and, while it is still classified as a least developed country, its gross domestic product (GDP) grew by 2.3% in 2013 and by 5% in 2018 (AfDB, 2019; World Bank, 2019a). The main economic activities in Madagascar are agriculture and services, corresponding to 25% and 59% of GDP in 2008, respectively (MEF, 2015). Its industry has been growing in recent years, but remains incipient, driven mainly by the production of textiles and essential oils (AfDB, 2019; MEF, 2015).

Greenhouse gas (GHG) emissions in Madagascar are mainly driven by the agriculture, forestry and other land use (AFOLU) sector (Madagascar, 2015; UNCCD, 2018). AFOLU accounted for 89% of total national GHG emissions in 2010 according to the 'Global Mechanism' of the United Nations Convention to Combat Desertification (UNCCD, 2018). However, statistics on GHG emissions and carbon dioxide removal (CDR) are inconsistent across different data sources. The official communication to the United Nations Framework Convention on Climate Change Control (UNFCCC) on Madagascar's Nationally Determined Contribution (NDC; see Madagascar, 2015) reports that, in 2010, gross and net GHG emissions corresponded to 157 MtCO₂eq and -63 MtCO₂eq, respectively, while CDR amounted to 220 MtCO₂eq. Madagascar's Yearbook on Environmental Statistics (Balgobin & Iharimamy, 2016) reports a total of 87 MtCO₂eq of (presumably) gross GHG emissions in 2010, while the CDR level is reported only for the year 2000 (233 MtCO₂eq). The Climate Analysis Indicators Tool (CAIT) from the Climate Watch database (Climate Watch, 2019) reports for Madagascar 60 MtCO₂eq of (presumably) gross GHG emissions in 2010. This database reports a slight decrease of GHG emissions in Madagascar after 2010, reaching 59 MtCO₂eq in 2016. No information on CDR is provided by Climate Watch. These three examples show that a large discrepancy exists with regards to GHG emission statistics across different sources. This may be explained by how environmental change impacts are represented and which areas are considered managed, which affects estimation methods of forest sinks and, hence, the accounting of GHG emissions in AFOLU (Grassi et al., 2018).

The main primary energy source in Madagascar is currently solid biomass, at 1,148 ktOE in 2015 (AFREC, 2018). Biomass use is mostly driven by cooking demand in the residential sector. Electrification in the country is low, with an average access-to-electricity level of around 15%. The rural electrification level was only about 4% in 2015 (USAID, 2016). The installed capacity in the power sector was around 500 MW in 2015, generating 2.7 GWh of electricity mainly from fossil fuels (63%) and hydropower (36%; see AFREC, 2018; USAID, 2016). Imports of oil products are essential not only for power generation, but also for the transport sector (AFREC, 2018). Energy-related GHG emissions in Madagascar represented less than 5% of gross GHG emissions in 2010 (Balgobin & Iharimamy, 2016; Climate Watch, 2019).

Although Madagascar's share in global GHG emissions is negligible, its government is committed to climate change mitigation and adaptation measures. The country is highly vulnerable to climate change effects, such as extended drought periods, increased variability of the rainfall season, intensification of cyclones and floods (Madagascar, 2015). Madagascar has an exceptional biodiversity in its tropical forests, which is severely affected by deforestation due to human activities such as 'tavy' (slash-and-burn agriculture), cash cropping (large-scale crop production for commercialization) and pasture. Logging for timber and other wood-based products for export is also an important driver of deforestation (EC, 2014). Since tropical forests store large amounts of carbon (MEDD, 2017; Vieilledent et al., 2016), these activities explain the pivotal role that AFOLU plays in managing national net GHG emission levels.

Madagascar's current NDC sets targets of 14% reduction for gross GHG emissions and 32% increase for CDR in 2030, both relative to 'business-as-usual' (BAU) projections. In absolute terms, these percentages correspond to 184 MtCO₂eq gross GHG emissions and 254 MtCO₂eq CDR in 2030 (Madagascar, 2015). The Annex of the NDC document indicates that GHG emissions in the energy sector and in agriculture may be reduced by 14% and 10% in 2030 relative to BAU, respectively, so to achieve the national GHG reduction target. The present NDC lists several actions per sector available to achieve these goals, including deforestation reduction, forest

recovery, improved farming and conservation measures, along with actions for the energy sector and related to waste management (Madagascar, 2015).

So far, few studies have focused on the assessment of NDCs proposed by African countries, and most of them lack an integrated approach that evaluates mitigation options under a cost-optimal perspective (Ouedraogo, 2019; Roche et al., 2019; van Zyl et al., 2018). Given the intimate link between land-use change and the energy sector, and their respective contributions to Madagascar's GHG emission reduction ambitions, its NDC targets and their implications must be assessed from a holistic perspective. We therefore use an Integrated Assessment Model (IAM) to inspect Madagascar's NDC under different scenarios. IAMs are extensively used by the Intergovernmental Panel on Climate Change (IPCC) and inform the policy-making process at the national level as well as in international climate negotiations (IAMC, 2019; IPCC, 2014, 2018). Previous studies have also used IAMs to inspect energy system challenges (Lucas et al., 2015), low carbon pathways (van der Zwaan et al., 2018b) and financial aspects of renewable energy investments (Sweerts et al., 2019) in Africa. An IAM approach has also been applied to assess policies in African countries more specifically, such as Kenya (Dalla Longa & van der Zwaan, 2017) and Ethiopia (van der Zwaan et al., 2018a).

Our aim in this paper is to inspect the way in which Madagascar can achieve its NDC by investigating the role of mitigation in AFOLU and in the energy system in 2030 and beyond. We demonstrate how mitigation in the energy system may cost-effectively complement mitigation in AFOLU, and show which technologies are key for the transition towards a low-carbon economy. The tool that we use for this purpose in the present study is TIAM-ECN (the TIMES Integrated Assessment Model operated at the Energy Transition department of TNO), an established global IAM that allows for analyzing the dynamics of the energy system, while covering all main elements that drive GHG emissions beyond the energy and the economy, such as AFOLU.

In section 2 of this article we concisely describe our methodology. In section 3 we summarize our main findings for Madagascar's current NDC, as well as the extrapolation thereof until 2050. We choose to extend our analysis beyond 2030, which is the year to which the NDC target applies, because climate change is a long-term issue and mitigation action needs to be sustainably addressed during the next decades (UNFCCC, 2019). Moreover, the investments in mitigation have an economic lifetime that extends beyond 2030, and therefore impact the technology mix and system costs in the following decades. In section 4 we discuss our results, draw some overall conclusions and formulate several recommendations.

2. Methodology

2.1. TIAM-ECN

TIAM-ECN is a linear programming cost-optimization model linking energy, economy and environment to find cost-minimal energy system pathways, subject to constraints and scenarios specified *a priori*. It is a technology-rich energy systems model derived from TIAM, which is a global IAM based on the TIMES model generator (see Loulou, 2008; Loulou & Labriet, 2008). Its time horizon spans up to 2100 so as to duly account for climate change dynamics. The framework of TIAM-ECN disaggregates the world into 36 distinct geographical areas, which allows for a representative set of regional and national studies to be performed (see van der Zwaan et al., 2018b).

TIAM-ECN covers all main economic sectors: power and heat supply, industry, transport, residential and commercial. It reaches a partial equilibrium so as to meet end-use service demands with the least-cost set of energy commodities produced by different conversion technologies. Its objective function minimizes the total discounted global energy system costs aggregated over time and regions, accounting for investment costs, fuel costs and fixed plus variable operation and maintenance (O&M) costs along the whole energy chains from resource extraction to final consumption. Other cost components, such as decommissioning and infrastructure costs, are also taken into account, but in a more simplified way. For a generic description of the main elements of the energy system represented in TIAM-ECN, see Syri et al. (2008).

Thanks to its richness in technology detail, TIAM-ECN has been employed for assessments that cover a diverse number of topics, including transport (see Rösler et al., 2014), power supply (Keppo & van der Zwaan, 2012; Kober et al., 2016), regional burden-sharing regimes for GHG mitigation (Kober et al., 2014), and

technology diffusion (see van der Zwaan et al., 2013, 2016). These publications contain elaborate explanations of the main features and data inputs of TIAM-ECN. We thus restrict ourselves to listing only the elements of the energy system that are relevant to our study: renewable power generation and cooking stoves used in the residential sector. Information on these technologies can be found in the Appendix.

2.2. Model developments focusing on Africa and Madagascar

The TIAM-ECN model has been substantially improved in terms of the level of detail with which it simulates Africa (see Dalla Longa & van der Zwaan, 2017; Dalla Longa et al., 2018; Sweerts et al., 2019; van der Zwaan et al., 2018a, 2018b). For this study, we have updated and adjusted relevant input data and the simulated structure of AFOLU to better reflect the reality on the ground in Madagascar. We have also substantially improved the representation of non-energy GHG emissions and abatement options, as well as their respective potentials. For this purpose, we have considered a simplified sequence of AFOLU activities, based on EC (2014). Under this sequence, forest is first harvested for logging and timber production. Second, remaining biomass is harvested for energy purposes. Third, harvested land is burned and used for low-productivity agriculture or for cash-cropping (depending on the land type) without prospects for near-term recovery via reforestation. We assume that the sum of these activities leads to GHG emissions, the level of which is determined by the carbon stock of different types of forests in Madagascar (MEDD, 2017). We assume that the evolution of biomass demand for energy purposes constitutes the main driver of deforestation (Scales, 2014). By allocating emission coefficients to the production of biomass for energy purposes, we account for GHG emissions due to land use. For details behind our data and assumptions, see the Appendix.

Madagascar has four main types of forests: humid, dry, spiny and mangroves. In TIAM-ECN, we group the last two types into one category, since they represent only a small percentage of non-protected land. Emission coefficients accounting for carbon stock levels are taken from Madagascar's Ministry of Environment, Ecology, Sea and Forests (MEDD, 2017). We assume that 5% of the carbon content of harvested forests is kept as timber, which therefore is not burned on land or for energy purposes (Rochedo et al., 2018). Estimates of non-protected areas per forest type, historical annual deforestation rates, and energy yields of various biomass types, are taken from MEDD (2017) and EC (2014). The evolution of biomass supply for energy usage up to 2050 is based on WWF (2012). From this source, we estimate GHG emissions per unit of biomass used for energy purposes, the annual availability of biomass, as well as its cumulative potential.

Seven GHG mitigation alternatives in AFOLU are modelled: three afforestation and/or reforestation options and four options in agriculture. Madagascar's NDC reports eight mitigation actions for AFOLU. Some of these actions may overlap, such as in agroforestry and reforestation. Moreover, some measures are not detailed enough for deriving cost and potential assumptions, such as conservation in agriculture. In those cases, we model mitigation measures on the basis of data and descriptions available in the literature to reflect the situation in Madagascar as closely as possible.

We differentiate between afforestation and reforestation options (see Table 1) in terms of GHG mitigation potential (EC, 2014; MEDD, 2017) and costs¹ (Sathaye et al., 2006). Potentials and costs are dependent on the type of forest. In our set-up, the available GHG abatement potential from reforestation and/or afforestation options is not sufficient to fully counterbalance emissions from deforestation. This is assumed to be the

Table 1. Annual abatement potentials and costs of forestry mitigation options.

Forest type	Annual Potential (MtCO ₂ eq)	Investment Cost ^a (US\$(2010)/tCO ₂ eq)	Variable Cost ^b (US\$(2010)/tCO ₂ eq)
Humid	80.2	1.8	0.3
Dry	88.4	6.3	0.9
Other	50.8	15.1	2.8

Source: (based on Sathaye et al., 2006).

^aInitial cost.

^bRecurring and monitoring cost.

combined consequence of both population and economic growth, which leads to pressure on other kinds of land use, such as for crop cultivation and logging.

We simulate four mitigation options for agriculture (based on Smith et al., 2008):

- **Land conservation, agronomy:** adopting improved varieties of crop, extending crop rotations and reducing the use of bare fallow so to increase soil carbon storage, thereby decreasing CO₂ emissions.
- **Land conservation, nutrient management:** improving the efficiency of nitrogen usage, so as to reduce nitrous oxide (N₂O) emissions. Practices include adjusting application doses based on precision farming and using slow-release forms of fertilizers.
- **Land conservation, tillage and residue management:** adopting weed control methods and farm machinery that allow tillage reduction, which results in increased carbon stock in soil and thereby reduces CO₂ emissions.
- **Rice field management:** implementing methane (CH₄) emission reduction during rice growing and off-season periods based on water management practices, such as frequent wetland draining. Timing adjustments of organic residue additions, residue composting, and biogas production might also reduce CH₄ emissions. This option has the highest mitigation potential, as rice is the main crop cultivated in Madagascar (FAO, 2019).

We estimate annual potentials for GHG mitigation in agriculture according to historical data on land harvested for rice and other crops between 2005 and 2015 as reported in the database of the Food and Agriculture Organisation of the United Nations (FAOSTAT, see FAO, 2019). We combine these with data on GHG emissions from rice cultivation (Hussain et al., 2015) and data on abatement potentials and costs for different conservation measures (Smith et al., 2008). Table 2 summarizes our assumptions for potentials and abatement costs of mitigation options in agriculture.

Further assumptions in TIAM-ECN for Madagascar's energy system relate to fossil fuel production and imports, as we assume a limited expansion of fossil fuel consumption and no local oil refining. Biofuels production is subject to the potential linked to land availability, while renewables other than biomass are also limited by local techno-economic potentials (see Appendix). Since cooking constitutes the main final energy use in the residential sector, data on cooking stoves has been updated. Costs are based on Fernandes and Keemink (2017) and ethanol stoves are included as an option, given reported efforts on expanding the use of liquid biofuels for cooking (CCM, 2019; Project Gaia, 2019). On the basis of air quality concerns related to solid biomass use in the residential sector, we assume that its consumption steadily decreases, down to 75% and 30% of cooking demand in 2030 and 2050 respectively.

2.3. Scenarios

For the present study we run three scenarios in TIAM-ECN, summarized in Table 3. The first one is a reference (i.e. 'baseline' or 'business-as-usual') scenario, called REF, in which no mitigation policy is imposed. GHG emissions from forestry evolve in accordance with biomass consumption for energy purposes. CDR through AFOLU is assumed to remain constant at its 2010 level throughout our modelling time horizon, which reflects that no additional effort is made with regard to forest and farming conservation practices. In the second scenario, entitled NDC, the current commitment to the Paris Agreement is implemented, implying a 14% GHG emission reduction in 2030 with respect to the REF scenario. The maximum allowed emission level is kept constant up to

Table 2. Annual abatement potentials and costs of cropland mitigation options.

	Annual Potential (MtCO ₂ eq)	Abatement Cost (US\$(2010)/tCO ₂ eq)
Land conservation, agronomy	1.7	20–50
Land conservation, nutrient management	1.1	8–15
Land conservation, tillage and residue management	0.6	7–14
Rice field management	15.7	1.2

Source: (FAO, 2017, 2019; Hussain et al., 2015; Smith et al., 2008).

Table 3. Summary of scenarios.

Scenario	GHG reduction	GHG emissions in AFOLU
REF	none	Fixed GHG emissions and CDR
NDC	–14% in 2030 w.r.t. REF	Fixed GHG emissions and upper limit on CDR, with moderate costs
NDC+	–14% in 2030 w.r.t. REF	Fixed GHG emissions and upper limit on CDR, with high costs

2050. We assume the same level of GHG emissions from forestry as in the REF scenario in all time periods. With regard to CDR, we let the model optimize the expansion of available mitigation options in AFOLU, keeping in mind the discrepancies in AFOLU emissions between IAM results and national inventories pointed out by Grassi et al. (2018). The third scenario, called NDC+, resembles the NDC scenario in all respects except for the assumption that the costs for mitigation in AFOLU are much higher. For this purpose, we consider that all AFOLU-related mitigation costs are around ten times higher than available literature estimates. This assumption reflects the difficulties that Madagascar faces with regards to corruption, which includes land property issues and illegal logging practices (EC, 2014; Scales, 2014; Vieilledent et al., 2018). It draws on the work of Gusti et al. (2019) on the estimation of mitigation costs in contexts where institutions are weak and corruption is rife. Another reason for considering two distinct NDC scenarios is the high uncertainty of mitigation costs and potentials from AFOLU in Madagascar. This uncertainty derives mainly from the difficulty of measuring the carbon storage capacity for different types of forest (Brinck et al., 2017) and for diverse geographical locations (Saatchi et al., 2011; Vieilledent et al., 2016), as well as from a lack of reliable statistical data for a developing country such as Madagascar. Both NDC scenarios simulate ambitious global climate action in which the 2° C target of the Paris Agreement is met (for details, see van der Zwaan et al., 2018b). Table 3 summarizes the main features of our three scenarios.

As Table 3 confirms, our three scenarios are differentiated at the national level both by a domestic GHG reduction target and by limits imposed on GHG emissions and CDR in AFOLU. These are constraints applied as input parameters by the user of the model. TIAM-ECN results should therefore be interpreted as projections – rather than forecasts – of how GHG emissions and the energy system could potentially evolve in the long-term future. Other inputs common to the three scenarios considered in this paper concern the techno-economic characterization of GHG abatement options and energy conversion technologies, the resource availability of energy commodities and land use, as well as the energy demand implications of GDP and population growth. The three scenarios also adopt common assumptions related to the global context and inter-regional interactions, such as in terms of worldwide fossil fuel reserves (disaggregated per region), renewable energy potentials (also broken down per region), energy trade possibilities between regions, autonomous energy efficiency and decarbonization processes, as well as energy-climate policies at the global and regional/national level.

3. Results

Figure 1 shows the GHG emissions for Madagascar projected by TIAM-ECN in our three scenarios up to 2050. Gross GHG emissions and CDR efforts are plotted as bars, while net GHG emissions are shown as dotted lines. Gross GHG emissions are 87 MtCO₂eq in 2010, as reported in the environmental statistics of Madagascar (Balgobin & Iharimamy, 2016). As can be seen, the REF scenario yields a steady growth of both gross and net GHG emissions driven by an expected future increase in energy demand and land-use change. Net GHG emissions reach 87 MtCO₂eq in 2030 and 135 MtCO₂eq in 2050. These outcomes correspond to a doubling of GHG emission levels in 2030 relative to 2010, and a threefold increase in 2050.

Results for both NDC scenarios show that a high level of CDR is needed in order to meet the 14% net GHG emission reduction target. In the NDC scenario, gross GHG emissions are roughly the same as in REF, which indicates that this scenario relies fully on mitigation in AFOLU via CDR to bring net GHG emissions to the level of the NDC target. Gross GHG emissions do show a decrease in the NDC+ scenario, down to 167 MtCO₂eq in 2050, against 180 MtCO₂eq in the REF and NDC scenarios. This decrease is enabled by an increase of mitigation in the energy sector, and results from the higher mitigation costs in land-use-related sectors, which reduces the role of CDR in AFOLU.

Figure 1. Projections for gross GHG emissions, CDR and net GHG emissions across three scenarios for Madagascar.

In Figure 2, the sectoral breakdown of gross GHG emissions (bars) as well as net GHG emissions (diamonds) across our three scenarios for Madagascar are reported. The bars show that land use still accounts for by far the highest share of gross GHG emissions in 2050, varying between 82% (REF) and 90% (NDC+). Results for the NDC + scenario show that, if GHG emission abatement in AFOLU is costly, GHG mitigation is triggered in the energy system. GHG emissions associated with energy use in the residential sector are particularly strongly impacted, with a 20% and 60% reduction in gross GHG emissions relative to REF in 2030 and 2050 respectively.

Figure 2. Sectoral break-down of gross GHG emissions across three scenarios for Madagascar.

Figure 3. Projections for final energy use in Madagascar: energy carrier breakdown (left) and sectoral breakdown (right).

Projections for final energy use in our three scenarios are depicted in Figure 3 disaggregated by energy carrier (left panel) and by sector (right panel). In 2010 final energy supply amounted to 261 PJ, 90% of which derived from solid biomass, while the remaining 10% was provided by petroleum products. The latter are assumed to be imported throughout the entire modelling time horizon, since no refining capacity is currently available in Madagascar and no investment plans are envisaged in the foreseeable future. In the REF scenario, imports of petroleum products gradually increase, up to 21% of total final energy supply in 2050. Meanwhile, the use of solid biomass decreases to 39% during this period. Still, Madagascar's energy system remains highly dependent on bioenergy, not only because of the continued role played by solid biomass, but also by liquid biofuels (especially bioethanol) that represent close to 30% of final energy supply in 2050. Electricity production becomes relevant from around 2030 and increases its share to 9% of total final energy supply in 2050.

Because the NDC target can be reached entirely through CDR in AFOLU, the energy system in the NDC scenario remains essentially the same as that in the REF scenario. It will thus partly stay dependent on imports of fossil fuel products. The NDC+ scenario, on the other hand, shows significant changes in the final energy mix in comparison to the REF scenario. First, as can be seen in both panels of Figure 3, total final energy consumption in 2050 is higher in the NDC+ scenario than in both REF and NDC (570 PJ vs. 545 PJ). Second, the need for GHG emission reductions in combination with high abatement costs in AFOLU triggers an energy transition based particularly on higher utilization of biomass in NDC+, in comparison to the REF and NDC scenarios. Solid biomass and liquid biofuels taken together account for around 73% of total final energy in 2050. Bioethanol is the main liquid biofuel and it is utilized predominantly in transportation (for private vehicles) and the residential sector (in cooking stoves). Third, in NDC+ electricity generation reaches a share of 26% of total final energy supply in 2050, mainly triggered by a partial electrification of the residential and industrial sectors. Energy demand in industry and transport is slightly reduced in NDC+, but not enough to compensate for the higher energy demand in the residential sector. The latter drives total final energy use upwards in all years with respect to REF and NDC (see the right panel of Figure 3).

Figure 4 zooms in on the residential sector by depicting the evolution of its final energy consumption (similar figures for transport and industry can be found in the Appendix). A diversification in the fuel mix can be observed between 2020 and 2050 in all scenarios. In both REF and NDC scenarios, the utilization of solid biomass for cooking is substituted initially by the adoption of petroleum products (mainly diesel), and by bioethanol and electricity

Figure 4. Projections for final energy use in the residential sector in Madagascar.

from 2030 onwards. Our projections for the NDC+ scenario show a modest uptake of petroleum products in 2030 and 2040, which disappears in 2050. Electricity reaches a 25% share of final energy demand in the residential sector by the middle of the century, thanks to the increased deployment of decentralized grids and the uptake of electric cooking stoves in households. Total residential energy use in NDC+ is higher than in the other two scenarios throughout our modelling time horizon. This results from the increased use of low-carbon ethanol cooking stoves in this scenario, which are less energy efficient than the diesel-fueled ones used in REF and NDC. Because Madagascar's NDC does not define what would constitute 'improved stoves', we cannot state that our results show

Figure 5. Projections for electricity supply and consumption in Madagascar: technology breakdown (left) and sectoral breakdown (right).

Figure 6. Additional annual energy system costs in Madagascar between NDC+ and NDC.

that this goal could be met even in the REF scenario. However, our results indicate that more than 50% of renewable-based cookstoves in households can be achieved.

Results for the power supply sector are summarized in Figure 5, both with an energy resource breakdown (left panel) and a sectoral consumption breakdown (right panel). The REF and NDC scenarios show a substantial growth in electricity supply, from 2 TWh in 2010–16 TWh in 2050. Our results for NDC+ show that power generation in this scenario increases even more rapidly. All scenarios share a 100% renewable mix from 2030 onwards, since imported petroleum products are replaced by domestic resources based on hydropower, solid biomass, wind and solar energy. In the NDC+ scenario, wind and decentralized solar power become prominent in 2050, supplying 32% and 40% of total electricity, respectively. Investments in biomass-based thermal plants are also triggered from 2030 onwards in all three scenarios. NDC+ yields the highest production of bio-electricity. A marginal part hereof is produced with power plants equipped with carbon dioxide capture and storage (CCS) technology in 2040 and 2050. The right panel of Figure 5 shows that the sharp increase in power generation in the NDC+ scenario is mainly driven by power consumption in the residential sector, which requires 67% of electricity supply in 2050. The industry sector also becomes more electrified, doubling its power demand in NDC+ relative to REF in 2050. Overall power consumption in 2050 amounts to 47 TWh in NDC+, against 16 TWh in REF. All scenarios account for transmission and distribution losses, which explains the differences between the power supply and consumption graphs.

Figure 6 shows the difference in undiscounted annual energy system costs between our two NDC scenarios. It expresses the extent to which shifting mitigation efforts from AFOLU to the energy sector impacts the costs of Madagascar's energy system when the country attempts to achieve its stipulated NDC goal. Additional annual energy system costs include investment requirements for energy technology deployment in all sectors, as well as the corresponding fixed and variable operation and maintenance (O&M) costs and the net costs of trade (accounting for both import expenditures and export revenues). Our results show that additional annual energy system costs in 2030 may exceed 1 billion US\$. If the same emission limit is to be kept after 2030, additional annual costs may increase to 5 billion US\$ by the middle of the century. These additional costs mainly consist of investments necessitated by an expansion of the power sector, required in order to increase the electrification levels in the residential and industrial sectors.

4. Conclusions

Using the integrated assessment model TIAM-ECN, we have analyzed how Madagascar could achieve its emission reduction target under its NDC. We do so under two different assumptions for the costs of land-use-based climate change mitigation efforts. Distinguishing between two cost alternatives reflects the uncertainties associated with AFOLU-related GHG emission reduction options in Madagascar, as well as the lack of accurate and reliable data regarding land-use change in the country. By considering a scenario with higher GHG abatement

costs in AFOLU, we account for additional costs associated with addressing land-use issues, which are typically not internalized in abatement cost calculations. Our integrated assessment allows for establishing a link between land-use change and energy generation in Madagascar.

We derive policy recommendations based on the scenario assessment developed with our model and, hence, focus on cost optimal possibilities for GHG mitigation. Under the Paris Agreement, all countries are required to regularly update and enhance the level of stringency of their NDCs. This also applies, of course, to Madagascar. We therefore recommend that the present research is updated and refined on a regular basis, so as to account for the gradual sharpening of our climate mitigation ambition level, in Madagascar as well as other nations. Our main conclusion from this study is that Madagascar can reach its 14% GHG emission reduction target employing mitigation in AFOLU only. However, overlooking mitigation options in the energy sector could be a missed opportunity to exploit the country's abundance of domestic low-carbon energy resources that can contribute to climate change mitigation. GHG mitigation in the energy system alone can at best only partially support Madagascar's NDC target. Hence, the country's efforts should in any case be directed towards improving land-use change practices. This can be achieved by, for example, land-use-regulatory measures, related notably to tenure rights and illegal deforestation; however, assessing how this can be done is beyond the scope of this paper. We do not link our recommendations to past experiences in Africa or other developing countries, which we believe should be subject of further investigation in order to complement the conclusions from our assessment.

Our results also show that, under all our scenarios, biomass remains the most important energy resource in Madagascar until 2050. The type of bioenergy used, however, gradually and partially changes from solid (traditional) to liquid (new, mainly bioethanol based) types, as a result of the expectations we simulated based on the desired objective of reducing traditional solid biomass utilization. The overall increase in biomass use accounts for investment requirements and potentials all along the energy chain from resource extraction to final use, and puts pressure on land use by triggering deforestation and cultivation of energy crops on previously untouched land. This modeling outcome should be duly internalized in energy and environmental policy design.

Enabling GHG mitigation in Madagascar's energy system might help it to become independent from fossil fuel imports by favouring the use of domestic renewable energy resources. Our results show that, if low-carbon development is based only on mitigation in AFOLU, the energy system remains dependent on fossil fuels that are neither produced nor processed domestically in the country itself.

In view of the sustainable development goals (SDGs, see UN, 2015), our results show that tackling climate change by reducing GHG emissions in AFOLU brings together 'climate action' (SDG 13), as embedded in the Paris Agreement, and protecting 'life on land' by maintaining forests and their biodiversity (SDG 15). Tackling climate change by combining mitigation in both the energy sector and AFOLU would allow Madagascar to implement not only SDGs 13 and 15, but also SDG 7, 'affordable and clean energy', as well as SDG 9, 'good health and well-being'. Meeting Madagascar's energy demand with its own domestic renewable resources can enhance the overall affordability of energy services, decrease air pollution caused by fossil fuels and thereby ameliorate living standards, and improve national energy security by reducing the reliance on fossil fuel imports.

Increasing energy access in Madagascar is mostly a matter of providing electricity services to support social and economic development, especially in rural areas (World Bank, 2019b). Our results show that providing electricity for household services, such as cooking, is an important issue to be addressed. Energy supply is expected to remain dominated by renewable sources in our scenarios for Madagascar, even in the absence of additional climate policies. Under the NDC+ scenario, by 2030, the country could achieve 91% renewables in the total energy mix, with 100% renewables in the power sector, (see Figures 3 and 5). Investments in power distribution infrastructure and decentralized electricity generation will be needed in order to achieve electrification of households in rural areas. These should thus be further investigated.

The energy transition in Madagascar in the long term will be mostly driven by the residential sector, especially induced by increased cooking demand. Within this sector, traditional biomass is expected to be gradually substituted by bioethanol and electricity, which would address issues related not only to GHG emissions, but also to air pollutants. Even with higher levels of electrification, as observed in our NDC+ scenario, solid biomass will likely still play an important role for cooking purposes. Hence, the adoption of stoves with efficient

combustion that minimizes the emission of particulates and other local pollutants should be promoted, which can go hand-in-hand with the adoption of novel technologies using alternative fuels such as bioethanol.

Our estimates project an additional cumulative undiscounted investment requirement of US\$ 8.5 billion up to 2050, in order to enable a low-carbon transition in the energy system. The high share of intermittent renewable energy resources in the power sector, such as based on wind and solar energy, might render extra investments in storage and other balancing options a necessity. These costs are only stylistically accounted for in our analysis. More detailed studies should be performed in order to estimate them more accurately.

Note

1. All costs reported in this paper are in US\$(2010).

Acknowledgements

The research that allowed the publication of this paper has been produced with financial support from the TRANSRISK project (EU Horizon 2020 research and innovation programme, grant agreement No. 642260). The findings and views reported in this article are the sole responsibility of the authors and can in no way be taken to reflect the views of the European Union. The authors would like to thank Mamy Nirina Rolland Randrianarivelo (Rinah) for her research assistance.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The research that allowed the publication of this paper has been produced with financial support from the TRANSRISK project (EU Horizon 2020 research and innovation programme, grant agreement No. 642260).

ORCID

Larissa P. Nogueira <http://orcid.org/0000-0003-3156-5998>

References

- AfDB. (2019). *African economic outlook 2019*. https://www.afdb.org/fileadmin/uploads/afdb/Documents/Publications/African_Economic_Outlook_2018_-_EN.pdf
- AFREC. (2018). *Africa energy database - Base de données énergétiques africaines Edition 2018*. https://afrec-energy.org/Docs/En/PDF/2018/statistics_2018_afrec.pdf
- Balgobin, D., & Iharimamy, A. (2016). *Annuaire des Statistiques Environnementales Sous le Cadre pour le Développement des Statistiques sur L'Environnement (CDSE)*.
- Brinck, K., Fischer, R., Groeneveld, J., Lehmann, S., De Paula, M. D., Pütz, S., Sexton, J. O., Song, D., & Huth, A. (2017). High resolution analysis of tropical forest fragmentation and its impact on the global carbon cycle. *Nature Communications*, Nature Publishing Group, 8(1), 14855. <https://doi.org/10.1038/ncomms14855>
- CCM. (2019). *Clean Cooking Madagascar*. Retrieved 23 April, 2019, from <http://madagascarethanolstoveprogram.org/clean-cooking-madagascar/>
- Climate Watch. (2019). *Climate Watch: Data for Climate Action*. Retrieved 18 February 2020, from <https://www.climatewatchdata.org/countries/MDG>
- Dalla Longa, F., Strikkers, T., Kober, T., & van der Zwaan, B. (2018). Advancing energy access modelling with geographical Information system data. *Environmental Modeling and Assessment*, 23(6), 627–637. <https://doi.org/10.1007/s10666-018-9627-1>
- Dalla Longa, F., & van der Zwaan, B. (2017). Do Kenya's climate change mitigation ambitions necessitate large-scale renewable energy deployment and dedicated low-carbon energy policy? *Renewable Energy*, Pergamon, 113, 1559–1568. <https://doi.org/10.1016/j.renene.2017.06.026>
- EC. (2014). *Forest governance and timber trade flows within, to and from eastern and southern African countries: Madagascar study*. <https://europa.eu/capacity4dev/public-flegt/blog/new-timber-report-timber-trade-flows-within-and-eastern-and-southern-african-countries>

- FAO. (2017). *Regional Analysis of the Nationally Determined Contributions of Eastern Africa: Gaps and Opportunities in the Agriculture Sectors. Environment and Resources Management*. Working Paper 67. <http://www.fao.org/3/a-i8165e.pdf>
- FAO. (2019). *FAOSTAT, Food and Agriculture statistics*. Retrieved February 18, 2019, from <http://www.fao.org/faostat/en/#data>
- Fernandes, F. G., & Keemink, M. (2017). Prospects for bioenergy in Africa.
- GIZ. (2014). *Multiple-Household Fuel Use - a balanced choice between firewood, charcoal and LPG*. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.
- Grassi, G., House, J., Kurz, W. A., Cescatti, A., Houghton, R. A., Peters, G. P., Sanz, M. J., Viñas, R. A., Alkama, R., Arneth, A., Bondeau, A., Dentener, F., Fader, M., Federici, S., Friedlingstein, P., Jain, A. K., Kato, E., Koven, C. D., Lee, D., ... Zaehle, S. (2018). Reconciling global-model estimates and country reporting of anthropogenic forest CO₂ sinks. *Nature Climate Change*, 8, 914–920. <https://doi.org/10.1038/s41558-018-0283-x>
- Gusti, M., Forsell, N., Havlik, P., Khabarov, N., Kraxner, F., & Obersteiner, M. (2019). The sensitivity of the costs of reducing emissions from deforestation and degradation (REDD) to future socioeconomic drivers and its implications for mitigation policy design. *Mitigation and Adaptation Strategies for Global Change*, 24, 1123–1141. <https://doi.org/10.1007/s11027-018-9817-9>
- Hussain, S., Peng, S., Fahad, F., Khaliq, A., Huang, J., Cui, K., & Nie, L. (2015). Rice management interventions to mitigate greenhouse gas emissions: A review. *Environmental Science and Pollution Research*, 22(5), 3342–3360. <https://doi.org/10.1007/s11356-014-3760-4>
- IAMC. (2019). IAMC — Integrated Assessment Modeling Consortium. Retrieved April 23, 2019, from <http://www.globalchange.umd.edu/iamc/>
- IEA. (2014). *Africa Energy Outlook – A focus on energy prospects in sub-Saharan Africa*. World Energy Outlook Special Report.
- IEA. (2019). *Africa Energy Outlook 2019*. World Energy Outlook Special Report.
- IPCC. (2014). *Climate change 2014: Mitigation of climate change*. Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on. <http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Climate+Change+2014+Mitigation+of+Climate+Change+Working+Group+III+Contribution+to+the+Fifth+Assessment+Report+of+the+Intergovernmental+Panel+on+Climate+Change#0>
- IPCC. (2018). Global warming of 1.5°C – SR15, Ipcc – Sr15. <http://www.ipcc.ch/report/sr15/>
- Keppo, I., & van der Zwaan, B. (2012). The impact of uncertainty in climate targets and CO₂ storage availability on long-term emissions abatement. *Environmental Modeling and Assessment*, 17(1–2), 177–191. <https://doi.org/10.1007/s10666-011-9283-1>
- Kober, T., Falzon, J., van der Zwaan, B., Calvin, K., Kanudia, A., Kitous, A., & Labriet, M. (2016). A Multi-model study of energy supply investments in latin America under climate control policy. *Energy Economics*, Elsevier B.V. <https://doi.org/10.1016/j.eneco.2016.01.005>
- Kober, T., van der Zwaan, B. C. C., & Rösler, H. (2014). Emission certificate trade and costs under regional burden-sharing regimes for a 2°C climate change control target. *Climate Change Economics*, World Scientific Publishing Company, 5(1), 1440001. <https://doi.org/10.1142/S2010007814400016>
- Loulou, R. (2008). ETSAP-TIAM: The TIMES integrated assessment model. Part II: Mathematical formulation. *Computational Management Science*, 5(1–2), 41–66. <https://doi.org/10.1007/s10287-007-0045-0>
- Loulou, R., & Labriet, M. (2008). ETSAP-TIAM: The TIMES integrated assessment model part I: Model structure. *Computational Management Science*, 5(1–2), 7–40. <https://doi.org/10.1007/s10287-007-0046-z>
- Lucas, P. L., Nielsen, J., Calvin, K., McCollum, D., Marangoni, G., Streffer, J., van der Zwaan, B., & van Vuuren, D. P. (2015). Future energy system challenges for Africa: Insights from integrated assessment Models. *Energy Policy*, 86, 705–717. <https://doi.org/10.1016/j.enpol.2015.08.017>
- Madagascar. (2015). Madagascar's intended nationally determined contribution. *United Nations Climate Change*, 1–13. [https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Madagascar First/Madagascar INDC Eng.pdf](https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Madagascar%20First/Madagascar%20INDC%20Eng.pdf)
- MEDD. (2017). *Niveaux d'émissions de référence des forêts de Madagascar pour la réduction des émissions dues à la déforestation et à la dégradation des forêts. Soumission à la Convention-Cadre des Nations Unies sur les Changements Climatiques*. Ministry of Environment and Sustainable Development.
- MEF. (2015). *Plan national de développement 2015–2019*. Ministry of Economy and Finance.
- Ouedraogo, N. S. (2019). Transition pathways for North Africa to meet its (intended) nationally determined contributions ((I)NDCs) under the Paris agreement: A model-based assessment. *Climate Policy*, Taylor & Francis, 20(1), 71–94. <https://doi.org/10.1080/14693062.2019.1685449>
- Project Gaia. (2019). Madagascar. Retrieved April 23, 2019, from <https://projectgaia.com/projects/madagascar/>
- Roche, M. Y., Verolme, H., Agbaegbu, C., Binnington, T., Fischerdick, M., & Oladipo, E. O. (2019). Forthcoming special issue: Development and mitigation pathways. *Climate Policy*, Taylor & Francis. <https://doi.org/10.1080/14693062.2019.1661818>
- Rochedo, P. R. R., Soares-Filho, B., Schaeffer, R., Viola, E., Szklo, A., de Lucena, A. F. P., Davis, J. L., Rajão, R., & Rathmann, R. (2018). The threat of political bargaining to climate mitigation in Brazil. *Nature Climate Change*, Nature Publishing Group, 8(8), 695–698. <https://doi.org/10.1038/s41558-018-0213-y>
- Rösler, H., van der Zwaan, B., Keppo, I., & Bruggink, J. (2014). Electricity versus hydrogen for passenger cars under stringent climate change control. *Sustainable Energy Technologies and Assessments*, Elsevier, 5, 106–118. <https://doi.org/10.1016/j.seta.2013.11.006>
- Saatchi, S. S., Harris, N. L., Brown, S., Lefsky, M., Mitchard, E. T. A., Salas, W., Zutta, B. R., Buermann, W., Lewis, S. L., Hagen, S., Petrova, S., White, L., Silman, M., & Morel, A. (2011). Benchmark map of forest carbon stocks in tropical regions across three continents. *Proceedings of the National Academy of Sciences*, National Academy of Sciences, 108(24), 9899–9904. <https://doi.org/10.1073/pnas.1019576108>

- Sathaye, J., Makundi, W., Dale, L., & Chan, P. (2006). GHG mitigation potential, costs and benefits in global forests: A dynamic partial equilibrium approach. *The Energy Journal*, 27(Special Issue #3), 127–162. <https://www.jstor.org/stable/23297079?seq=1>
- Scales, I. R. (2014). The drivers of deforestation and the complexity of land use in Madagascar. *Conservation and Environmental Management in Madagascar*, Routledge, 129–150. <https://doi.org/10.4324/9780203118313-16>
- Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., & Smith, J. (2008). Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 363(1492), 789–813. <https://doi.org/10.1098/rstb.2007.2184>
- Sweerts, B., Dalla Longa, F., & van der Zwaan, B. (2019). Financial de-risking to unlock Africa's renewable energy potential. *Renewable and Sustainable Energy Reviews*, 102, Pergamon, 75–82. <https://doi.org/10.1016/j.rser.2018.11.039>
- Syri, S., Lehtilä, A., Ekholm, T., Savolainen, I., Holttinen, H., & Peltola, E. (2008). Global energy and emissions scenarios for effective climate change mitigation—Deterministic and stochastic scenarios with the TIAM model. *International Journal of Greenhouse Gas Control*, Elsevier, 2(2), 274–285. <https://doi.org/10.1016/J.IJGGC.2008.01.001>
- UN. (2015). *Sustainable development goals – United Nations sustainable development*. Retrieved April 23, 2019, from <https://www.un.org/sustainabledevelopment/sustainable-development-goals/>
- UNCCD. (2018). *Country profile of Madagascar. Investing in land degradation Neutrality: Making a case. An overview of indicators and assessments*. Global Mechanism of the United Nations Convention to Combat Desertification.
- UNEP. (2019). *Energy profile: Madagascar UN environment, Energy Profile*. Retrieved February 18, 2019, from <https://www.unenvironment.org/resources/fact-sheet/energy-profile-madagascar>
- UNFCCC. (2015). *Paris agreement*, p. 36 <http://unfccc.int/resource/docs/2015/cop21/eng/10a01.pdf>
- UNFCCC. (2019). *Communication of long-term strategies*. Retrieved February 10, 2020, from <https://unfccc.int/process/the-paris-agreement/long-term-strategies>
- USAID. (2016). *Power Africa in Madagascar*, pp. 1–2. <http://www.doingbusiness.org/data/exploreeconomies/madagascar/getting-electricity/>
- van der Laan, A. (2015). *Leapfrogging in the African power sector: The Effect of mitigation policies on regional African power sector development* [Master's thesis]. Utrecht University.
- van der Zwaan, B., Boccalon, A., & Dalla Longa, F. (2018a). Prospects for hydropower in Ethiopia: An energy-water nexus analysis. *Energy Strategy Reviews*, Elsevier Ltd, 19, 19–30. <https://doi.org/10.1016/j.esr.2017.11.001>
- van der Zwaan, B., Kober, T., Calderon, S., Clarke, L., Daenzer, K., Kitous, A., Labriet, M., de Lucena, A. F. P., Octaviano, C., & Di Sbroiaavacca, N. (2016). Energy technology roll-out for climate change mitigation: A multi-model study for Latin America. *Energy Economics*, North-Holland, 56, 526–542. <https://doi.org/10.1016/j.eneco.2015.11.019>
- van der Zwaan, B., Kober, T., Dalla Longa, F., van der Laan, A., & Kramer, G. J. (2018b). An integrated assessment of pathways for low-carbon development in Africa. *Energy Policy*, Elsevier, 117, 387–395. <https://doi.org/10.1016/j.enpol.2018.03.017>
- van der Zwaan, B., Rösler, H., Kober, T., Aboumahboub, T., Calvin, K. V., Gernaat, D. E. H. J., Marangoni, G., & McCollum, D. (2013). A cross-model comparison of global long-term technology diffusion under a 2°C climate change control target. *Climate Change Economics*, World Scientific Publishing Company, 4(4), 1340013. <https://doi.org/10.1142/S2010007813400137>
- van Zyl, H., Lewis, Y., Kinghorn, J., & Reeler, J. (2018). The cost of achieving South Africa's 'fair share' of global climate change mitigation'. *Climate Policy*, Taylor & Francis, 18(10), 1327–1339. <https://doi.org/10.1080/14693062.2018.1437019>
- Vieilledent, G., Gardi, O., Grinand, C., Burren, C., Andriamanjato, M., Camara, C., Gardner, C. J., Glass, L., Rasolohery, A., Rakoto Ratsimba, H., Gond, V., Rakotoarijaona, J.-R., & Lines, E. (2016). Bioclimatic envelope models predict a decrease in tropical forest carbon stocks with climate change in Madagascar. *Journal of Ecology*, Edited by E. Lines. John Wiley & Sons, Ltd (10.1111), 104(3), 703–715. <https://doi.org/10.1111/1365-2745.12548>
- Vieilledent, G., Grinand, C., Rakotomalala, F. A., Ranaivosoa, R., Rakotoarijaona, J., Allnutt, T. F., & Achard, F. (2018). Combining global tree cover loss data with historical national forest cover maps to look at six decades of deforestation and forest fragmentation in Madagascar. *Biological Conservation*, Elsevier, 222(March), 189–197. <https://doi.org/10.1016/j.biocon.2018.04.008>
- World Bank. (2011). *Ethanol as a household fuel in Madagascar: Health benefits, economic assessment, and review of African lessons for scaling-up: Summary report*. Retrieved April 23, 2019, from <http://documents.worldbank.org/curated/pt/564801468055752320/Ethanol-as-a-household-fuel-in-Madagascar-health-benefits-economic-assessment-and-review-of-African-lessons-for-scaling-up-summary-report>
- World Bank. (2019a). *Madagascar overview*. Retrieved April 23, 2019, from <http://www.worldbank.org/en/country/madagascar/overview>
- World Bank. (2019b). *Madagascar: \$150 million to increase access to electricity services for households, enterprises, and health facilities*. Retrieved September 1, 2019, from <https://www.worldbank.org/en/news/press-release/2019/03/01/madagascar-150-million-to-increase-access-to-electricity-services-for-households-enterprises-and-health-facilities>
- WWF. (2012). *Diagnostic du Secteur Energie a Madagascar*. Ministerie de L'Energie.

Appendix

I Additional Information on Model's Input Data

(a) Power Sector

Table 4 shows our assumptions for power generation technologies in Africa and Madagascar. The data provided is based on TIAM-ECN input data and can be further consulted in van der Laan (2015):

(b) Cooking Stoves for the Residential Sector

Our techno-economic assumptions for cooking stoves available for Madagascar's residential sector are widely based on Fernandes and Keemink (2017), as described in Table 5:

Table 4. Assumptions on power sector technologies.

Technology	Average Efficiency (%)	Investment Costs [USD(2010)/kW]			Fixed O&M [USD (2010)/kW]			Variable O&M [USD(2010)/MWh]	Lifetime (Years)	Average Availability (Hours per Year)
		2020	2030	2050	2020	2030	2050			
Gas/Oil Combined Cycle (NGCC)	60	683	683	683	24	24	24	0.1	35	7,900
NGCC with CCS	48	1,411	1,243	1,243	41	36	36	0.2	35	7,900
Generic Large-Scale Hydropower	100	2,442	2,834	2,834	57	66	66	0.3	80	5,300
Solar PV – Centralized	100	2,195	1,803	1,411	22	21	21	0.0	20	2,500
Solar PV – Decentralized	100	2,307	1,875	1,875	100	100	100	0.0	25	1,400
On-Shore Wind	100	1,478	1,456	1,344	27	26	22	0.0	25	2,000
Off-Shore Wind	100	3,248	2,946	2,352	77	71	56	0.0	20	3,700
Solid Biomass Gasification	46	2,699	2,486	2,486	103	95	95	0.2	30	7,900
Solid Biomass with CCS	37	3,948	3,562	3,170	158	142	127	0.3	30	7,900

Table 5. Assumptions on cooking stoves for households.

Stove per Fuel Type	Average Efficiency (%)	Investment Costs [USD (2010)]	Lifetime
Natural Gas	75	58	17
Kerosene	67	167	17
Diesel	70	48	17
Coal	40	74	17
LPG	70	58	17
Electricity	85	122	17
Solid Biomass/Charcoal	50	161	17
Traditional Solid Biomass	70	40	17
Solar	100	294	17
Ethanol	46	28	17

Source: own elaboration based on TIAM-ECN.

(II) Additional Information on Methodology

(a) AFOLU

Table 6 shows our annual estimates for biomass production for energy purposes based on historical deforestation rates and land availability, e.g. excluding protected areas. Forest types aggregated as 'others' correspond to cropland, plantations and urban areas.

Estimates for net GHG emission per unit of biomass harvested are depicted in petajoules in Table 7. We have calculated these numbers by subtracting the carbon content of timber production from gross GHG emissions of MEDD (MEDD, 2017) per hectare of forest and by considering the energy yield of one hectare of exploited forest (EC, 2014), per each type of forest.

The potentials of biomass for energy purposes from 2010 to 2050 were updated according to WWF (2012). The increasing potential towards 2050 follows the higher biomass availability scenario for Madagascar, assuming land use and biomass extraction practices

Table 6. Assumptions on available land, annual deforestation rates and annual biomass production for energy purposes.

Land Type	Total Area ('000 ha)	Non-Protected Area ('000 ha)	Annual Deforestation Rate 2005–2013 (%)	Theoretical Energy Biomass Production ^b (m ³ /ha.yr)
Humid Forest	4,386	2,895	0.47	287
Dry Forest	2,938	1,010	1.89	21
Thorny Forest	1,593	1,167	1.58	25
Mangrove	243	197	0.25	354
Others ^a	50,006	n.a.	n.a.	n.a.
Total	59,167	5,269	4.19	687

Source: EC, 2014; MEDD, 2017.

^aMostly cropland. Includes also plantations and urban areas.

^bAssuming 50% losses due to illegal harvesting in forests (EC, 2014).

Table 7. Assumptions on GHG emission coefficients from land-use change per type of forests.

	Gross Emission Coefficient (tCO ₂ eq/ha)	Net Emission Coefficient (tCO ₂ eq/ha)	Energy Yield ^b (GJ/ha)	Net Emission Coefficient per Harvested Energy (MtCO ₂ eq/PJ)
Humid forest	560	532	2,868	0.186
Dry forest	135	128	194	0.660
Others ^a	58	55	496	0.172

Source: EC, 2014; MEDD, 2017.

^aSpiny and Mangroves.

^bNet Calorific Value: 13.8 MJ/kg (FAO, 2019); Density: 0.725 ton/cum (GIZ, 2014).

Table 8. Assumptions on energy biomass potential.

Forest Type	Energy Biomass Potential (PJ)	
	2010	2050
Humid	274	530
Dry	299	579
Others*	172	333
Total	745	1,442

Source: MEDD, 2017; WWF, 2012.

*Spiny and Mangroves.

will increase in efficiency over time. The total potential for energy biomass was then divided into the three forest categories considered in TIAM-ECN, according to available data from MEDD, 2017 (Table 8).

(b) Other Assumptions

(i) Fossil Fuel Production and Trade

Madagascar does not have significant fossil fuel resources (AFREC, 2018; UNEP, 2019; WWF, 2012). Hence, currently there are no officially stated plans to exploit oil, natural gas or coal resources in the country beyond current levels.

There has been no conversion of crude oil into oil products in the country since 2006 (AFREC, 2018). Therefore, we assume that there will be neither domestic exploitation nor conversion of crude oil and natural gas within the time horizon considered in this study, which means that any fossil fuel input in the energy system derives from imports. Coal extraction is limited to 530 Mtoe, as defined in previous versions of the model.

The country can import oil products after 2010, limited to a maximum of 20% of final energy consumption in all time periods. This bound stylistically accounts for physical and cost limitations of liquids imports and distribution infrastructure, which relates to pipelines, port capacity, etc.

(ii) Renewable Resources Other than Solid Biomass

Renewable resources other than solid biomass include wind, centralized and decentralized solar power and hydropower. Power generation potentials and costs, as well as seasonal profiles impacting availability factors, are kept as previous versions of TIAM-ECN for most of power technologies.

Figure 7. Projections for final energy use in the transport sector (left) and industry (right) in Madagascar.

For hydropower, however, the potential was updated to 7.8 GW, as reported by (USAID, 2016). The minimum generation is 7 PJ in 2030 and 15 PJ in 2050. These constraints were implemented to keep results aligned with power expansion plans of Madagascar.

The conversion of solid biomass into liquid biofuels, such as ethanol, and their corresponding costs are fully aligned with literature (World Bank, 2011).

(III) Additional Information on Results

Figure 7 depicts our projections for final energy use in both the transport and industry sectors under each of our three scenarios. In the transport sector (left panel), oil products are partially substituted by biofuels, mostly bioethanol, from 2030 onwards in REF and NDC scenarios. Still, 25% of energy consumption in 2050 remains based on fossil fuels. In NDC+, both bioethanol and biodiesel substitute oil products at a faster pace, reaching more than 90% of fuel consumption for transport in 2050. Total final energy consumption in the transport sector is lower in NDC+, indicating that vehicles adopted in that scenario are more efficient. Regarding the industry sector (right panel), the final energy mix is based on oil products, biomass, electricity and coal (the latter is phased out in the long-term). Most of energy consumption is based on biomass for heat purposes, corresponding to 83% of total consumption in 2030 and 78% in 2050 in both REF and NDC scenarios. The NDC+ scenario yields a higher uptake of electricity from 2030 onwards. In 2050, the share of biomass in NDC+ is limited to 58% due to a higher use of electricity.