Competitiveness of economic growth based on renewable energy: the case of Uganda to 2035

Gauthier Limpens
iMMC
Université Catholique de Louvain
Louvain-la-Neuve, Belgium
gauthier.limpens@uclouvain.be

Paolo Thiran
iMMC
Université Catholique de Louvain
Louvain-la-Neuve, Belgium
paolo.thiran@uclouvain.be

Eileen Lara
CREEC
Makerere University
Kampala, Uganda
elara@creec.or.ug

Matija Pavičević
Faculty of Engineering Technology
KU Leuven
Geel, Belgium
matija.pavicevic@kuleuven.be

Sylvain Quoilin
Faculté des Sciences appliquées
Université de Liège
Liège, Belgium
squoilin@uliege.be

2022 IEEE PES/IAS PowerAfrica | 978-1-6654-6639-4/22/$31.00 ©2022 IEEE | DOI: 10.1109/PowerAfrica53997.2022.9905398

***Abstract*—Emerging economies are experiencing significant growth, which implies a booming demand for energy, especially electricity. In order to meet the 2050 climate target, this growth will have to rely mainly on renewable energy. This contrasts with the fossil fuel-based growth experienced by developed countries. This paper analyses, for the case of Uganda, the difference between a fossil fuel-based energy development and leapfrogging to a renewable one. The analysis covers all energy sectors (electricity, heat and mobility) and shows that priority should be given to heat and mobility. Results show that the cheapest growth is based on fossil energies. Nevertheless, favouring renewable energy is not far from being competitive; not to mention the other positive impacts such as increasing energy sovereignty, increasing national employment and addressing climate change. The work estimates a penalty of 15-30 €/ton of CO_2 equivalent is sufficient to achieve the competitiveness of a highly sustainable society.**

***Index Terms*—Sustainable growth, renewable energies, energy system modelling, energy development, SDG7**

I. Introduction

Developing economies are in the midst of an economic boom and are undergoing a strong growth in energy demand. Universal energy access is, according to the 7th sustainable development goal of the United Nations, a universal right to provide access to affordable, reliable and modern energy services and is an important driver for this growth.

Energy development has historically been based on the presence of fossil resources. With the climate change, this is no longer an option. As a result, emerging economies face a double challenge: shifting from non-sustainable fuels to renewable sources while at the same time covering an increasing demand. With the plummeting costs of renewables, there is now a clear opportunity for these countries to leapfrog to a cleaner energy system without following the fossil-fuel path that has been followed by most countries.

This paper compares different scenarios for the case of Uganda, an East-African country. A fossil based growth is compared to a renewable based growth in terms of investment decisions, cost impact, energy sovereignty and greenhouse gas emissions. The whole-energy system - i.e. electricity, heat, mobility and non-energy - [1] of the country is considered to avoid omitting the sectors with the highest greenhouse gas emissions.

To do this, we use an energy system optimisation model presented in the Section 2. Then, we will analyse Uganda's energy situation in 2019 (Section 3) and analyse its potential for 2035 (Section 4). Finally, the model will be applied to analyse the impact of reducing the greenhouse gas emissions (Section 5) and the competitiveness of a renewable growth will be depicted in Section 6.

II. Energy system modelling

The energy system is the machine that provides energy services to end users: industries, services and households. It can be split in three parts: resources, technologies and end-use demands. '*Resources*´ can either be imported or produced in the country. '*End use demands*´ represent the energy service provided to the end-user. '*Technologies*´ enable to transform, store or transport a resource, such as the conversion of solar irradiation into electricity through photovoltaic panels.

The model used is *EnergyScope TD* [2], an open-source and documented model [3] which optimises the design and hourly operation of a whole-energy system over a year. Its short computational time and concise formulation makes it a suitable model to be applied to a wide variety of case studies. In this work, the model version corresponding to Limpens' thesis [4] has been used. The model optimises the sizing of each technology and the system operation. The required inputs are availability and costs of resources; techno-economic characterisation of technologies such as specific cost or conversion efficiency; yearly end-use demand; and weather and demand hourly profiles.

The model was initially developed for European countries and account for more than 100 technologies. However, the model must be adapted to the case study. In this case, the energy services and technologies available are not the same. The main changes are: add a heat demand for cooking and adapt mobility (include moto-taxi and vans). Other demands, such as space heating, or technologies, such as nuclear power plants, are not relevant and have been removed. The adapted version can be found on GitHub [1].

III. Ugandan energy system in 2019

Uganda benefits from a humid tropical climate covering a majority of the country. It offers significant water resources and a luxuriant nature. Since it is close to the equator, the country's sunshine is more or less constant throughout the year with two rainy seasons and two dry seasons, the latter corresponding to the solstices. Finally, the country is located between the two African rifts and therefore has privileged access to geothermal energy.

In 2019, only 26.7% of the population had access to electricity [5], but this number has steadily increased in the past years, contributing to the electricity demand. As a consequence, the installed generation capacity in Uganda grown from 872 MW in 2012 to 1179 MW in 2019 [5].

A. Macro-economical situation

The country has been politically stable for decades. This has favoured the development of the economy, which is growing at a rate of 5% per year [6] The economy faces several challenges; internally, the majority of Ugandans have very low purchasing power due to a high poverty rate. However, this purchasing power is not representative of the quality of life of the population, as a large part of the basic needs are covered through an informal economy. Another external challenge is that Uganda is a landlocked country in East Africa and is highly dependent on imports/exports [6]. The majority of these are done via the road network, mainly through Kenya, which has an impact on the price of commodities.

The unemployment rate in Uganda is high, reflecting the difficult access to work for the younger generation which can benefits from a university degree [6]. This is partially due to a booming population which experiences a annual growth of 3% since 1960 increasing the population from 10 million in 1973 to 46 million in 2020 and possibly 67 million in 2035. This results in one million citizens getting into the labour market every year. The growing economy therefore faces the double challenge of getting a part of the population out of poverty while at the same time providing young people with work.

B. Energy landscape in 2019

The Ministry of Energy and Minerals Development of Uganda published the energy balance for the year 2019 [7]. The data has been compiled and summarised into a Sankey diagram (Figure 1). It represents the energy flow from primary energy to the final energy consumed in the different economical sectors (i.e. households, services and industry). The actual landscape of energy use in Uganda can be split into the following energy sectors: electricity, mobility and heat.

[1] https://github.com/energyscope/EnergyScope/tree/EnergyScopeUGA

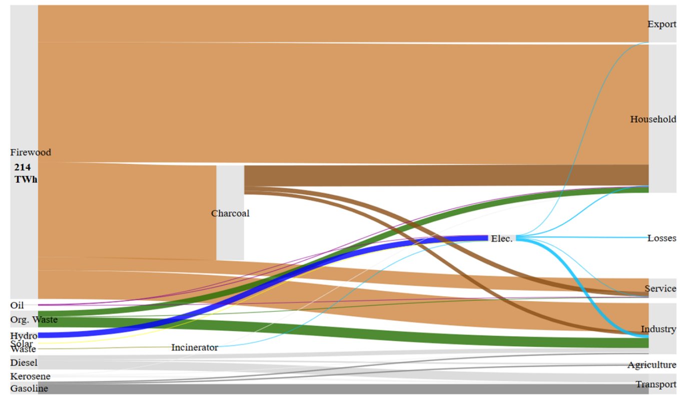

Fig. 1. Sankey diagram of the existing energy system in 2019. End use represents the final energy consumption per sectors

The electricity production is dominated by run-of-river hydro-electricity on the Nile river. But diesel generators are also used to provide reliable electricity locally. Indeed, the grid experiences regular shortages. In 2019, a survey addressed to 1200 Ugandan adults revealed that : 4% of the connected people complain to have zero electricity; 18% occasionally; 10% about half of the time; and the rest most of the time [8]).

The mobility sector is split into pedestrians, public transportation through small vans or coaches, and private mobility through private cars or moto-taxi. Historically, a train was connecting most of the major cities in the country, but insufficient maintenance has put passenger trains out of action, with only rare trains used for freight. Thus, except pedestrians, the transportation is exclusively based on internal combustion engines, equitably split between gasoline and diesel.

The heat sector is split into two main demands: heat for cooking and heat for industrial processes, such as sugar production. Cooking is mainly based on '*traditional*´ biomass and is estimated to be the largest final energy consumed of the country with around 153 TWh per year [7]. '*Traditional*´ refers to the combustion of woody biomass in a non-efficient stove, such as the '*three stones stove*´ which is literally three stones with a sauce-pan on it. The industrial also relies on biomass as main energy source. Biomass exploitation is currently not sustainable, resulting in deforestation: from 2002 to 2020, Uganda lost 40km^2 per year [9].

IV. Ugandan energy system in 2035

The energy system of Uganda might drastically change due to a large panel of available technologies and a rapid growth of the economy. The time focus of this analysis is the year 2035, far enough to enable important system change, but close enough to know the existing available technologies at that time. Hereafter, the component of the energy system are listed by energy demand, resources and conversion technologies.

978-1-6654-6639-4/22/$31.00 ©2022 European Union

A. Energy demand

The energy demand in 2035 is forecast based on the one of 2019 using a scaling factor: the Gross Domestic Product (GDP). Such a simple proportional calculation could overestimate energy demand in 2035 since wood is currently non-efficiently converted, with significant losses. Therefore, the end use demand is used instead of the final energy consumed. The end use demand represents the amount of energy service that the final consumers requires. As an example, only 8.31 MJ could be used to cook 10 kg of rice, however 5 kg of wood are usually in a three stone stoves, which is equivalent to around 75 MJ [10]. Another example is mobility: users do not necessarily need 3 liters of gasoline for transportation, but the need a service to move from A to B. In that case, the end used demand will be expressed in kilometer passengers [km-pass] and not in energy.

Table I summarises the technologies and consequently the efficiencies used to convert final energy demand into end use demand for 2019.

TABLE I
EFFICIENCIES TO CONVERT FINAL ENERGY CONSUMED INTO END-USE DEMAND.

Conversion Efficiency	Conversion		
	Sectors [a]	***Value***	***Units***
Stone stove	Hh & Ser	10%	[Wh_{heat}/Wh_{wood}]
Improved stove	Hh & Ser	20%	[Wh_{heat}/Wh_{wood}]
Ind. Boilers	Ind	80%	[Wh_{heat}/Wh_{wood}]
Mob. Passenger	Tr	208	[Wh/km-pass]
Mob. Freight	Tr	143	[Wh/t-km]

[a] Technologies are expressed by sectors: Households (Hh), Services (Ser), Industries (Ind) and Transport (Tr).

The end use demands computed for 2019 are increased proportionally to the GDP growth to get the ones in 2035. The GDP growth was around 5% per year in the last decades [6]. This value is used to estimate the GDP in 2035, i.e. +118% compared to 2019. Table II summarises the yearly energy demand estimation in 2035. The use of the GDP as a scaling factor can be strongly criticized, but it is used in this study for sake of simplicity, no other quantitative relevant indicator being available.

TABLE II
END USE DEMAND FOR THE DIFFERENT SECTORS.

		Hh	Ser	Ind	Tr	Units
Elec	***Variable***	876	724	482		[GWh]
	base load	876	724	9139		[GWh]
Heat	***High T.***			57577		[GWh]
	Cook	28268	4448			[GWh]
Tr.	***Freight***				59.6	[Gt-km]
	Pass.				150.8	[Gpass-km]

[a] Abbreviations: Households (Hh), Industries (Ind), , Passenger (Pass), Services (Ser), Temperature (T) and Transport (Tr).

By scaling Table II per capita, the demand are 26 kWh of electricity, 423 kWh of heat for cooking (i.e. 2.2kg of wood per day with a three-stones) and 2254 km (i.e. 6 km per day) per year per person. This represents an increase of energy service needed per capita by a factor 1.49. Industry in 2035 consumes 9.62 TWh/y of electricity and 57.58 TWh/y of heat.

In addition to yearly demands, a hourly time series is used to dispatch the variable demand over the year. They were adapted from [11].

B. Resources

The resources available for the Ugandan energy system are fossil or renewable.

Fossil resources:
There is no major fossil fuel extraction in Uganda yet. A recent project has started to extract oil and gas from the Albertine region, which could facilitate the access to fossil energy [12]. Currently, Uganda imports all its fossil energy by road freight. This leads to a more expensive price for gaseous fuels than for liquid ones. Pavičević et al. [11] estimates the following prices of fossil resources for the horizon 2035 in Uganda: Coal (17.7€/MWh), oil (35€/MWh) and natural gas (44€/MWh). No distinction were made between gasoline, diesel and other type of liquid hydrocarbons. Municipal solid waste contains a lot of plastic that is actually not renewable. The estimated amount of this non-renewable waste is 22.3 TWh/y [13].

Renewable resources:
Renewable resources can be characterised by a limited deployment capacity of the associated technology, such as geothermal power plants; or by maximum sustainable potential such as biomass. For the first category: (i) The hydro potential is concentrated on the Nile river and reaches 2 000 MW_e; (ii) There is a potential to install 450 MW_e of geothermal power plant; (iii) The solar potential is virtually unlimited and has a low seasonal variability (less than 20% between different months) [14]; (iv) The wind potential is very limited. The most windy region (e.g. Kabale or Mukono) have wind below 3.7 m/s in average at 20 meters, which is insufficient even if extrapolated at higher altitudes. Locally, in some windy valley, a wind turbine could be profitable, but no large scale application are foreseen [14].

For the second category, the renewable and waste resource potential can be summarized as follows: 115.6 TWh/y of renewable woody biomass and 5.3 TWh/y of digestible biomass for large-scale application. Moreover, we assume an unlimited amount of non-renewable woody biomass available, corresponding to use of biomass which leads to deforestation. Nowadays, the ministry of Environment and Waste estimates that 41% of the wood is used in a non-sustainable way [14].

As many of those resources are variable, hourly time series are necessary to define their availability over the year. Two sources were used to define them: (i) [11] collected for all African countries the electricity demand and hydro time series for several years; (ii) Renewable Ninja offers a platform to extract time series for wind and solar [15]- [16].

C. Technologies

A typical energy system contains hundreds of different of technologies. Technologies are of three types: conversion,

978-1-6654-6639-4/22/$31.00 ©2022 European Union

storage or network. Conversion can transform one energy carrier into another with a conversion efficiency, such as a biodigester which convert digestible biomass into biogas. Storage technology can store energy over time and are characterised by a storage input/output efficiency, storage losses, ... Finally, networks enable to carry the some energy carriers through the country, such as the gas or electrical grid. In this case study, the electricity grid is characterised by 20% losses, its historical value [7].

V. Cost-emissions optimums

The model presented in Section II was applied for different greenhouse gas (GHG) targets. The accountancy of GHG can be performed in different ways. In this study, we accounted for the emissions related to the life-cycle of the fuels, i.e. the emissions related to the extraction, transportation and combustion according to the metric GWP100a-IPCC2013. Using this method, the emissions in 2019 are estimated to 7 $MtCO_2$ from hydrocarbons and 34 $MtCO_2$ due to unsustainable use of firewood.

Figure 2 illustrates the optimal primary energy mix in 2035 for different greenhouse gases emissions target.

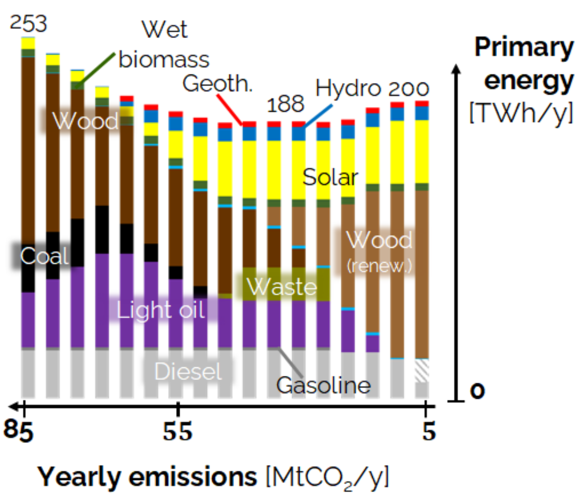

Fig. 2. Primary energy used for different greenhouse gases emissions. Grey stripes are renewable diesel.

A. The fossil fuel case (85 $MtCO_{2,eq}$/y)

Without greenhouse gas constraints (Figure 2 extreme left), the system uses non-renewable wood, coal and hydrocarbon fuels. There is also a slight integration of two renewable energies: digestible biomass and solar. Digestible biomass is used in domestic scale bio-digester to produce biogas later used for cooking. In this coutnry, PV is the most cost-effective technology for power generation and 3.87 GW of it are installed. Cheap coal, on the other hand, is used to produce flexible electricity to match the demand without need for storage assets. Mobility needs are covered by hydrocarbons, via trucks and mini-buses, and there is a partial electrification of motorcycles, cars and mini-buses.

B. The renewable energy case (5 $MtCO_{2,eq}$/y)

On the other extreme (Figure 2 extreme right), the low-emission scenario relies massively on renewable energy, more particularly renewable woody biomass (113 TWh/y), solar (42 TWh/y), bio-diesel (15.6 TWh/y), hydro (9.3 TWh/y), digestable biomass (5.3 TWh/y), geothermal energy (3.7 TWh/y) and finally imported electricity (0.77 TWh/y). There is also a fraction of fossil diesel (10.9 TWh.y).

Figure 3 illustrates the energy balance over a year from primary to final energy consumed for this solution. Biomass is mainly used for industrial process heat and the rest is converted into biofuels for cooking and mobility. The cooking demand relies on biofuels, biogas and electricity. The electricity sectors soars, reaching 56 TWh of electricity passing through the grid, which represents a growth of around 50% per year. The electricity is used as such (11.5 TWh.y), but also for industrial processes (5.8 TWh.y), cookers (18.0 TWh.y) and mobility (8.1 TWh.y). The rest of the mobility needs are covered by diesel, bio-diesel and local biofuels. The import of diesel and bio-diesel reflects the difficulty to decarbonize the transport sector, especially in a country where most of the vehicles are old and second-hand.

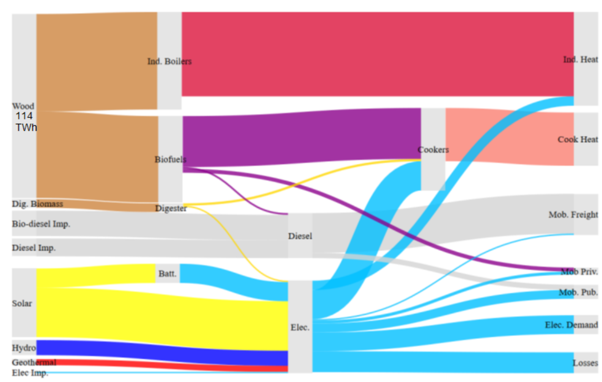

Fig. 3. Sankey diagram of an energy system in 2035 relying mainly on renewable resources. The left terms are primary energy, the right terms are final energy consumed per energy sector. In between are conversion and storage technologies. Abbreviations: digestable (Dig.), electricity (Elec.), imports (Imp.), industrial (Ind.), mobility (Mob.), private (Priv.) and public (Pub.).

The electricity production is dominated by PV. To handle its variability, 34 GWh of batteries are installed. This is equivalent to 1.5 GWh of storage per GW of panels installed (i.e. 1.5 hour of storage at nominal production). The batteries are used for daily variations, performing 341 full cycle equivalent over a year. Thanks to the lower seasonal variability of PV production and demands, there is no need for important seasonal storage. However, a part of the fuels are stored to ensure the adequacy between production and demand. Moreover, the losses in the grid are estimated to 20% [7] which represents 12.8 TWh/y.

978-1-6654-6639-4/22/$31.00 ©2022 European Union

VI. Is a growth based on renewables competitive?

Today, growth based on renewable energies is possible but appears more expensive than growth based on fossil energies. Indeed, the latter is less capital intensive (-3b€) but requires more resource imports (+2.1b€/year).

This additional 900 million represent an increase of 8% of the total cost of the energy system. However, it is combined with a series of positive effects, such as greater investment in the country's energy infrastructure and lower energy dependence; sustainable management of its resources; and reduced local pollution. This additional cost should then be compensated by a series of policies, such as sustainable forest management, access to efficient energy for cooking - especially in the cities - , and a penalty on non-sustainable energies. The later would be equivalent to penalise greenhouse gas emission by a 15-30 €/ton. This amount represents the the additional cost divided by the $CO_{2,eq}$ savings.

VII. Limits of the work

The energy system optimisation model used was tailored for developed economies where the networks are well established and where 100% of the population is electrified. A finer spatial resolution would be required to verify the dispatchability of the different resources, such as bio-fuels or electricity for cooking. Decentralized energy systems such as micro grids or solar home systems are also highly relevant [5] and should be explicitly accounted for in the model. In addition, a deeper market review is needed to better characterise the costs of the available technologies and their future evolution. Finally, the socio-economic impact of fossil- or renewable based growth is not discussed in this study. Future works could couple social or economic models with the one used here to study this question.

Conclusion

Uganda's energy system will undergo a metamorphosis to meet two local and one global challenge. In the country, a minority has access to modern, clean and affordable energy. In addition, the country is experiencing strong population and economic growth. At the global level, Uganda is committed to the Paris Agreement and aims to limit its greenhouse gases emissions.

The analysis of the overall energy system provides an insight into the reality of the country. As an indication, in 2019 the most important energy demand is heat for cooking, mainly supplied by wood (153 TWh). This is followed by heat demand for industry, also based on biomass (41 TWh), then mobility demand solely on hydrocarbons (15 TWh) and finally electricity demand (3.2 TWh/year).

A projection of the energy system by 2035 allows to identify the difficulties and opportunities. Without incentives, the system would economically prefer to experience a growth based on fossil energies. Indeed, non-sustainable wood or coal are cheaper than renewable options. Nevertheless, favouring renewable energy is not far from being cost competitive; not to mention the other positive impacts such as increasing energy sovereignty, increasing national employment and addressing climate change. The work estimates a penalty of 15-30 €/ton of CO_2 equivalent is sufficient to achieve the competitiveness of a highly sustainable society.

Growth based on sustainable energy would mean increased energy efficiency (especially in cooking), electrification of heat and mobility and increased renewable electricity production based on PV, geothermal and hydro.

A challenge which was not addressed in this work is how to extend the electricity and gas grid around the country. By coupling the framework with a dispatch tool, an optimal design of the grid could be provided together with a detailed expansion plan.

References

[1] F. Contino, S. Moret, G. Limpens, and H. Jeanmart, "Whole-energy system models: The advisors for the energy transition," *Progress in Energy and Combustion Science*, vol. 81, p. 100872, Nov. 2020.

[2] G. Limpens, S. Moret, H. Jeanmart, and F. Maréchal, "EnergyScope TD: A novel open-source model for regional energy systems," *Applied Energy*, vol. 255, p. 113729, Dec. 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0306261919314163

[3] "The EnergyScope model — EnergyScope_documentation." [Online]. Available: https://energyscope.readthedocs.io/en/latest/

[4] G. Limpens, "Generating energy transition pathways: application to Belgium," PhD Thesis, UCL-Université Catholique de Louvain, 2021.

[5] G. Mugagga and H. Chamdimba, "A Comprehensive Review on Status of Solar PV Growth in Uganda," *Journal of Energy Research and Reviews*, pp. 1–14, Dec. 2019.

[6] B. Looney, "Full Report—BP Statistical Review of World Energy 2020," London, Tech. Rep., 2020.

[7] Ugandan bureau of Statistics, "2019 Statistical Abstract," Tech. Rep., 2019.

[8] AFRO Barometer, "Despite hydropower surplus most Ugandans lack electricity," Apr. 2021. [Online]. Available: https://afrobarometer.org/sites/default/files/publications/Dispatches/ad441-despite_hydropower_surplus_most_ugandans_lack_electricity-afrobarometer_dispatch-14april21.pdf

[9] Vizzuality, "Uganda Deforestation Rates & Statistics | GFW." [Online]. Available: https://www.globalforestwatch.org/dashboards/country/UGA

[10] K. Dilip, M. Nathaniel, and O. Olawole, "Cooking with Minimum Energy and Protection of Environments and Health," *IERI Procedia*, vol. 9, pp. 148–155, Jan. 2014. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2212667814001038

[11] M. Pavičević, M. De Felice, S. Busch, I. Hidalgo González, and S. Quoilin, "Water-energy nexus in African power pools – The Dispa-SET Africa model," *Energy*, vol. 228, p. 120623, Aug. 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360544221008720

[12] Petroleum Authority of Uganda, "The Uganda Refinery Project – Petroleum Authority of Uganda (PAU)." [Online]. Available: https://www.pau.go.ug/the-uganda-refinery-project/

[13] A. Global Livinston Institute, "Building a Circular Economy in East Africa: Plastic Bottle Recycling in Uganda," Tech. Rep., 2021.

[14] Energypedia, "Uganda Energy Situation." [Online]. Available: https://energypedia.info/wiki/Uganda_Energy_Situation

[15] S. Pfenninger and I. Staffell, "Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data," *Energy*, vol. 114, pp. 1251–1265, Nov. 2016. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360544216311744

[16] I. Staffell and S. Pfenninger, "Using bias-corrected reanalysis to simulate current and future wind power output," *Energy*, vol. 114, pp. 1224–1239, Nov. 2016. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360544216311811

978-1-6654-6639-4/22/$31.00 ©2022 European Union