Compensation of CO_{2e} emissions from pedelecs partially replacing motorized vehicles in Uganda

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ABSTRACT

The aim of this paper is to estimate the reduction of CO_{2e} emissions due to pedelecs partially replacing motorized vehicles in Uganda in five steps: (A) Pedelec and lithium-ion battery production; (B) Transport from the manufacturer in India to its destination in Uganda. (C) CO_{2e} reduction due to pedelec use partially substituting motorized vehicles - passenger cars, boda-bodas and matatus. (D) The appropriate part of motorised vehicle emissions that should be credited to pedelecs partially replacing transport by these vehicles, increasing pedelec CO_{2e} reduction. The last step (E) is to combine all these individual estimates to a conservative estimate of the net reduction of CO_{2e} emissions due to pedelecs in Uganda. Two modal distributions are assumed for the partial replacement of motorised vehicles by pedelecs. Depending on the modal split the net CO_{2e} reduction per year of one pedelec ranges between approximately 2.5 and 2.9 tonnes CO_{2e}.

Keywords: CO_{2e} Emission Reduction, Pedelecs, Substituting Motorized Vehicles, Sustainable Transport

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I. INTRODUCTION

As of 2015, Uganda had about 129,500 kilometers of roads, with approximately 5,200 kilometers (four per cent) paved. Most paved roads radiate from Kampala, the country's capital, and largest city (MWT, 2021). Currently, only 20% of the roads are in a fair condition (IGC, 2017). Kampala, like other African cities, is urbanizing at an unprecedented rate; it was originally intended to support a population of 150,000 people but the current resident population is 1.5 million, with a daytime population of over 4.5 million people (IGC, 2017). To date, in Kampala most of urban dweller's commute by foot, which is not efficient in connecting people to jobs (Stucki, 2015). Most of the daytime population enter and commute in the city via over 16.000 14-seater minibus vans, called matatus, more than 100.000 motorcycle taxis, called boda-bodas, and via approximately 400.000 private vehicles. This leads to extreme traffic congestion each workday (IGC, 2017).

Three options for mass public transportation - a bus rapid transit system, a light rail train and a cable car - are being discussed in view of their capability to alleviate congestion (IGC, 2017). A massive introduction of pedelecs in Kampala could help increase mobility by decreasing traffic jams via replacing part of the use of passenger cars, matatus, matatu-ambulances and boda-bodas. It could also contribute to decrease air pollution, cut down greenhouse gas (GHG) emissions to 21-22 g CO_2/km as compared to 271 g CO_2/km traveled for cars (JB, 2020, data from the United States of America), and increase road safety (provided

dedicated lanes are available for pedelec bikers; Wegman et al., 2012; Civitas, 2020), all of which are major and ubiquitous challenges in Kampala (UN, 2018;). In addition to these positive contributions, the use of pedelecs and bicycles improves cardiovascular health in terms of oxygen consumption, lowered blood pressure, overall improved heart function, fights obesity, and reduces stress (JB, 2020; ECF, 2013).

In rural areas of Uganda walking is the most common and dominant form of transport. Many footpaths have developed informally and connect rural people to each other, but also to essential places, such as wells, fields and local facilities. Walking along these footpaths is often necessary to access the road network, and is of crucial importance to reach health facilities, education, employment, and civic responsibilities (MWT, 2012). In particular, women use these footpaths for the transport of water or agricultural products between the homestead, the farm and the market (Kleih et al., 2004). Bicycles provide a cheap and safe alternative to walking in rural Uganda and are therefore a familiar means of transport (MWT, 2012). However, along with the expansion of mobile phone services in Uganda, boda-bodas have expanded in the remote areas of the country, as they allow quick and on-demand transport services (Mbabazi, 2019). Boda-bodas sometimes are the only available form of transport during the rainy season but cost more than twice the price of scarce public minibuses, which makes them the most expensive form of transport available in rural areas (Mbabazi, 2019).

Rural mobility plays a central role in enabling livelihood opportunities to the remote population, but the lack of access to affordable transportation widens the mobility gap between the different income classes (MWT, 2012; Naybor et al., 2016). The global e-bike market has grown steadily in recent years and is revolutionizing mobility in many cities around the world (Rérat, 2021; HBS, 2021, ECF, 2020; JB, 2020). Sales in Europe and Asia are expected to grow from US$ 25 billion in 2020 to US$ 45 billion by 2028. Many people see e-bikes as a reliable alternative to public transport. In addition, they are affordable, climate-friendly, and particularly suitable for solving urban mobility problems such as air pollution and traffic jams. Up to now Africa remained largely untouched by the e-bike boom but this is likely to change soon. The European Institute for Sustainable Transport (EURIST) in Hamburg, Germany, and the First African Bicycle Information Organization (FABIO) in Jinja, Uganda, have been promoting sustainable and affordable mobility on the African continent for many years (EURIST, 2021; FABIO, 2021).

The first pilot projects with standard e-bikes started in 2019 and covered a total of 20,000 km using exclusively solar energy. The pilot phase carried out in Uganda was accepted with a great enthusiasm from the start; even motorcycle taxi drivers were very interested because of the opportunity to replace a borrowed motorcycle by an owned pedelec (Najjiba, 2021). While many people are accustomed to using the traditional bicycle, existing e-bikes had some limitations when used in the African context. It became clear that more robust and affordable e-bikes were needed. As a result, EURIST and FABIO initiated in 2019 a new partnership with Hero Cycles and the German designer company HNF Nicolai (EURIST/FABIO, 2021). Their collaboration succeeded in securing a grant from the German Investment Corporation (Deutsche Investitions- und Entwicklungsgesellschaft, DEG), which offers financing, advice and support to private sector enterprises operating in developing and emerging-market countries and is affiliated with the Kreditanstalt für Wiederaufbau (KfW) (DEG, 2021). The aim of the collaboration is to develop and test the first pedelec built especially for Africa with robust frame for high load, high charging capacity and a speed of up to 30 km /h. In addition, local service centers and a solar charging infrastructure are being set up by FABIO, including training courses for mechanics and beneficiaries. EURIST receives further support in the areas of battery recycling and solar technology from BODAWERK, a Ugandan social enterprise developing cutting-edge solutions in the field of lithium-ion batteries, and VET4Africa, the Vocational Education and Training for Africa (Bodawerk, 2022; VET4Africa, 2021).

The Ugandan partners created the name 'AfricroozE' for the pedelec. Delivery drivers and taxis can use it for business purposes, but it can also serve as an ambulance or water transporting bike in the non-profit sector. This initiative aims to bring clear benefits to the recipients and contributes to the achievement of 11 out of the 17 Sustainable Development Goals of the United Nations (EURIST, 2021):

- Goal 1: End poverty in all its forms everywhere
- Goal 2: End hunger, achieve food security and improved nutrition and promote sustainable agriculture
- Goal 3: Ensure healthy lives and promote well-being for all at all ages
- Goal 5: Achieve gender equality and empower all women and girls
- Goal 7: Ensure access to affordable, reliable, sustainable and modern energy for all
- Goal 8: Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
- Goal 9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
- Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable
- Goal 12: Ensure sustainable consumption and production patterns

- Goal 13: Take urgent action to combat climate change and its impacts
- Goal 17: Strengthen the means of implementation and revitalize the global partnership for sustainable development

Moreover, the introduction of pedelecs in Uganda at a large scale (and consequently in other sub-Saharan African countries) can contribute to the general policy goal of stabilizing greenhouse gas emissions in order to temper the impact of climate change in terms of the Clean Development Mechanism (CDM). The CDM meets the objective to assist parties included in Annex I of the Kyoto protocol in achieving compliance with their quantified emission limitation and reduction commitments (GHG emission caps) (A4ID, 2012).

The first 100 pedelecs rolled onto the roads of Jinja and the Jinja District in the eastern region of Uganda, in the first quarter of 2022. Jinja has a population of almost 100,000 and is located approximately 80 kilometres (km), by road, east of Kampala on the northern shores of Lake Victoria, at an average altitude of 1200 metres (UBOS, 2020; AZ_Nations, 2022; DC, 2015-2022; FM, 2020). Jinja District has a population of over 500,000 (UBOS, 2020). Jinja has the second largest economy in Uganda due to its industrialization (sugar works, steel manufacture, palm oil refining, car manufacture, breweries), commerce and the tourist sector (JT, 2022).

During the entire project phase, GPS and other data will be collected in order to evaluate the success of the pedelec and to further improve the product to better fulfil its intended services. The project is a pilot project which will be extended to other cities of Uganda once the data garnered are assessed and ascertain the successful reduction of CO_{2e} emissions from transportation.

The aim of this paper is to estimate the potential reduction of carbon dioxide equivalent (CO_{2e}) emissions due to pedelecs partially replacing motorized vehicles (passenger cars, boda-bodas, matatus) in Jinja and its rural environment. In these estimations CO_{2e} is defined as the weighted sum of CO_2, methane (CH_4) and nitrous oxide (N_2O) with the global warming potential (GWP) of 1 for CO_2, 25 for CH_4 and 298 for N_2O (U.S. EPA, 2014; 2019).

The paper advances previous research on the CO_{2e} emissions of pedelecs by including production of all parts, transport from manufacturer to the final destination of use, and disposal after the end of the pedelec lifetime. The potential compensation of the emissions from motorized vehicles in Uganda is estimated based on existing information on energy consumption. This estimation is only approximate as it does not consider Uganda's fleet composition of imported passenger vehicles, matatus, and motorcycles and their origins of manufacture due to lack of an existing documentation.

II. METHODOLOGY

To avoid confusion, one must be clear about the terminology of pedelec and e-bike. 'E-bikes are driven without pedal support or with a gas handle' (Stromer, 2019). Pedelec is the abbreviation of pedal electric cycle and was 'created in 1999 to differentiate between bicycles with automatic pedal support and those with a drive powered by a gas handle – meaning e-bikes. The terms e-bike and electric bicycle are still incorrectly used as synonyms for pedelecs, however.' (Stromer, 2019).

Pedelecs have an electric motor with maximum 250 watts (W) and support the rider when pedaling up to 25 km/h. Push assistance without pedaling is 6 km/h (Stromer, 2019). In contrast, the AfricoozE does 30 km/h and has an electric motor of 280 W. Throughout this paper, we will use the term 'pedelec', whenever appropriate, and even though the AfricoozE exceeds an electric motor power of 250 W and a top speed of 25 km/h.

In a first step we will estimate the CO_{2e} emissions of a pedelec and its lithium-ion battery of 0.5 kilowatt-hours (kWh) due to the energy use in their production. For the purpose of a realistic estimate in this step we review and summarize existing literature.

The second step is to estimate the CO_{2e} emissions per pedelec due to its transport from the manufacturer in New Delhi, India to the destination of its use by FABIO in Jinja, Uganda. This estimate starts from the fact that the 100 pedelecs can be transported in a 40 feet D container from the manufacturer in India to its destination in Uganda by truck and ship. A calculator for GHG emissions will be used in this step (EcoTransit, 2022)

The third step is to estimate the CO_{2e} emission reduction due to pedelecs when partially substituting motorized vehicles. For performing this estimate several assumptions must be made on the potential magnitude of the reduction in the use od passenger cars, matatus, matatu ambulances and boda-bodas in terms of km driven, and the fuel economy applicable in Uganda. These assumptions are specified in section III.

In passing, we also touch the issue of CO_{2e} emissions of the driver of the pedelec and those of solar services stations for recharging batteries.

The estimates of these three steps do not consider CO_{2e} emissions that occur during the manufacture of passenger cars, boda-bodas and matatus and due to their transport from the location in an exporting country

to their destination in Uganda. An appropriate part of these emissions should be credited to pedelecs partially replacing transport by motorized vehicles, increasing their pedelec CO_{2e} reduction. The corresponding estimates are performed in a fourth step. They are a very rough approximation because a documentation on the composition of the Ugandan vehicle fleet including vehicle country origin is not available.

The fifth step is to combine all these individual estimates to a conservative estimate of the net reduction of CO_{2e} emissions due to pedelecs replacing in part motorized transport in Uganda.

In all calculations below assumptions are necessary in each estimation step. These are explained in the sections where the estimates are performed.

III. Results and Discussion

A. Production and Disposal of a Pedelec

HERO LECTRO, a division of HERO Cycles LTD, will produce 7-speed pedelecs for ambulances, cargo and person transport designed by HNF Nicolai (HERO, 2022; HNF, 2021). The pedelec for person transport is shown in Figure 1.

Fig. 1: Design of the *AfticroozE* pedelec.
Source: EURIST Newsletter (2020/2021)

Critical components of a pedelec include the bicycle frame, additional parts, the lithium-ion battery, the smart Electric Drive Unit, controller, sensor, display (to switch the electric on & off; monitor the battery level & select the assist mode - low, medium, high. Raw materials include steel, solid alloy, and rubber. Published data are used to estimate the energy use and corresponding emission of carbon dioxide equivalent (CO_2e) for the extraction of raw materials. As the pedelecs are being produced in India energy use and corresponding CO_2e emissions must be based on the electricity mix of that country.

B. Production of the Pedelec Frame, Other Parts, and Electric Engine

A 20 kg pedelec is produced with approximately 14.6 kg aluminum, 3.7 kg steel and 1.6 kg rubber (Henriksen & van Gijlswijk, 2010). Using data from the Ecoinvent database 2.0 these authors estimated the CO_{2e} emissions from the production and maintenance of the pedelec to amount to 7 [g CO_{2e}/km] x 2400 [km/a] x 8 [a] = 134.4 [kg CO_{2e}], where it is assumed that the annual driving range is 2,400 km and the pedelec lifetime is 8 years. Similarly, the data used by these authors allows to estimate the annual emissions during use of the pedelec to amount to 24 [kg CO_{2e}/year (a)] or 192 [kg CO_{2e}] during pedelec lifetime.

The German Federal Environment Agency estimated the indirect emissions (manufacture) of CO_2 of a pedelec to amount to 0.564 [kg/100km] (UBA, 2014). Using an annual range of 2,400 [km/a] and a lifetime of the e-bike of 8 years as in the calculation above CO_{2e} emissions due to manufacture and maintenance are estimated to be 108.3 [kg CO_{2e}].

Johnson et al. (2014) estimated the global warming potential of the manufacture of two specialized bicycles (racers) to range between 123.5 [kg CO_{2e}] and 315 [kg CO_{2e}].

A more recent life cycle analysis estimates of the manufacturing of an aluminum framed and a steel framed bike of 15 kg resulted in a release of 137 [kg CO_{2e}] and 84.5 [kg CO_{2e}], respectively (Lacap & Barney, 2015). Assuming linearity, the production of a 20 kg aluminum framed pedelec would release approximately 183 [kg CO_{2e}].

In the following we assume a larger annual range of pedelec use of 7.750 km during a lifetime of eight years (see below) which results in a conservative estimate of 434 [kg CO_{2e}] emissions due to the manufacture and maintenance of a 20 kg pedelec. This amount does not include the GHG emissions for recycling and/or disposal of the pedelec. There are indications that these emissions are comparatively small compared to those of manufacturing (Roy et al., 2019; Chen et al., 2020). CO_2 emissions from natural degradation of 20 [kg] of solid waste materials amount to 3.2 [kg CO_2], and methane (CH_4) emissions of 3.7 kg steel are estimated to be 0.265 [kg CH_4] (Chen et al., 2020). Thus, with a warming potential of CH_4 by a factor of 25 higher than that of CO_2, CO_{2e} emissions due to natural degradation of a pedelec amount to 9.8 [kg CO_{2e}]. This value will affect the results reported below only insignificantly and is, therefore, not included.

C. CO_{2e} Emissions in Lithium-Ion Battery Production

Principal data include the electric capacity in kWh, the distance covered with a fully charged battery, the battery charge in Volt, the charging cycle and the lifetime of the battery. These are assumed to be:

- Capacity: 0.5 kWh
- Distance covered in one full charge: 60 [km]
- Battery charge: 36 Volt
- Charging cycle: 800 (Note: If possible, battery should be kept at moderate temperatures, see BU, 2021)
- Time to fully charge battery: 4 hours
- Lifetime of battery: 4 years

Recently, several papers have used life cycle analysis (LCA), which estimate the cradle-to-gate GHG emissions in units of kg CO_{2e}/kWh (IVL, 2020; Romare & Dahllöf, 2017; Regett et al., 2017; ANL, 2018; Dai et al., 2019; Melin, 2019; Kelly et al., 2019). Wang & Yu, 2020 estimated the cradle to grave GHG emissions.

Results are compiled in Table I.

TABLE I: CRADLE-TO-GATE CO_{2E} EMISSIONS OF LITHIUM-ION BATTERIES

Model/Data Source	Emission [kg CO_{2e} /kWh]	Source
Cradle-to-gate	150-200	Romare & Dahllöf, 2017; IVL, 2020
Cradle-to-gate/FfE*	106	Regett et al., 2017
Cradle-to-gate/GREET 2018	114.8	Dai et al., 2019; ANL 2018
Cradle to gate/Ecoinvent 2.2	67-72.8	Dai et al., 2019; Melin, 2019
Cradle-to-gate/European-dominant supply chain	65	Kelly et al., 2019
Cradle-to-gate/Chinese-dominant supply chain	100	Kelly et al., 2019
Cradle-to-grave/China	146	Wang & Yu, 2020

*EfE Forschungsstelle für Energiewirtschaft

In the following we assume an average estimate of 150 [kg CO_{2e}/kWh] emissions due to the manufacture and recycling of a lithium-ion battery. This value is conservative. For a battery of 0.5 kWh electrical energy the GHG emissions would amount to 75 [kg CO_{2e}].

D. Transport

HERO LECTRO is in Gurugram, Haryana (Southwest of New Delhi), will produce a first charge of 100 pedelecs, each weighing approximately 20 kg. The pedelecs will be land-transported in a 40 feet D container from New Delhi to Nhava Sheva Port (Jawaharlal Nehru Port Trust) in Navi Mumbai. The road distance between Delhi and Navi Mumbai is 1,412 km. By sea transport the container will be shipped to the port of Mombasa, Kenya, over 4,462 km. From Mombasa the container will be transported to Jinja, Uganda, with a road distance of 1,062 km. In the following the GHG emissions in units [kg CO_{2e}] will be estimated using the following assumptions:

- Packed mass of container of 2,000 kg from 100 pedelecs weighing 20 kg each
- Empty mass of 40-feet D container is 4,000 kg (approximate average between an ISO 668:2020 standard and a high cube container), leading to a Verified Gross Mass (VGM) of 6,000 kg (FF, 2022)
- Estimation is performed via the CO_2 calculator algorithm of Eco TransIT World (2022)
- 6,000 kg mass per heavy duty vehicle from New Delhi to Navi Mumbai: CO_{2e} = 610 [kg/100 pedelecs]
- 6,000 kg mass per seaway: Navi Mumbai > Kemba, Mombasa: 217 [kg CO_{2e}/100 pedelecs]

- 6,000 kg mass per heavy duty vehicle from Kemba, Mombasa > Jinja: 480 [kg CO_{2e}/100 pedelecs]

Table II summarizes the results for the CO_{2e} emissions of one pedelec.

TABLE II: SUMMARY OF CO_{2E} EMISSIONS FOR PRODUCTION,
TRANSPORT, AND DISPOSAL OF PEDELECS

Pedelec production, maintenance, and transport	GHG emissions per pedelec [kg CO_{2e}/pedelec]
Production and maintenance pedelec	434.0
Production and disposal/recycling of lithium battery	75.0
Natural degradation of a pedelc	9.8
Land transport India (WTW*)	6.1
Maritime transport India-Kenya (WTW)	2.2
Land Transport Kenya to Uganda (WTW)	4.8
Sum	**531.9**

*WTW = Well to Wheel

E. CO_{2e} emission from pedelec use

While CO_{2e} emissions from the use of the pedelec are negligible, the cyclist will need additional food to compensate for the work he has performed when pedaling. It is assumed that a 70 kg cyclist is burning in average 9 kilocalories (kcal) per minute or approximately 540 [kcal/h] when cycling the pedelec (U.S. HSS, 1999; CapCal, 2020). At an hourly distance of 25 [km/h] covered by the cyclist he will burn 22 [kcal/km] and, therefore, will emit 22 [kcal/km] x 1.44 [g CO_{2e}/kcal] = 32 [g CO_{2e}/km]. In this calculation the conversion factor from CO_{2e} to kcal adopted by the European Cyclist Federation has been used (ECF, 2011). At an annual range of 7,750 km and pedelec lifetime of 8 years (a) the CO_{2e} emissions of the driver during pedelec lifetime will amount to

$$32 \text{ [g } CO_{2e}/km] \text{ x } 7{,}750 \text{ [km/a] x } 8 \text{ [a]} = 1{,}984 \text{ [kg } CO_{2e}].$$

This emission of CO_{2e}, however, does not increase the carbon dioxide concentration in the atmosphere - because this originates from food that previously filtered the CO_{2e} from the atmosphere through photosynthesis during life. The CO_{2e} released when breathing is part of the natural carbon cycle. For this reason, it will be ignored for the rest of this estimation, in contrast to the approach chosen by ECF (2011).

F. CO_{2e} Emissions from Solar Services Stations for Charging of Batteries

Solar Services Stations, called E-Hubs, make the renewable source of solar energy more accessible for entrepreneurs and communities with low to middle incomes. Based on the idea of E-Hubs, shipping containers are being modified to provide communities with a more sustainable source of energy and affordable mobility (EURIST/FABIO, 2022). The concept features photovoltaic and battery storage systems designed to support corporate hubs that meet the electricity, mobility, and other basic needs of the community without using fossil fuels.

In this paper, the CO_{2e} emission of constructing and maintaining an E-Hub for charging pedelecs is not estimated, because it is considered small due to the small number of solar panels needed for recharging one pedelec. The carbon footprint of the production of a solar panel - monocrystalline or polycrystalline - can be quite significant due to their manufacturing process (Cool Effect 2021). However, based on a recent LCA the operation during the first year of one solar panel emits about 43 [g CO_{2e}/kWh] in order to account for the CO_{2e} produced during solar panel manufacturing (NREL, 2021). This is even an overestimate because the cited report does not account for recent advances in photovoltaic production (new solar panels are significantly more efficient). After their first three years of use, the panels will reduce that footprint even further, with the system remaining carbon neutral throughout the remainder of its lifespan of more than 20 years (GVEC, 2022).

G. Estimation of CO_{2e} emission reduction due to pedelecs substituting motorized vehicle use

CO_{2e} reduction occurs only if distances covered by pedelecs are substituting distances normally covered by passenger cars, matatus (minibuses, usually Toyota cabin transporters of 1990 or later make) and boda-bodas (Kamuhanda & Schmidt, 2008). Applications include:

- Pedelec taxi replaces passenger car or boda-boda (max driver and one person).
- Pedelec ambulance replaces passenger car (max driver and one person) or matatu ambulance (max driver and two persons, one of them is medical personnel).
- Pedelec use replaces 1/14 of 14-seater matatu use.
- Pedelec water o other burden transporter replaces passenger car or boda-boda.

- Pedelec everyday use replaces boda-boda (max one person.)

An analysis of vehicle mode use in terms of distance is necessary, i.e., the per cent share of distances up to 60 km covered by passenger cars, boda-bodas, matatus (1/14), matatu ambulances, and pedelecs is needed.

For the purpose of this paper the following assumptions are made:

1. 50 percent of kilometers driven annually by passenger cars, matatus, matatu ambulances and boda-bodas are replaced by distances driven by pedelecs.
2. Pedelec daily use: 50 km.
3. Pedelec annual use: 310 days per year.
4. Annual distance covered by pedelecs: 15.500 km.
5. Charging cycle: every day.
6. Number of charging cycles per year: 310.
7. Useful life of battery: 4 years.

A lower lifetime for the battery has been assumed for less favorable environmental conditions in sub-Saharan Africa.

From assumption 1 it follows that in a first approximation one pedelec may replace 7.750 km driven per year by passenger cars, matatus and boda-bodas in total. In order to separate the compensations of GHGs from the different vehicle modes we are forced to make assumptions on the potential modal split due to the lack of documented data on the Uganda (especially Jinja) vehicle fleet composition and use. For the modal split two assumptions are made:

8. One pedelec replaces annually a distance of 7.750 km traveled by 1/3 of passenger cars, 1/6 of matatus (1/14), 1/6 matatu ambulances and 1/3 of boda-bodas.
9. One pedelec replaces annually a distance of 7.750 km 1/3 of passenger cars, 4/9 of boda-bodas and 1/9 each of matatus (1/14) and matatus ambulances.

These assumptions are admittedly subjective and ought to be verified in subsequent assessments when data on the use of the pedelecs and the induced replacement of motorized vehicle use become available during the pilot project

A last assumption refers to the actual consumption of gasoline and diesel of passenger cars, boda-bodas and matatus, i.e. the fuel economy. Such data is not available in Uganda. In a study on the fuel economy of motorized vehicles in Nairobi, Kenya it was established that boda-bodas and passenger cars are consuming petrol in units Litre (L) per 100 km to be (4.6 ± 0.4) [L/100 km] and (22.8 ± 3.0) [L/100 km], respectively, and matatus (33.1 ± 2.5) [L/100 km] diesel (Mbandi et al., 2019). It is assumed that the fuel consumption of these vehicles can also be used for Uganda, i.e.:

10. Passenger cars in Uganda are consuming 22.8 [L/100 km] petrol, boda-bodas are consuming [4.6 L/100km] petrol, and matatus are consuming 33.1 [L/100 km] diesel.

From all 10 assumptions the annual CO_{2e} reduction due to the use of pedelecs instead of motorized vehicles can be estimated as shown in Tables III and IV.

In these tables the CO_{2e} emission factors for motor gasoline combustion in units [kg CO_{2e}/L] are calculated from the U.S. EPA emission factors for GHG inventories in EPA's Table 1 to be 2.33 [kg CO_{2e}/L] using the factors 25 and 298 for the 100-year global warming potential of CH_4 and N_2O, respectively (U.S. EPA, 2014; 2019). Similarly, the emission factor for diesel motor combustion has been estimated to be approximately 2.70 [kg CO_{2e}/L] using the data of EPA's Tables 2 and 4 (U.S. EPA, 2014).

Table III needs some explanation for a better understanding of the calculations. The avoided range per year in Table III, line 5 follows from assumption 8 on the modal split for passenger car, boda-boda, matatu ambulance and matatu 14-seater use. As a pedelec taxi transports only one person, the matatu fuel saved and corresponding CO_{2e} reduction must be weighted by a factor of 14. The CO_{2e} reduction per year in line 8 of Table III is the sum of the individual reductions for passenger cars, boda-bodas and matatus (Table III, line 7) for the second to fourth and sixth to eighth year because in these years the CO_{2e} emissions for production, maintenance, disposal and transport of the pedelec estimated in Table II need not be subtracted, as has been done for year 1 in line 9 of Table III. As after four years the lithium-ion battery is planned to be replaced, its CO_{2e} emissions for production and disposal were taken care of in the entry in line 10 of Table III. The last line in Table III calculates the annual average CO_{2e} reduction due to the use of pedelec instead of motorized vehicles from the estimations over eight years of pedelec lifetime.

TABLE III: NET REDUCTION PER YEAR AND PER PEDELEC WITH MODAL SPLIT OF ASSUMPTION 8

Parameter	Passenger car	Boda-boda	Matatu ambulance	Matatu
Consumption/100 km [L]	22.8	4.6	33.1	33.1
Fuel type	Petrol	Petrol	Diesel	Diesel
Emission factor [kg CO_{2e}/L]	2.33	2.33	2.70	2.70

Avoided range/year [km]	2,583	2,583	1,292	1,292
Saved fuel [L]	589	119	427	31
CO_2e-reduction [kg]	1,372	277	1,124	80
Reduction/year [kg CO_2e], year 2-4, 6-8		**2,886**		
Net reduction/first year per pedelec [kg CO_2e]		**2,354**		
Net reduction/fifth year per pedelec [kg CO_2e]		**2,811**		
Average net reduction/year [kg CO_2e]		**2,810**		

In this case the annual average net reduction and per one hundred pedelecs amounts to 288,000 [kg CO_2e]. It must be emphasized at this point that the validity of the assumption made above is to be verified in field observations once the pedelecs are being used in Uganda.

Table IV is built analogously to Table III using the modal split described in assumption 9. The explanations given for Table III, lines 5-10 apply to Table IV as well.

TABLE IV: Net Reduction per Year and Per Pedelec with Modal Split of Assumption 9

Parameter	Passenger car	Boda-boda	Matatu ambulance	Matatu
Consumption/100 km [L]	22.8	4.6	33.1	33.1
Fuel type	Petrol	Petrol	Diesel	Diesel
Emission factor [kg CO_2/L]	2.33	2.33	2.70	2.70
Avoided range/year [km]	2,583	3,444	861	861
Saved fuel [L]	589	158	285	20
CO_2e-reduction [kg]	1,372	369	750	54
Reduction/year [kg CO_2e], year 2-4, 6-8		**2,511**		
Net reduction/first year per pedelec [kg CO_2e]		**1,979**		
Net reduction/fifth year per pedelec [kg CO_2e]		**2,436**		
Average net reduction/year [kg CO_2e]		**2,435**		

In this case the annual average net reduction and per one hundred pedelecs amounts to 243,500 [kg CO_2e].

The net CO_2e reduction for a single pedelec shown in Table III and IV is substantially higher than that reported by other authors for pedelec use in developed countries (McQueen et al., 2020; Philips et al., 2020; Winslott Hiselius & Svensson, 2017; Fyhri et al., 2016), see Table V. This result may be due to the much higher fuel intensity of African motorized vehicles, at least for passenger cars and matatus, and to the modal splits used in Tables III and IV. In addition, the linear extrapolation to 310 days of values for emissions savings reported by Fyhri et al. (2016) in units [kg CO_2/day], and in units [kg CO_2/week] by Winslott and Svennsson (2017) and the downscaling of the annual values reported by McQueen et al. (2020) and Philips et al. (2020) may be not appropriate.

Actual determination of the modal split in Uganda may change our estimates to lower values but still possibly higher ones than those reported in the literature from developed countries.

TABLE V: Results for Net Reduction of GHG Emissions from Developed Countries

Methodology for pedelec	Methodology for substituted motorized transport emissions	Net reduction per year and per pedelec [kg CO_2]	Reference
Questionnaire on self-reported behavior	Transport usage measured by GPS	136-223*	Fyhri et al., 2016
Questionnaire on self-reported behavior	Frequency of substituted trips	251-354**	Winslott & Svensson, 2017
Accounting for reduction in trips and distance travelled in other modes given a 15 per cent increase in E-bike mode share	Estimation of average carbon footprint per person mile for public transit	191***	McQueen et al., 2020

Simulation of distance people can travel	Information of car use neighborhoods of 1.500 people	595+	Philips et al., 2020

*Assuming the reported emission saving of (0.44-0.72) [kg CO_2] per day for 310 days** Assuming the reported emission saving of (5.7-8.2) [kg CO_2] per week for 310 days; ***Assuming the reported emission saving of 225 [kg CO_2] per capita and year for 310 days; +Assuming the reported emission saving of 700 [kg CO_2] per person and year for 310 days.

Current estimates do not consider CO_{2e} emissions that occur when manufacturing passenger cars, boda-bodas and matatus. If part of these emissions is credited to pedelec use, they will increase pedelec CO_{2e} reduction. In a life cycle analysis performed in 2017 by the European Environment Agency based on a TNO report and modified in 2020 the CO_{2e} emissions from the production and disposal of internal combustion engine passenger vehicles and the fuel production have been estimated in units [g CO_{2e}/km] (EEA, 2017-2020; TNO, 2015). The results of these calculations can be used to estimate the corresponding credits attributable to pedelec use by evaluation of the product of km range avoided by pedelec replacing motorized passenger cars (Table III, Table IV) and the sum of CO_{2e} emissions per km for vehicle production and disposal and fuel production. The results are shown in Table VI.

TABLE VI: RANGE OF LIFE CYCLE CO2E EMISSIONS FOR PASSENGER CARS AND DIFFERENT FUEL TYPES IN THE EU

Parameter	Petrol	Diesel
Avoided range/year [km] (see Table 3)	2,583	1,292
Vehicle production and disposal [g CO2e/km]	46	50
Fuel production [g CO2e/km]	27	27
Credit for pedelec [kg CO2e]	189	97

The credit to be attributed to pedelec production and transport amounts to 189 [kg CO_{2e}] and 99 [kg CO_{2e}] for petrol-driven and diesel-passenger cars, respectively. This already compensates between 19 and 36 per cent of the pedelec production, maintenance and transport estimated in Table II. The third column of Table VI only serves for the purpose of illustration as passenger cars in Uganda can run on both petrol and diesel. It should be noted that these credits for pedelec use can be considered lower limits since most passenger cars in Uganda are second hand cars imported from Europe, Japan, and the United States, which often undergo manipulation of engines such as the elimination of catalytic converters. Also, the marking of fuel to avoid adulteration and smuggling into and in sub-Saharan African countries may be factors which increase fuel production CO_{2e} emissions.

A similar estimate of pedelec credit for matatus can be under the following assumptions for minibus (matatu) and fuel production:
1. A minibus has 1.5 the weight of a passenger car.
2. Fuel production for minibus is the same as that of a passenger car.

Table VII shows the corresponding credit for a pedelec to range between 88 and 124 [kg CO_{2e}]. As before, the credits attributable to pedelec use by evaluation are the product of km range avoided by pedelec replacing motorized passenger cars (Table III, Table IV) and the sum of CO_{2e} emissions for vehicle and fuel production and including vehicle disposal.

TABLE VII: ESTIMATES OF CO2e EMISSIONS FOR MATATU AND FUEL PRODUCTION

Parameter	Table III	Table IV
Avoided range/year [km]	1,292	861
Vehicle production and disposal [g CO2e/km]	69	75
Fuel production [g CO2e/km]	27	27
Credit for pedelec [kg CO2e]	124	88

These estimates do not include the attributable part of transport of passenger cars and minibuses to Uganda from Europe and Asia. A rough estimate of the CO_{2e} emissions due to transport of passenger cars and minibuses by assuming the following:
1. The annual distances driven by matatus in Uganda are 50.000 kilometers; those for passenger cars and motorcycles are 25.000 km each.
2. Second-hand passenger vehicles weighing 1000 kg are transported in D 40' containers from Hamburg to Kampala, five vehicles per container (Searates, 2021). The harbour of Hamburg is taken as a representative example for secondary vehicle transport from Europe. Real transport distances may be shorter or longer.
3. Minibuses weighing 1500 kg are transported in D 40' containers from Nagoya to Kampala, three minibuses per container (Searates, 2021). As most minibuses are Toyota 14 seaters imported from Japan to sub-Saharan African countries, the harbour of Nagoya is taken as representative for matatu transport.

4. Motorcycles weighing 100 kg are transported in D 40' containers from Pune to Kampala, 35 motorcycles per container (WCS, 2021; TS Export, 2021). The harbour of Pune is chosen because a high influx of cheap imports stem from Indian manufacturers. However, boda-bodas manufactured locally, e.g., UG Boss, Kampala are also starting to float the motorcycle market, meaning that transport CO_{2e} emission credits for pedelec may converge to near zero.

5. Transport CO_{2e} emissions are estimated via the CO_2 calculator algorithm of Eco TransIT World (2022).

6. Annual credits attributable to pedelec use are estimated through the quotient of annually avoided distances due to pedelec use and the annual driven distances of passenger cars and matatus, respectively.

Results of this estimation are compiled in Table VIII.

TABLE VIII: ESTIMATES OF PEDELEC CO_{2E} CREDIT DUE TO TRANSPORT OF PASSENGER CARS, MOTORCYCLES AND MATATU AMBULANCES

Parameter	Passenger car	Matatu (Table III)	Matatu (Table IV)	Boda-boda (Table III)	Boda-boda (Table IV)
Annual range [km]	25,000	50,000	50,000	25,000	25,000
Avoided km by pedelec use	2,583	1,292	861	2,583	3,444
CO_{2e} emissions due to transport per vehicle [kg CO_{2e}]	317	503	503	27	27
Credit for pedelec use [kg CO_{2e}]	33	13	9	3	4

For an estimate of pedelec credit from the production of motorcycles (boda-bodas) and fuels we use the life cycle analysis for GHG emission estimates of the Low Carbon Vehicle Partnership (LowCVP, 2018). The needed data for the LCA total CO_{2e} emissions are taken from the entries for the climate change impacts of internal combustion engine vehicles (ICEV) in column 9 of the LowCVP table on p. 34 of that publication. The percentages from vehicle and fuel production are the sum of the relative contributions of each LCA stage – vehicle and fuel production - for the four stage of ICEV motorcycle power [kW] compiled in rows 3, 5, 7,and 9, respectively. The estimated credit for a pedelec in unit [kg CO_{2e}] is calculated as the km-weighed product of total CO2e emission and the percentage from vehicle and fuel production. The corresponding pedelec credits for the avoided kilometers due to pedelec replacement of boda-bodas noted in Tables III and IV are compiled in Table IX.

TABLE IX: CREDIT FOR PEDELECS FROM LIFE CYCLE ANALYSIS OF GHG EMISSION ESTIMATES FOR PRODUCTION OF BODA-BODAS AND FUEL PRODUCTION

Power of motorcycle (kW)	4	11	25	50
Total LCA emissions [g CO_{2e}/km]	80.8	113.9	155.4	177.1
Percentage from vehicle and fuel production [%]	41.5	30.9	27.5	26.8
Credit for pedelec [kg CO_{2e}] (Table III)	87	91	110	123
Credit for pedelec [kg CO_{2e}] (Table IV)	115	121	147	163

As expected, the credits attributable to the use of pedelecs from motorcycle replacement turn out to be somewhat lower than those for passenger cars, and their magnitude increases with motorcycle power. The numbers in table IX range between 87 and 163 [kg CO_{2e}] and apply for the motorcycle transport of one person. If two or three persons are transported on the boda-boda pedelec credit will decrease as has been demonstrated by Sopha et al. (2017) for motorcycle use in Indonesia.

Now we are able to put together all credits attributable to annual pedelec use by partial motorized vehicle substitution in Table X. In this table the entries are built as follows.

- Row 2, columns 2 and 3 are the sum of credits from passenger car production and disposal and petrol and diesel production, respectively, as estimated in tables VI and VIII.
- Row 3, columns 4 and 5 are the sum of credits from matatu production, transport and disposal as well as diesel production, as estimated in Tables VII and VIII, for the modal splits of assumption 8 (Table III) and 9 (Table IV), respectively.
- Row 4, columns 4 and 5 are the sum of credits from boda-boda production, averaged over the motorcycle power equipment, and fuel production, as estimated in Tables VIII and IX, for the modal splits of assumption 8 (Table III) and 9 (Table IV), respectively.
- Row 5, columns 2 and 3 sum up the previous entries in Table X for passenger cars, matatus and boda-bodas, petrol- or diesel-driven, repectively, for the modal split of assumption 8.
- The entries in row 6, columns 2 and 3 have a similar meaning for the modal split of assumption 9.
- The final net reduction per year of pedelec use sum of all individua contributions under the two

modal splits.

TABLE X: CREDIT PER PEDELEC FOR PASSENGER CAR, BODA-BODA, AND MATATU PRODUCTION AND TRANSPORT

Vehicle	Petrol	Diesel	Assumption 8 (Table III)	Assumption 9 (Table IV)
Passenger cars: vehicle & fuel production, and transport (Tables VI and VIII) [kg CO_{2e}]	221	130		
Matatus: vehicle & fuel production, and transport (Tables VII and VIII) [kg CO_{2e}]			137	96
Boda-bodas: Average of vehicle production and transport [kg CO_{2e}]			105	141
Passenger cars (petrol/diesel) + Matatus (assumption 8) + Boda-bodas (assumption 8)	464	375		
Passenger cars (petrol/diesel) + Matatus (assumption 9 + Boda-bodas (assumption 9)	458	369		
	Total net reduction estimates attributable to a pedelec when including replaced vehicle production, fuel and transport CO_{2e} emissions			
Net reduction/year per pedelec [kg CO_{2e}] (Table III, assumption 8)	**2,862**			
Net reduction/year per pedelec [kg CO_{2e}] (Table IV, assumption 9)	**2,487**			

In case the modal split of assumption 8 applies, the net reduction per year and per 100 pedelecs amounts to 286,200 [kg CO_{2e}].

In case the model split of assumption 9 applies, the net reduction per year and per 100 pedelecs amounts to 248,700 [kg CO_{2e}].

IV. CONCLUSIONS AND OUTLOOK

Under the two modal splits for motorized vehicles - passenger cars, boda-bodas, matatu ambulances, matatus - partially replaced by use of pedelecs the CO_{2e} reduction per year and per 100 pedelecs amount to between 249 and 287 tons CO_{2e} and is approximately five times, respectively, higher than CO_{2e} emissions from the production of 100 pedelecs. Thus, our study demonstrates that the introduction of pedelecs in Uganda and their partial replacement of motorized vehicle use substantially will help reduce greenhouse gas emissions and bring clear benefits to the recipients and contribute to the achievement of 11 of the 17 Sustainable Development Goals of the United Nations. Thus, the question if the introduction of pedelecs in an African country can substantially reduce CO_{2e} emissions by reducing motorized vehicle use is reasonably answered. This is particularly true since our estimates are conservative. They do not include CO_{2e} credits attributable to pedelec use due to motorized vehicles idling in urban and peri-urban traffic congestions, at traffic lights, or the eventual need of passenger cars to go a long way round. Moreover, the CO_{2e} emissions of matatus on the journey to the starting point of their respective routes, or from the end of their last routes to a minibus depot are not included as well.

A more exact estimate of reduced CO_{2e} emissions will be possible once concrete data of pedelec use will be garnered and data on the replacement of motor vehicle use will become available. The results of this paper, when verified for the Jinja District, may be applicable in other Ugandan cities and in most other sub-Saharan African countries. The pilot project thus may lead to a rapid expansion of pedelec use in these countries for transportation of passengers, ambulances, logistics and small goods delivery in urban areas. In addition, pedelec use can reduce traffic congestion when less private motorized vehicles are used. For African rural areas the introduction of pedelecs will provide people with easier access to public services such as hospitals, libraries, commercial shops, and educational institutions, among others. For students, who must often cover long distances (10-15 km) between home and their academic institutions pedelecs can help increase attendance levels. This is particularly true for female students who often must choose between household chores and attendance to higher educational facilities. Also, older pupils living in rural areas may benefit from the use of pedelecs. The results of this paper may be used by politicians and decision makers to formulate, implement and enforce more sustainable transportation policies.

As an extension of this DEG-funded pedelec project, a small team of old and new EURIST members have come together to develop a new EURIST branch called African Ebike, which will focus on pedelec activities after the KfW-DEG project has terminated (post-project phase). This new project has been phrased the 'African Ebike Project'. The additional activities will be carried out in close cooperation with FABIO, Uganda, and SunCycles Namibia, a social business NGO, which is sharing knowledge with interested partners and follows an open-source strategy regarding electric mobility in Africa.

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