Hochschule Bochum
Bochum University
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MoNaL - Mobilität nachhaltig über den Lebenszyklus gedacht

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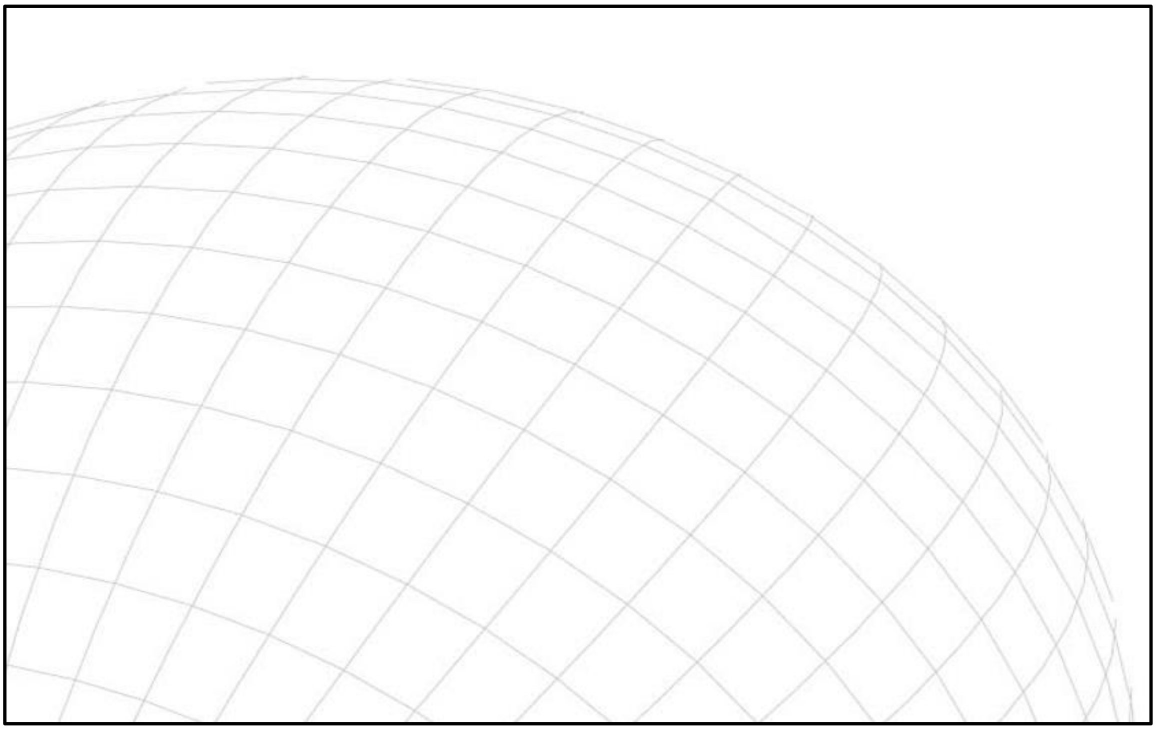
Evaluationsbericht

Analyse des Umweltnutzens sowie der sozialen und ökonomischen Wirkung von E-Fahrzeugen in Kombination mit Mini-Grids zur Energieversorgung



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Inhalt

Einführung

Dieser Evaluationsbericht hat das Ziel den Umweltnutzen sowie die soziale und ökonomische Wirkung von E-Fahrzeugen in Kombination mit Mini-Grids zur Energieversorgung zu analysieren und zu bewerten. Die Analyse des Produktsystems, bestehend aus E-Fahrzeugen, Solar-Ladestation und Mini-Grid, in Bezug auf die soziale Akzeptanz, die Wirtschaftlichkeit sowie das Umweltentlastungspotential erfolgte auf der Grundlage von Arbeitspaket 6 (AP 6).

Um die soziale Wirkung zu ermitteln, wurde eine Befragung mit der lokalen Bevölkerung durchgeführt. In einer Befragung zur sozialen Akzeptanz im Rahmen einer Produktklinik (AP 6.1) zeigte sich die Bereitschaft der lokalen Bevölkerung, leichte Elektrofahrzeuge mit einigen technischen Anpassungen der Geräte an die lokale Umgebung (AP 3.1-3.3) zu befürworten. Faktoren wie Anschaffungskosten, niedrige Lärmemissionen, Reichweite, Traglast, Sicherheit, Reparierbarkeit, Leistung, Umweltverträglichkeit, Wartungskosten und Design erwiesen sich in abstufender Reihenfolge als signifikant für die Akzeptanz von leichten Elektrofahrzeugen. Faktoren wie Standort, Benutzerfreundlichkeit, Verfügbarkeit von Geräten, Kosten und Produktvielfalt wurden als signifikant für die Akzeptanz von Sharing-Systemen eingestuft.

Um den ökonomischen Nutzen zu messen, wurde eine Wirtschaftlichkeitsanalyse (AP 6.2) durchgeführt. Auf Grundlage des pilotierten Produktsystems wurde ein exemplarisches Geschäftsmodells entwickelt. Die Beispielrechnungen zu Kosten und Erträgen auf Grundlage weiterer recherchierter Annahmen ergaben, dass in diesem Kontext ein E-Moped nach 6,3 Jahren gewinnbringend betrieben werden kann.

Eine Analyse zum Umweltnutzen des Produktsystems (AP 6.3) wurde mittels Ökobilanzen der Elektroleichtfahrzeuge und des Solar-Mini-Grid durchgeführt. Es konnte gezeigt werden, dass E-Lastenräder einen geringeren Einfluss auf das Treibhauspotenzial in Tonnenkilometern haben als Dieseltransporter. Die Analyse ergab zudem, dass die Treibhausgasemissionen über den Lebenszyklus deutlich geringer sind, wenn die Batterien mit Solarenergie betrieben werden. Die Einbeziehung von solarbetriebenen E-Lastenrädern in den Verkehrsmix für den Güterverkehr in der Stadt Accra würde zu Treibhausgasemissionseinsparungen von 4-8 % führen. E-Moped-Sharing-Systeme, die auf dem Campus von Don Bosco eingesetzt werden, haben in Bezug auf die Personenkilometer eine ähnliche Auswirkung auf das Treibhauspotenzial wie der öffentliche Verkehr, insbesondere wenn eine lange Produktlebensdauer sowie eine effiziente Betriebslogistik realisiert werden.

Zusätzlich zeigen die Ergebnisse der ersten Fallstudie am Don Bosco Mini-Grid in Tema, dass die Emissionen stark von der Technologie und Kapazität des Energiespeichers sowie der Auslastung abhängen. Tiefergehende Untersuchen ergaben außerdem, dass das installierte Mini-Grid zu einer Energieversorgung der E-Fahrzeuge vollständig ausreicht. Konkrete Einsparmöglichkeiten für Solar- und Batteriekapazitäten konnten am Beispiel der Kapellenbatterie auf dem Campus aufgezeigt werden.

Detaillierte Ergebnisse zu den Teilaspekten der Evaluation werden in den folgenden Abschnitten aufgeführt.

1. Wie hoch ist die soziale Akzeptanz für die Nutzung von E-Fahrzeugen?

Ausgangslage

Die gesellschaftliche Akzeptanz für neue Technologien ist grundlegend für ihre Verbreitung und Nutzung. Wesentlich für die Technologieakzeptanz sind dabei sowohl Bedürfnisse, Alternativen als auch - bei der Einführung von Technologien in einen anderen geographischen sowie sozio-ökonomischen Kontext – Anpassungen an die örtlichen Gegebenheiten. Die Nachfrage nach zuverlässigen Transportlösungen steigt in Ghana aufgrund der Urbanisierung und des Bevölkerungswachstums in den letzten Jahrzehnten. Mopeds mit Verbrennungsmotor sind dabei eine akzeptierte und vielfach genutzte, aber emissionsintensive Mobilitätslösung. Sharing-Systeme als eine umwelt- und ressourcenfreundliche Option sind kaum erprobt. Über die Faktoren einer Neuorientierung der Bevölkerung hin zur Nutzung von elektrisierten Leichtfahrzeugen und Sharing-Systemen gibt es bisher kaum Daten. Die auf dem Don-Bosco-Campus durchgeführte Produktklinik mit Fokusgruppenbefragung und Probefahrten der E-Fahrzeuge sollte die folgende Forschungsfrage beantworten:

I. Welche Faktoren beeinflussen die gesellschaftliche Akzeptanz von Elektroleichtfahrzeugen und Sharing-Systemen in Ghana?

Methodische Vorgehensweise

Um die soziale Akzeptanz von LEV in Ghana zu erfassen, wurden im Rahmen einer Produktklinik Probefahrten sowie Befragungen mit Probanden auf dem Campus Don Bosco durchgeführt. Die Befragten wurden gebeten, Faktoren zu benennen bzw. zu bewerten, welche ihnen bei der Nutzung eines Sharing-Systems und von E-Mopeds wichtig sind. Die Befragten hatten sowohl Zugang zu E-Mopeds als auch E-Lastenrädern vor Ort und konnten sich mit der Nutzung beider Geräte vertraut machen. Der vollständige Fragebogen ist im Anhang einzusehen. Sowohl qualitative als auch quantitative Fragen zur Nutzung von LEV sowie Sharing-Systemen wurden in einem gemischten Methodenansatz gestellt. Die Befragten bewerteten die Faktoren, die für ihre Nutzung von LEVs und ihren Sharing-Systemen wichtig sind auf einer Lickert-Skala, die dann mit Hilfe der Statistiksoftware SPSS weiter analysiert wurde.

Aufbauend auf dem theoretischen Rahmen von Schäfer et al. wurde die soziale Akzeptanz von LEVs anhand von drei Dimensionen definiert: Akzeptanzsubjekt, -objekt und -kontext (Schäfer und Keppler 2013). Akzeptanz bedeutet demnach, dass jemand (Akzeptanzsubjekt) etwas (Akzeptanzobjekt) innerhalb der jeweiligen bzw. Ausgangsbedingungen (Akzeptanzkontext) akzeptiert. Als Akzeptanzsubjekt können die potenziellen Nutzer des Sharing-Systems oder Personen, welche die Nutzung ablehnen, verstanden werden. Das E-Fahrzeug-Sharing-System selbst wird als Objekt definiert und der Kontext beschreibt alle Faktoren, die weder dem Subjekt noch dem Objekt zugerechnet werden, wie z.B. gesellschaftliche und kulturelle Tendenzen (Abbildung 1).

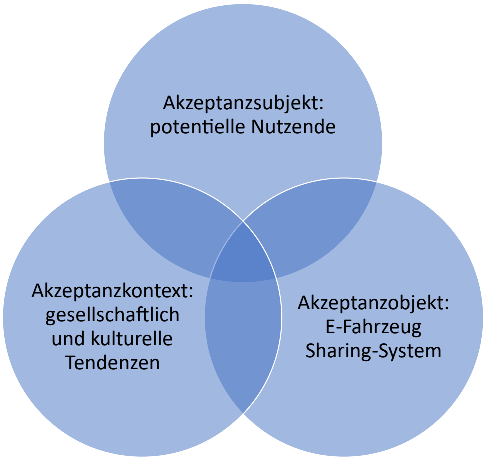

Abbildung 1: Eigene Darstellung der sozialen Akzeptanz nach Schäfer et al.

Ergebnisse

Die Ergebnisse zeigen die Bewertung der Faktoren, welche für die Befragten die soziale Akzeptanz von Elektroleichtfahrzeugen (LEVs) in Ghana beeinflussen. Die Befragten hatten sowohl Zugang zu E-Mopeds als auch E-Lastenrädern. Die Akzeptanzfaktoren der E-Mopeds sind daher ähnlich, wenn nicht sogar identisch mit denen für die Akzeptanz von E-Lastenrädern. Die Faktoren, welche die soziale Akzeptanz von E-Mopeds und Sharing-Systemen beeinflussen, werden in den nachstehenden Tabellen 1 und 2 näher erläutert.

Tabelle 1: Rangfolge der Faktoren zu E-Mopeds nach Relevanz (aus Basis der Antworten von Befragten)

Rang	Faktoren	Mittlere Punktzahl
1.	Anschaffungskosten	5.31
2.	Geringe Lärmentwicklung	5.32
3.	Mögliche Reichweite	5.34
4.	Tragslast	5.37
5.	Sicherheit	5.38
6.	Reparierbarkeit	5.46
7.	Leistung	5.53
8.	Umweltverträglichkeit	5.57
9.	Wartungskosten	5.77
10	Design	5.95

Bei der Auswertung der Faktoren für E-Mopeds, basierend auf 50 Beobachtungen, lag der Kendallsche Konkordanzkoeffizient bei 0,013. Des Weiteren ergab die statistische Analyse für den Freiheitsgrad einen Wert von 9 und für das Qui-Quadrat von 5,806. Die Asymptotische Signifikanz lag bei 0,000.

Tabelle 2: Rangfolge der Faktoren zu Sharing-Systemen nach Relevanz (aus Basis der Antworten von Befragten)

Rang	Faktoren	Mittlere Punktzahl
1.	Standort	2.89
2.	Einfache Nutzung	2.94
3.	Verfügbarkeit	2.95
4.	Preis	2.97
5.	Auswahl	3.26

Für die Auswertung der Faktorenrangfolge bei Sharing-Systemen wurden 49 Beobachtungen evaluiert. Der Kendallsche Konkordanzkoeffizient lag dabei bei 0,020. Des Weiteren ergab die statistische Analyse für den Freiheitsgrad einen Wert von 4 und für das Qui-Quadrat von 3,867. Die Asymptotische Signifikanz lag bei 0,000.

Die oben dargelegten Ergebnisse bieten konkrete Einblicke in die soziale Akzeptanz von LEVs und Sharing-Systemen in Gesellschaften wie Ghana und anderen Schwellenländern. Die Ergebnisse bestätigen bzw. stimmen mit früheren Arbeiten von Adjei et al. überein, bei denen herkömmliche Motorräder anstelle von LEVs verwendet wurden, da diese im Land zu dem damaligen Zeitpunkt nicht verfügbar waren (Adjei, Cimador und Severengiz 2022). Die Analyseergebnisse zeigen, dass die ökologische Nachhaltigkeit nicht der treibende Faktor für einen Wechsel zu einem nachhaltigeren Verkehrsmittel für die örtliche Bevölkerung ist. Eine Einstiegsstrategie für künftige Anbieter oder Dienstleister müsste sich auf die Kernbedürfnisse oder -zwecke des Verkehrs konzentrieren und nicht auf den Schutz des Planeten oder den Klimawandel. Der Hauptfaktor für einen Wechsel sind die Kosten, was die derzeitigen wirtschaftlichen Bedingungen im Land widerspiegelt. Weitere Faktoren wie Entfernung, Gewicht oder Ladekapazität reflektieren den Bedarf dieser Geräte für ihre spezifischen Anwendungsfälle: Kurzstreckenfahrten und den Transport von Personen und Materialien. Für die Nutzung von Sharing-Angeboten sind vor allem der Standort sowie die einfache Nutzung entscheidend.

2. Lässt sich das Konzept in ein wirtschaftliches Geschäftsmodell überführen?

Ausgangslage

Die steigende Bevölkerung und das Wirtschaftswachstum stehen in direktem Zusammenhang mit einem erhöhten Mobilitätsbedarf (G.K. Ayetor et al. 2021). Von den 72 Millionen Fahrzeugen, die in Afrika im Einsatz sind, entfallen 2,5 Millionen auf Ghana (G. K. Ayetor et al. 2022). Der Mobilitätsbedarf in Ghana basierte bisher auf fossilen Brennstoffen, wobei nachhaltige Mobilitätsoptionen nur begrenzt erforscht und umgesetzt wurden. In diesem Abschnitt wird die Rentabilität eines Geschäftsmodells bewertet, welches auf dem Sharing-System von leichten Elektrofahrzeugen (Light Electric Vehicles, LEVs) auf dem Campus der Kwame Nkrumah University of Science and Technology (KNUST) basiert. Das Ziel einer solchen nachhaltigen Mobilitätslösung wäre die Bereitstellung von Transportmöglichkeiten bei gleichzeitiger Minimierung des Ressourcenverbrauchs und der Verkehrsüberlastung.

Etwa 8 % der Haushalte gaben bei Erhebungen des ghanaischen Straßen- und Verkehrsministeriums an, zwischen einem und vier Motorräder zu besitzen, die für die private Nutzung in gutem Zustand waren. Insgesamt gab es im Jahr 2012 einen Bestand von etwa 2,4 Millionen konventionellen Motorrädern. Bei einer geschätzten Bevölkerung von derzeit 30,8 Millionen Menschen und der Annahme eines konstanten Anteils an konventionellen Motorrädern pro Person könnte der Bestand im Jahr 2022 bei 2,86 Millionen konventionellen Motorrädern liegen. Bei einer solchen Schätzung beläuft sich die derzeitige potenzielle Nachfrage nach Motorrädern, und damit bei einem Umstieg nach E-Motorädern, auf 2,8 Millionen. Es besteht eine Forschungslücke hinsichtlich der Tragfähigkeit eines nachhaltigen Geschäftsmodells auf der Grundlage von E-Mopeds. Eine Wirtschaftlichkeitsanalyse wurde durchgeführt, welche auf der folgenden Forschungsfrage basiert:

I. Können Geschäftsmodelle auf einem Universitätscampus, die auf ausleihbaren Elektroleichtfahrzeugen basieren, wirtschaftlich betrieben werden?

Methodische Vorgehensweise

Das umgesetzte E-Moped-Sharing-System an der KNUST-Universität in Kumasi wurde als Ausgangspunkt genommen, um ein Geschäftsmodell zu entwickeln, welches auf ähnliche Kontexte in Ghana ausgeweitet werden kann. Für das Pilotprojekt wurde ein nachhaltiges Geschäftsmodell nach Geissdoerfer et al. entworfen. Nachhaltige Geschäftsmodelle basieren in ihren Grundsätzen auf klassischen Geschäftsmodellen. Letztere sind traditionell auf den wirtschaftlichen Nutzen ausgerichtet. Die Definitionen in der Literatur sehen nachhaltige Geschäftsmodelle als eine Abwandlung des konventionellen Geschäftsmodellkonzepts. Es werden bestimmte Aspekte und Ziele hinzugefügt, so dass sie entweder 1) Konzepte, Grundsätze oder Ziele beinhalten, die auf Nachhaltigkeit abzielen, oder 2) Nachhaltigkeit in ihr Leitbild und ihre Wertschöpfungsprozesse integrieren. Geissdoerfer et al. definieren das nachhaltige Geschäftsmodell konkret als ein Geschäftsmodell, das ein proaktives Multi-Stakeholder-Management, die Schaffung von monetärem und nicht-monetärem Wert für ein breites Spektrum von Stakeholdern und eine Langzeitperspektive beinhaltet.

Zusätzlich wurde die Wirtschaftlichkeit des Geschäftsmodells im Rahmen einer Kosten- und Ertragsrechnung untersucht. Dazu wurden fundierte Annahmen sowohl auf Basis von Erkenntnissen aus dem Pilotprojekt als auch in Austausch mit Experten und basierend auf gesetzlichen Rahmenbedingungen getroffen. Die Annahmen wurden auf der Grundlage von Einzelgesprächen und E-Mail-Korrespondenz mit Experten auf dem Gebiet von E-Moped-Sharing-Systemen (Russ P., Tier Mobility GmbH, 2021), Erkenntnissen aus Überprüfungen des ghanaischen Steuer- und Unternehmensregistrierungssystems (Aryee M.A., MEK Consult und HR Essentials LLC, 2021) und dem Geschäftsmodell des privaten E-Mobilitätsdienstleisters Solar Taxi Ghana geschätzt.

Ergebnisse

Im Folgenden wird ein Überblick über das Geschäftsmodell gegeben, das in dem Pilotprojekt auf dem Campus von KNUST verwendet wurde:

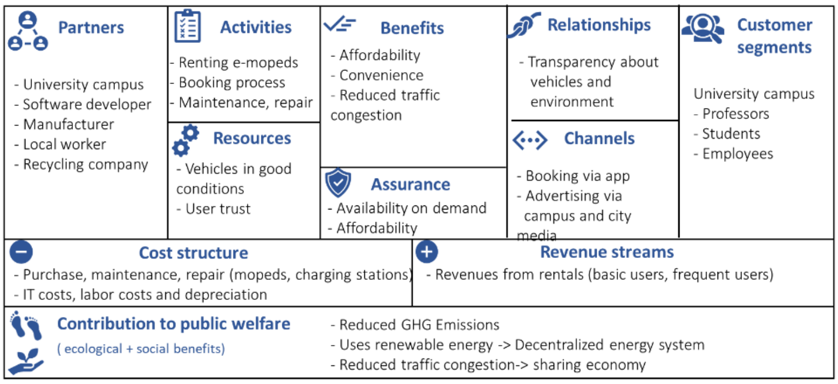

Abbildung 2 Geschäftsmodell Entwurf für ein Campus Sharing-System basierend auf der Arbeit von Osterwalder & Pigneur

In Tabelle 3 ist eine Übersicht über die Kosten und Erträge je E-Moped dargestellt. Basierend auf dem bestehenden Shuttle-Service auf dem Campus, Geschwindigkeitsbegrenzungen und einer Umfrage unter Studierenden und Mitarbeitenden auf dem KNUST-Campus dauert eine durchschnittliche Fahrt auf dem Campus acht Minuten. Als Gebühr pro Fahrt wurden 10 Cent pro Minute festgelegt, ausgehend von den aktuellen Kosten auf dem Campus. So wird der Ertrag pro Fahrt/ pro E-Moped auf ca. 1,40€ geschätzt. Dieser steht den einmaligen Anschaffungskosten des Produktsystems, sowie den monatlichen Kosten und den Kosten pro Fahrt gegenüber.

Tabelle 3 - Überblick über Kosten und Erträge je E-Moped

Kostentyp	Beschreibung	Kosten	Kosten/E-Moped
Einmalige Kosten	E-Mopeds, Solaradestation, Ausstattung	387.760€	9.694€
Monatliche Fixkosten	Gehälter, Miet- und Betriebskosten	2.968€	2,44€
Variable monatliche Kosten	Ersatz, Diebstahl, Software-Nutzung, Updates	313,38€	1,83€
Kosten pro Fahrt	Kreditkarte, Versicherung, Reparatur, Genehmigungen	6.393,23€	0,53€
Ertrag pro Fahrt	Festpreis und mindestens 8 Minuten Fahrt		1,40€

Abbildung 3 zeigt die graphische Darstellung der Erträge im Verhältnis zu den bekannten Kosten runtergerechnet auf je ein E-Moped. So ergibt sich ein Break-even-Punkt ca. nach 2.300 Tagen bzw. nach 6,3 Jahren. Da die genauen Kosten für die Softwareentwicklung derzeit nicht bekannt sind, kann davon ausgegangen werden, dass sich die Berechnung verschiebt und die Rentabilität früher erreicht wird. Es ist zu beachten, dass das Geschäftsmodell auf lokal beschafften E-Mopeds basiert. Europäische Modelle sind teurer und es fallen zzgl. Zollkosten an, so dass die Wirtschaftlichkeit dieser Modelle für die Nutzung im präsentierten Geschäftsmodell angepasst werden muss.

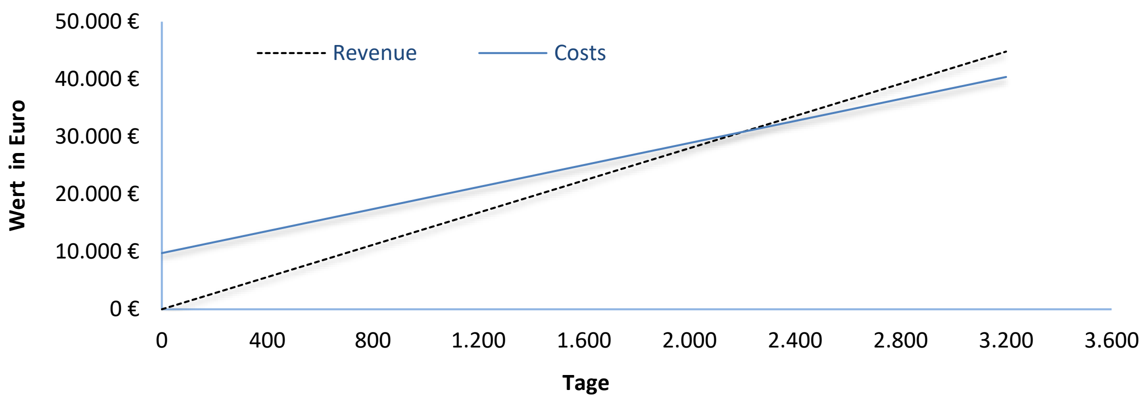

Abbildung 3: Tage, bis ein E-Moped im System wirtschaftlich ist

3. Welchen Umweltnutzen bieten das entwickelte Produktsystem sowie die Recyclingkonzepte?

Methodische Vorgehensweise

Die Quantifizierung des Umweltnutzens des Produktsystems aus Mini-Grid, E-Lastenrad und E-Mopeds wurde im Rahmen von mehreren Ökobilanzen (Life Cycle Assessments) durchgeführt:

1. LCA zur Sharing-Nutzung von elektrischen-Mopeds in Ghana
2. LCA zur Nutzung von E-Lastenfahrräder für den Einsatz im städtischen Güterverkehr in Ghana
3. LCA zu einem Smart-Mini-Grid zur Stromversorgung am Beispiel des Don-Bosco-Mini-Netzes.

Recyclingmöglichkeiten wurde im Rahmen der Auswahl von Systemgrenzen innerhalb der Ökobilanzen berücksichtigt. So wurde jeweils der Cradle-to-Grave Ansatz gewählt.

Die Ökobilanz ist eine Methodik zur Quantifizierung der Umweltwirkungen von Produkten, Prozessen oder Dienstleistungen und kann für alle Lebensphasen von der Wiege (Rohstoffextraktion) bis zur Bahre (End-of-Life, z.B Recycling oder Deponierung) angewendet werden. Die Methodik ist standardisiert und in ISO 14040 sowie ISO 14044 beschrieben. Die Ökobilanz ist die am besten geeignete Methode, um Informationen über die Umweltwirkungen zu erhalten und daraus abgeleitet Potentiale zur Verbesserung von Produkten und Komponenten hinsichtlich der Verringerung negativer Umweltwirkungen zu identifizieren. Die Ökobilanz umfasst vier Phasen, Ziel- und Untersuchungsrahmen, Sachbilanz (LCI), Wirkungsabschätzung (LCIA) und Interpretation. Diese Phasen folgen aufeinander, wobei es sich um einen iterativen Prozess handelt. Das heißt bei neuen Erkenntnissen aus einer Phase können Anpassungen in anderen Phasen vorgenommen werden z.B. Anpassung des Untersuchungsrahmens, bei neuen Erkenntnissen aus der Sachbilanz und darauffolgend erneute Auswertungen.

Bei der Methode werden systematisch alle Bestandteile von Produkten, Prozessen und Dienstleistungen analysiert. Wenn die Ökobilanz alle Aspekte von der Rohstoffbeschaffung und Herstellung (cradle) bis zum Recycling und zur Entsorgung (grave) berücksichtigt, spricht man von „cradle-to-grave". In Abbildung 4 wird ein Überblick über die Lebensphasen gegeben am Beispiel eines e-mopeds.

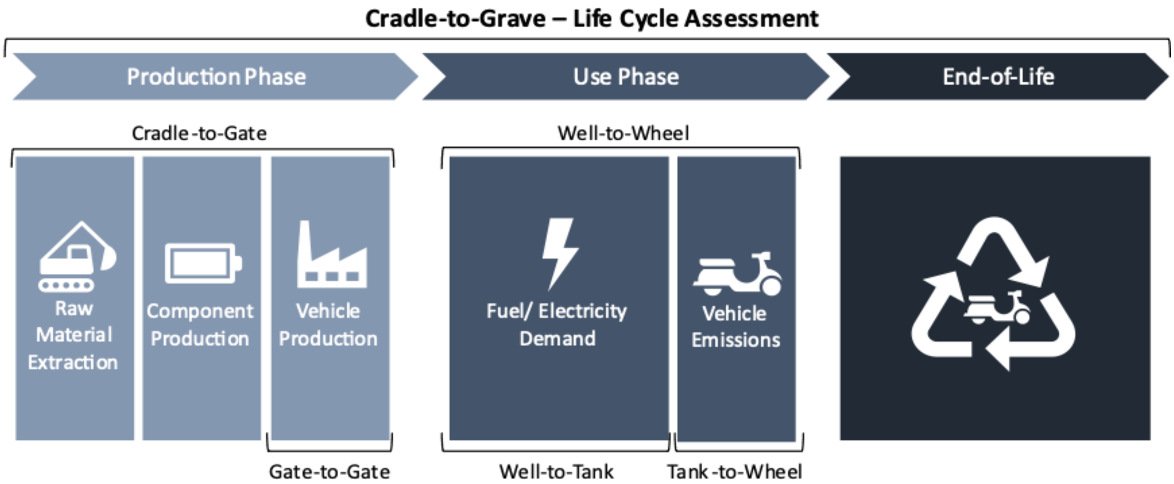

Abbildung 4: Phasen einer Lebenszyklusanalyse von Fahrzeugen von der Wiege bis zur Bahre. Eigene Darstellung.

Neben den betrachteten Lebenszyklusphasen, welche in Abbildung 4 dargestellt sind, ist die funktionelle Einheit zur Vergleichbarkeit der Ergebnisse mit anderen Produkten oder Dienstleistungen relevant, sowie die Systemgrenzen, welche Bestandteile zum Produktsystem gezählt werden. Diese Parameter werden innerhalb der Ergebnisse für die einzelnen LCAs separat dargestellt.

Ergebnisse

Die Methodik und die Ergebnisse der drei Ökobilanzen werden im Folgenden einzeln vorgestellt.

Mini Grid

Das untersuchte Mini-Grid wurde auf dem Campus von Don Bosco in Tema, Ghana installiert und genutzt. Die Ökobilanz des Mini-Grid basiert auf einer Cradle-to-Grave-Analyse. Die funktionale Einheit ist die verbrauchte Kilowattstunde (kWh). Die Nutzungsphase und die damit verbundenen Transport- und Wartungsmaßnahmen wurden nicht betrachtet, da die ökologischen Auswirkungen hier als nicht signifikant angenommen wurden. Die allgemeinen Systemgrenzen sind in Abbildung 5 dargestellt.

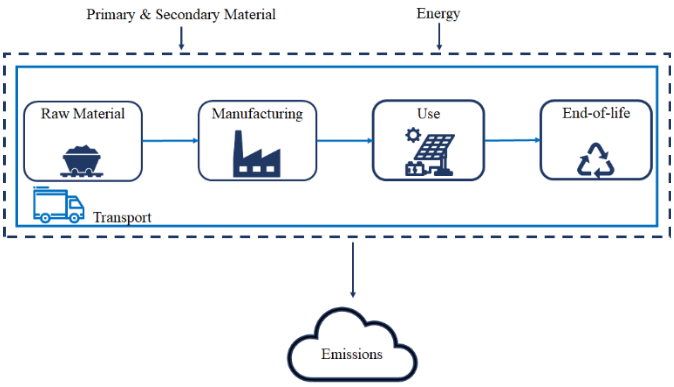

Abbildung 5: Systemgrenzdiagramm für die Ökobilanz des Mini Grid

Der Aufbau des Don Bosco Mini Grids zeigt Abbildung 6.

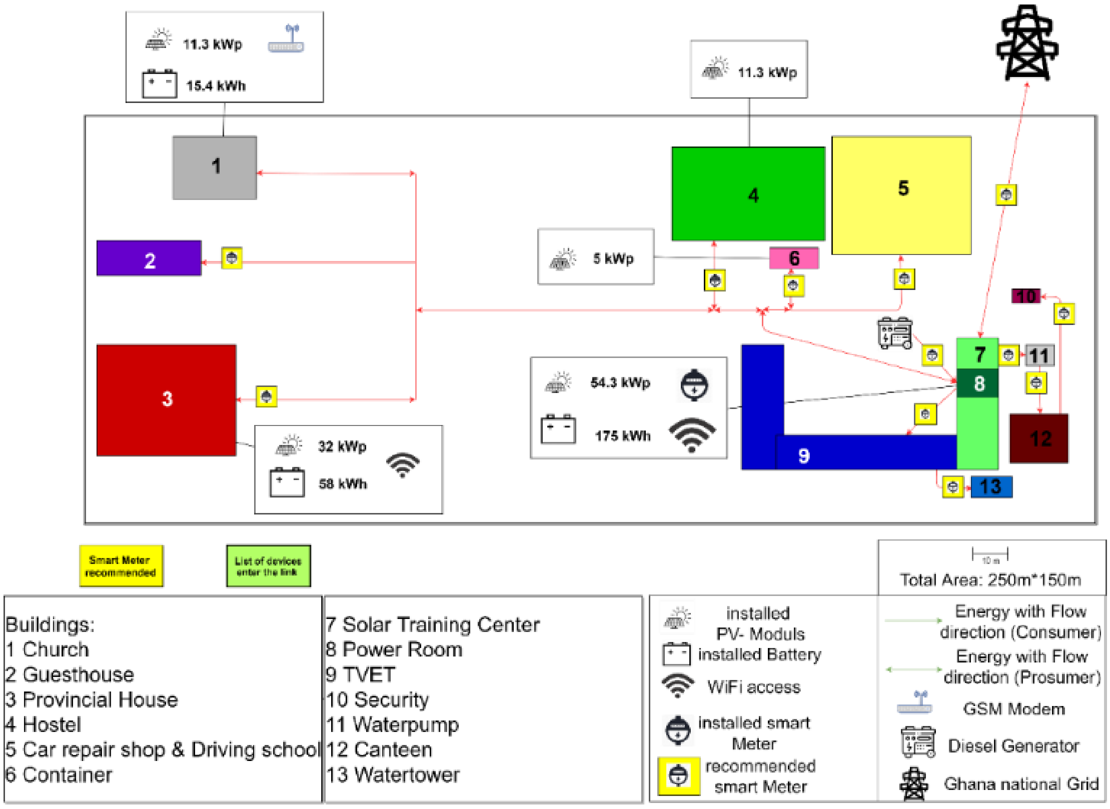

Abbildung 6: Schema des Don Bosco Mini Grid

Die Ergebnisse zeigen, dass die über den Lebenszyklus ganzheitlich ermittelten Treibhausgasemissionen des Mini-Grids 235.304 kg CO_2eq betragen. Abgeleitet vom gesamten GWP ergeben sich relative Emissionen von 0,055 kgCO_2eq/verbrauchte kWh. Abbildung 7 zeigt den Anteil der Umweltauswirkungen für die Lebenszyklusphasen Herstellung, Transport und Lebensende (Recycling). 86,8 % der Emissionen entfallen auf die Herstellung, 12,9 % auf den Transport und 0,3 % auf das Recycling. Eine Aufschlüsselung der Komponenten in der Herstellung zeigt, dass die PV-Module 37,9 % der Emissionen und damit den größten Anteil an den Gesamtemissionen ausmachen. An zweiter Stelle folgen die Emissionen der Wechselrichter mit 33,7 %. Diese zwei Komponenten machen fast zwei Drittel der Emissionen der gesamten Mini-Grid Konstruktion aus. Die Blei-Säure-Batterien folgen mit 17,1 %. Die weiteren Komponenten Elektronik, Steuerung, PV-Montage, Kabel und die Lithium-Ionen-Batterie bilden zusammengenommen 11,3 % der Emissionen.

Abbildung 7 zeigt die Aufteilung der Emissionen nach Lebenszyklusphasen, sowie den Anteil der Emissionen für die Komponenten während der Fertigung und des Transports. Diese Ergebnisse zeigen, dass beim Transport nicht die Entfernung, sondern das Gewicht und die Anzahl der Komponenten relevanter sind. Aufgrund des hohen Gewichts der Blei-Säure-Batterien, die 71,4 % der Gesamtmasse ausmachen, haben sie mit 15.364,7 $kgCO_2eq$ die größten Auswirkungen. Dies entspricht 50,8 % des gesamten Transports, gefolgt von den PV-Modulen mit 29,9 %. 11,5 % der Emissionen während des Transports entfallen auf den Wechselrichter. Die Elektronik, die Steuerung, die PV-Montage und die Kabel machen zusammen den Rest von 8,2 % aus.

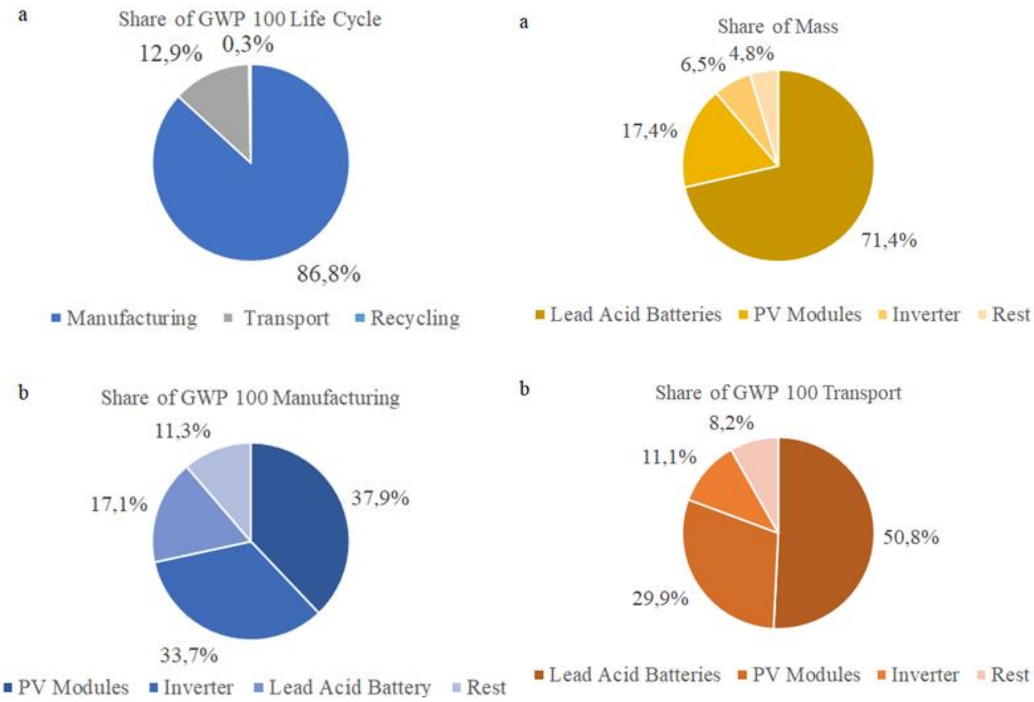

Abbildung 7: Links: (a) Gesamtmenge der GWP-Emissionen; (b) Anteil des GWP für das Don Bosco Mini Grid; Rechts: (a) Gesamtanteil des GWP für die zugehörige Masse; (b) Gesamtanteil des Verkehrs

Um die Umweltauswirkungen des Mini-Grid zu bewerten, wird es mit dem Stromnetz in Ghana und einem Dieselgenerator verglichen. Für die Stromproduktion des Mini-Grids wird eine Produktion von 4,5 vollen Stunden pro Tag angenommen, was 1.643 Volllaststunden pro Jahr ergibt. Multipliziert mit der verfügbaren Kapazität von 103 kW beträgt die Stromproduktion für den gesamten Lebenszyklus 4.241 MWh. Abgeleitet vom gesamten GWP hat das Mini-Grid relative Emissionen von 0,055 $kgCO_2eq$/verbrauchte kWh. Nach Angaben der Ghana Energy Commission beträgt der Emissionsfaktor für die Netzenergie 0,460 $kgCO_2eq$/kWh. Für den Dieselgenerator beträgt der Emissionsfaktor 1,65 kg $kgCO_2eq$/kWh. Die Einsparungen über 25 Jahre belaufen sich auf 1.713 tCO_2eq im Vergleich zum Stromnetz und 6.769 tCO_2eq im Vergleich zum Dieselgenerator, wenn man den gesamten 25-jährigen Lebenszyklus des Mini Grid berücksichtigt.

E-Moped

Zur Ermittlung des Umweltimpacts durch E-Mopeds in Ghana wurde eine Ökobilanz mit dem von der Firma e-bility GmbH produzierten E-Moped der Marke Kumpan durchgeführt, welches in Abbildung 8 dargestellt ist. Hierfür wurde eine vorherige Arbeit des Labors als Ausgangsbasis genutzt, bei der eine Verwendung des E-Moped-Modells im Sharing-Betrieb in Deutschland untersucht wurde. Die Lebenszyklusphasen “Transport” und “Nutzung” wurden angepasst, um die Situation in Ghana zu reflektieren.

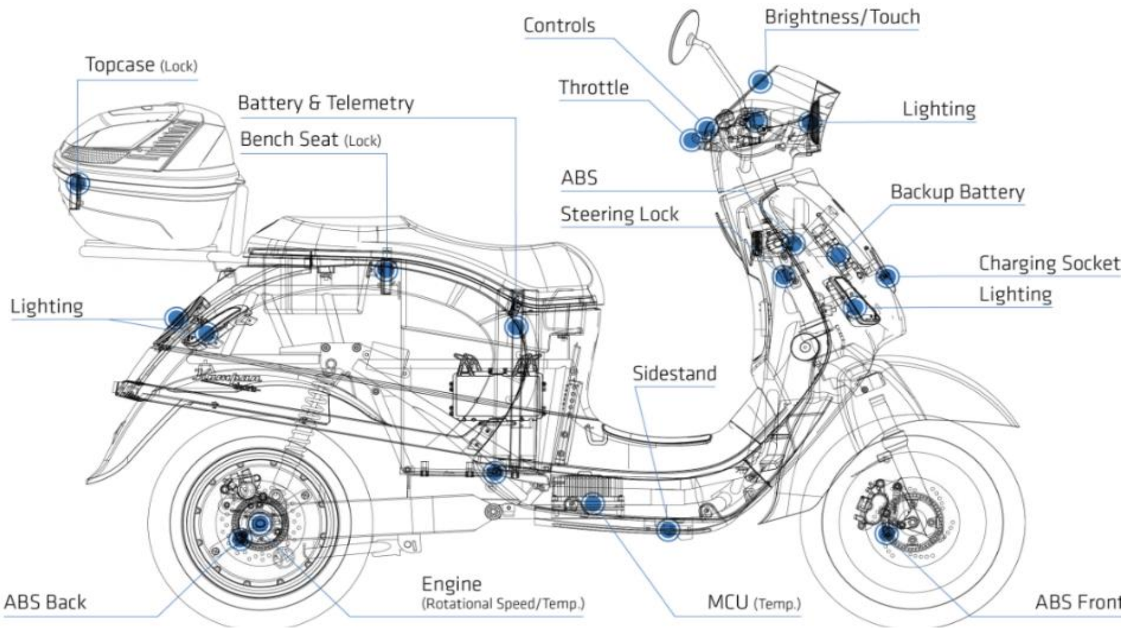

Abbildung 8: Technische Zeichnung des E-Mopeds Kumpan 1954, welches im MoNaL-Projekt verwendet wurde, bereitgestellt durch die e-bility GmbH

Die Systemgrenzen der Untersuchung sind in Abbildung 9 dargestellt. Sie umfassen die Umweltwirkungen, durch die Gewinnung von von Primär- und Sekundärmaterialien, die Komponentenproduktion, den Transport, die Nutzung und das End-of-Life. Die funktionale Einheit ist ein zurückgelegter Personenkilometer (pkm). Zur Wirkungsabschätzung wurde die CML-Methode in der Version von 2016 verwendet (Centrum voor Milieuwetenschappen Leiden 2016).

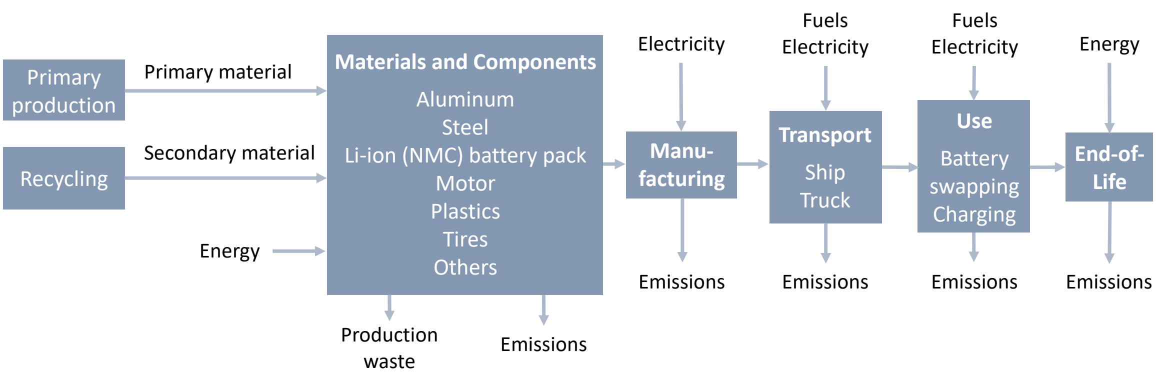

Abbildung 9: Systemgrenzdiagramm für die Ökobilanz von e-Mopeds in einem Sharing-System

Das E-Moped wird in Deutschland produziert, wobei einige Komponenten, wie beispielsweise die Batteriezellen, in China gefertigt werden. Das Moped wird anschließend nach Ghana verschifft und dort betrieben. Da bisher kein E-Moped-Sharing Dienst in Ghana etabliert ist und entsprechend keine Nutzungsdaten vorliegen, werden für den Betrieb verschiedene Szenarien entwickelt auf der Grundlage der Tests vor Ort und von E-Moped Sharing-Diensten in Deutschland. Folgende Nutzungsszenarien wurden betrachtet:

1. Laden mit ghanaischem Strommix + Servicefahrten mit Dieseltransportern (Nutzungsparameter Transporter entsprechend Sharing Diensten in Deutschland)
2. Laden mit Mini-Grid + Servicefahrten mit Dieseltransportern (Nutzungsparameter Transporter entsprechend Sharing Diensten in DE)
3. Laden mit ghanaischem Strommix, keine Servicefahrten (entspricht privater Nutzung bei Nutzung des Stromnetzes)
4. Laden mit Mini-Grid, keine Servicefahrten (Status Quo 2022 am Don-Bosco, entspricht privater Nutzung mit Off-Grid-PV)

Abbildung 10 zeigt die THG-Emissionen der vier betrachten Szenarien in Bezug auf einen zurückgelegten Personenkilometer. Im ersten Sharing-Szenario beträgt das durchschnittliche GWP 51 g CO_2eq./pkm, wobei 28% auf die Produktion, <1 % auf den Transport und 71 % auf die Nutzungsphase entfallen. In der Nutzungsphase werden 33 % des GWP durch die Emissionen verursacht, die durch die Stromerzeugung zur Deckung des Energiebedarfs der E-Mopeds entstehen. 67 % der Emissionen in der Nutzungsphase werden durch die direkten Emissionen der Transporter, welche die Batteriewechsel durchführen, verursacht. Die End-of-Life-Phase macht nur <1 % des GWP aus.

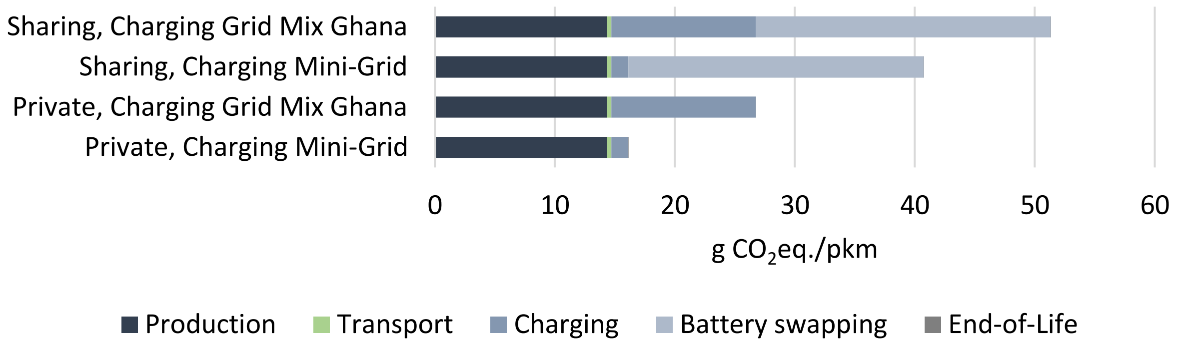

Abbildung 10: Umweltauswirkungen in bezug auf das Treibhauspotential (GWP) über den gesamten Lebenszyklus von elektrischen Mopeds im gemeinsamen Gebrauch unter Berücksichtigung verschiedener Nutzungsszenarien.

Durch das Laden mit Solarstrom aus dem Mini-Grid können 20% der THG-Emissionen, die über den Lebenszyklus anzurechnen sind, eingespart werden (41 g CO_2eq./pkm). Bei einer Nutzung der E-Mopeds ohne zusätzliche Servicefahrzeuge sind 27 g CO_2eq./pkm anzurechnen, wenn das Laden der Fahrzeuge über das Mini-Grid ghanaische Stromnetz erfolgt, bzw. 16 g CO_2eq./pkm, wenn über das solarbetriebene Mini-Grid geladen wird. Diese Szenarien entsprechen einer privaten Nutzung. Es ist jedoch auch möglich in einem kleinen Rahmen eine geteilte Nutzung der E-Mopeds ohne Servicefahrten zu ermöglichen, wenn diese bei leerem Akkustand zum Campus zurückgebracht und dort geladen werden.

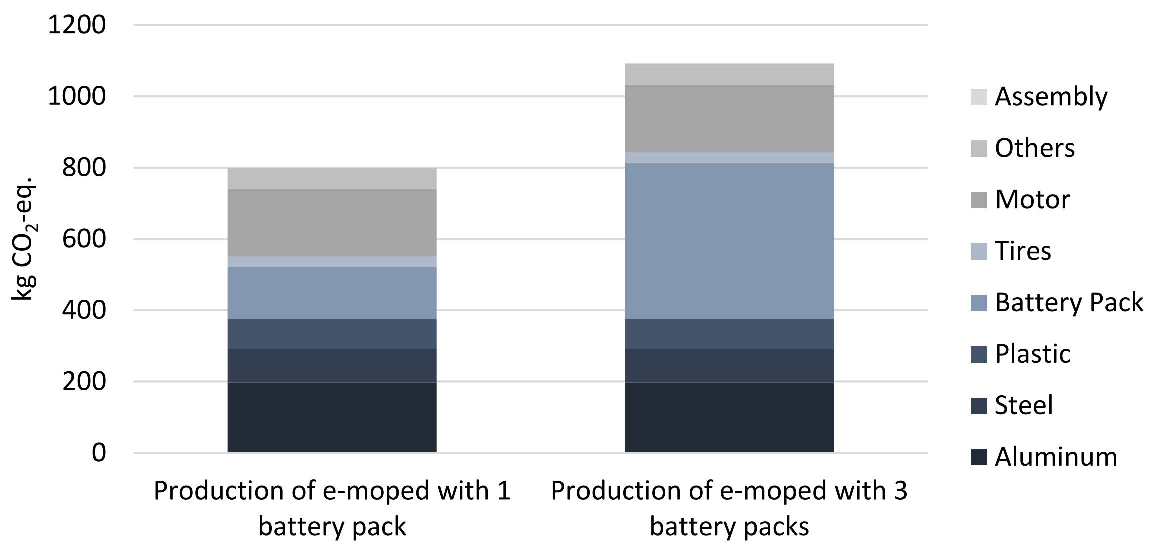

Abbildung 11: Treibhauspotenzial der Produktion eines E-Mopeds mit einem Akkupaket im Vergleich zu drei Akkupaketen.

Abbildung 11 zeigt das GWP der Produktion eines E-Mopeds. Einschließlich der Produktion eines Akkupacks beträgt das GWP 801 kg CO_2eq. Auf die Produktion von Aluminiumkomponenten entfallen 25 %, auf Stahlkomponenten 12 %, auf das Akku-Pack 18 %, auf den Motor 24 %, auf Kunststoffkomponenten 10 % und auf die Montage <1 %. Der Anteil von Aluminium am GWP ist besonders hoch, unter der Berücksichtigung, dass sein Anteil am Gewicht des E-Mopeds nur 11 % beträgt. Die hohen Emissionen der Aluminiumkomponenten sind auf die hohe Energieintensität der Aluminiumproduktion zurückzuführen. Bei der Produktion von drei Akku-Packs - entsprechend einem voll ausgestatteten E-Moped - erhöht sich das GWP um 36 %. Dies deutet darauf hin, dass das Akkupaket über seine volle Kilometerleistung, also über die Lebensdauer des E-Mopeds hinaus, genutzt werden sollte.

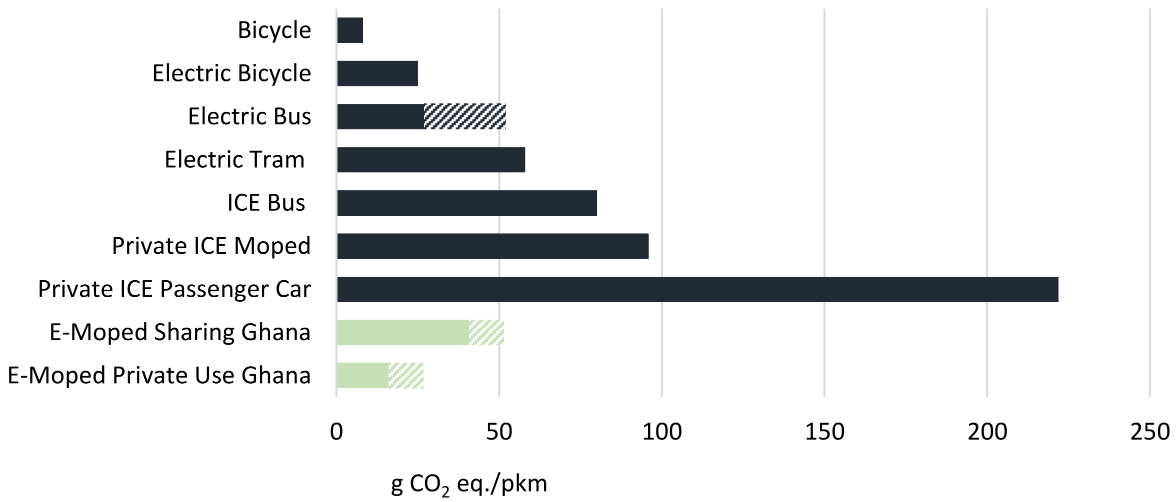

Abbildung 13: Vergleich des Treibhauspotenzials von Elektro-Mopeds in einem Sharing-System mit alternativen Verkehrsträgern auf der Basis von Personenkilometern. Die Daten für private Fahrräder, Elektrofahrräder und Mopeds mit Verbrennungsmotor (ICE) basieren auf (Weiss et al. 2015), Busse (ICE), Straßenbahnen und private PKW (ICE) basieren auf (Umweltbundesamt 2020), Elektrobusse basieren auf (Helmers, Dietz und Weiss 2020), Daten für die gemeinsame Nutzung von Elektro-Mopeds basieren auf (Severengiz et al. 2020)

Für eine umfassende Interpretation der Umweltauswirkungen des E-Mopeds wurden die Ergebnisse mit alternativen Verkehrsmitteln verglichen. Hierzu dienen frühere Studien zum Treibhauspotenzial verschiedener Verkehrsmittel als Vergleichswerte. Wie Abbildung 13 zeigt, hat E-Moped-Sharing ein geringeres Treibhauspotenzial als private ICE[1]-Mopeds (Weiss et al. 2015) sowie als ICE-Pkw und Busse des öffentlichen Nahverkehrs (Umweltbundesamt 2020), selbst im ungünstigsten Fall.
Die Analyse des E-Moped-Sharings zeigt Emissionsergebnisse in einem ähnlichen Bereich pro Personenkilometer (20-58 g CO_2-eq/pkm) wie bei Elektrobussen (27-52 g CO_2-eq/pkm) (Helmers, Dietz und Weiss 2020).
Bei E-Mopeds, für die keine Service-Fahrten anfallen, wie im untersuchten Fall auf dem Don-Bosco Campus in Ghana, fallen die THG-Emissionen noch geringer aus (16-27 g CO_2-eq/pkm) und sind vergleichbar mit privat genutzten E-Fahrrädern. Diese werden hier als Private E-Mopeds dargestellt, da die Nutzungsparameter einer privaten Nutzung entsprechen, auch wenn eine geteilte Nutzung ohne Servicesystem zum Akkutausch möglich ist. Es ist hierbei darauf hinzuweisen, dass das System weniger flexibel genutzt werden kann, als das E-Moped Sharing System, da die Akkus hier nicht von Servicemitarbeitern in der Stadt getauscht werden.

E-Cargobike

Die Auswirkungen von E-Lastenrädern auf die THG-Emissionen des städtischen Güterverkehrs in Ghana über den gesamten Lebenszyklus wurden untersucht. Der Umfang umfasst die Auswirkungen, die durch die Produktion von Primär- und Sekundärmaterialien, Komponenten und Ersatzteilen sowie durch den Transport, den Energieverbrauch während der Nutzung und das End-of-Life verursacht werden. Die funktionale Einheit ist ein Tonnenkilometer (tkm). Dies bedeutet, dass eine Fracht mit dem Gewicht einer Tonne über einen Kilometer transportiert wird.
Bei dem bewerteten E-Lastenrad handelt es sich um ein geländegängiges Modell mit großen Breitreifen und einer Lithium-Ionen-Batterie. Für die Bewertung der Produktion wurde die Stückliste gemeinsam mit dem Hersteller analysiert. Auch andere Annahmen wie Reichweite oder Lebensdauer einzelner Komponenten wurden in Absprache mit dem Hersteller festgelegt.
Abbildung 14 zeigt den Anteil der verschiedenen Lebensphasen und Ersatzteile an den THG-Emissionen des Lastenrads über seinen Lebenszyklus pro Tonnenkilometer in zwei Szenarien. Die Analyse zeigt, dass die Nutzungsphase und damit das Aufladen der Batterien für die THG-Emissionen von großer Bedeutung sind. Das Laden mit PV-Strom aus dem Mini-Grid führt zu Emissionen von etwa 193 g CO_2eq/pkm, während die Nutzung des ghanaischen Strommixes, der hauptsächlich auf Erdgas und Wasserkraft basiert (Internationale Energieagentur 2021), zu Emissionen von über 520 g CO_2eq/pkm führt. In der Veröffentlichung zur LCA auf der LCE-Konferenz wurde ein Szenario mit allgemeinen Daten zum PV-Strom genutzt, anstelle des Mini-Grids, da die LCA des Mini-Grids zu dem Zeitpunkt noch nicht abgeschlossen war, welches in 182 g CO_2eq/pkm resultiert.

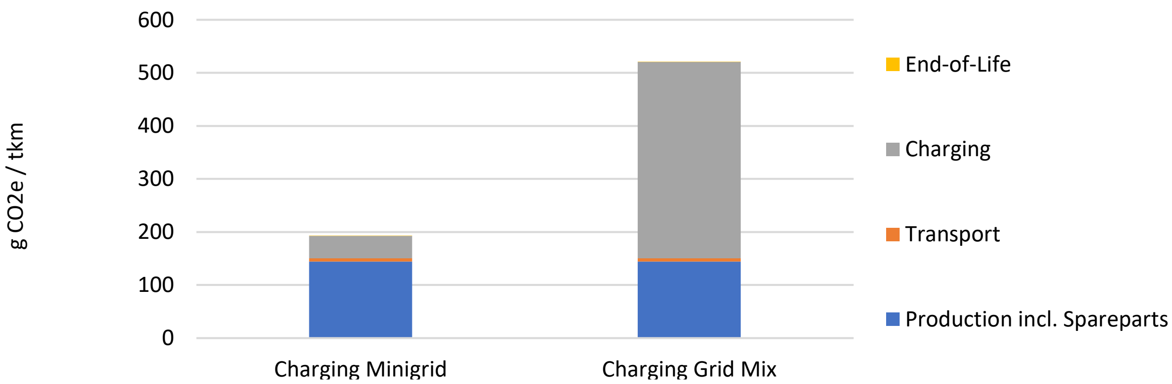

Abbildung 14: Lebenszyklus-THG-Emissionen pro Tonnenkilometer der in Ghana eingesetzten E-Lastenräder für verschiedene Szenarien

[1] ICE: internal Combustion Engiene, dt: Verbrennungsmotor

Abbildung 15 zeigt den Anteil der verschiedenen Komponenten an den THG-Emissionen bei der Herstellung eines E-Lastenrads im Vergleich zu ihrem Gewichtsanteil. Der Stahlrahmen leistet trotz seines beträchtlichen Gewichts keinen nennenswerten Beitrag. Die größten Anteile entfallen auf die Aluminiumteile, die Batterie und den Motor. In diesem Zusammenhang ist es wichtig, den gesamten Lebenszyklus zu betrachten. Die Batterie hat einen Anteil von 18 % an den THG-Emissionen bei der Herstellung eines Fahrzeugs. Dieser Anteil erhöht sich jedoch, wenn der gesamte Lebenszyklus betrachtet wird, da im Laufe des Lebenszyklus des E-Lastenrads vier zusätzliche Batterien benötigt werden. Der Anteil der Batterie an den THG-Emissionen für die Produktion einschließlich der Ersatzteile beträgt somit 40 %. Dieser Anteil könnte sogar noch höher sein, da die klimatischen Bedingungen in Ghana aufgrund der häufigen Hitze für die Batterie schwierig sind und es zu frühen Batterieverlusten kommen kann. Weitere hohe Anteile an den THG-Emissionen entfallen auf die Herstellung des Aluminiums und auf die Reifen, die aufgrund ihrer Geländetauglichkeit besonders groß sind und beim Einsatz auf unbefestigten Straßen in Ghana häufig ersetzt werden müssen. Die Anteile für Transport, Endmontage in Berlin und End-Of-Life sind im Vergleich zu den anderen Lebensphasen gering.

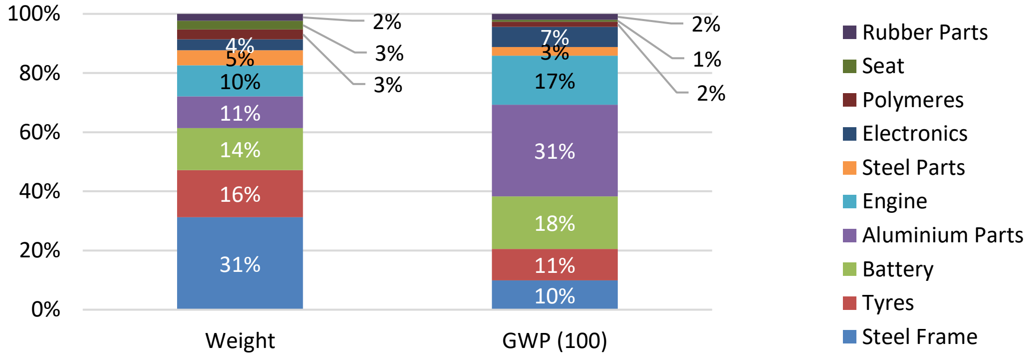

Abbildung 15: Anteil der Treibhausgasemissionen verschiedener Materialien bei der Herstellung eines E-Lastenrads im Vergleich zu ihrem Gewichtsanteil

Abbildung 16 zeigt den Vergleich von elektrischen Lastenrädern mit einem Dieseltransporter (3,5-7 t Nutzlast) in Ghana. Die Ergebnisse zeigen, dass der Betrieb mit Solarstrom über das Mini-Grid im Vergleich zum Dieseltransporter zu erheblichen Emissionseinsparungen führt. Wird das E-Lastenrad jedoch mit dem Strommix des Landes geladen, liegen die THG-Emissionen bezogen auf die transportierte Ladung auf einem ähnlich hohen Niveau wie bei einem Kleintransporter. Der Hauptgrund dafür ist das geringere Transportvolumen des Lastenrads im Vergleich zum Transporter. Das bedeutet, dass mehr Lastenräder benötigt würden, um die gleiche Menge an Gütern zu transportieren. Im Falle des Lastenfahrrads sind die Emissionen aus der Fahrzeugproduktion daher auf eine geringere Anzahl von Tonnenkilometern bezogen.

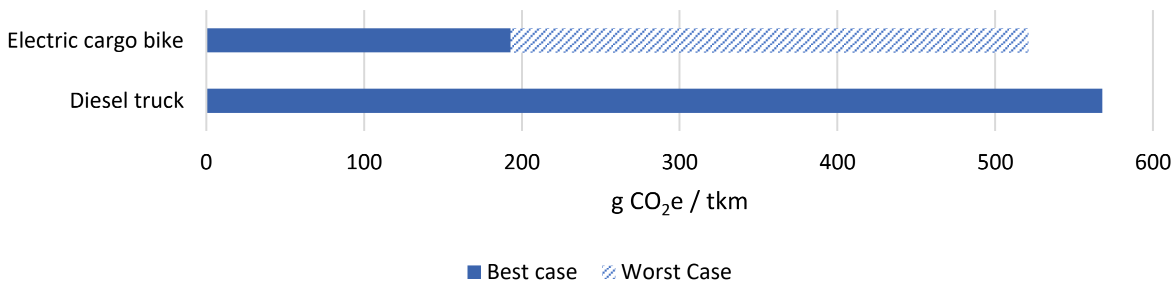

Abbildung 16: Vergleich der Treibhausgasemissionen pro Tonnenkilometer eines Dieseltransporters und eines elektrischen Lastenfahrrads für den Transport in Ghana

Zur Berechnung der Auswirkungen von Lastenrädern auf die Treibhausgasemissionen des städtischen Güterverkehrs wurde der Verkehrsmix der Region Accra als Basis genommen. Der Anteil der verschiedenen Verkehrsträger am Verkehrsmix wurde mit ihren Emissionen pro Tonnenkilometer multipliziert. Dabei wurde der Mix im Status Quo sowie in den entwickelten Szenarien für die Einführung von E-Lastenrädern berücksichtigt.
Abbildung 17 zeigt, dass ein 4 %-iger Anteil von Lastenrädern am Verkehrsmix (Szenario 1) die THG-Emissionen um 4 % von 549 g CO_2eq/pkm auf 528 g CO_2eq/pkm reduzieren kann, während ein Anteil von 8 % (Szenario 2) zu einer Reduktion von 8 % und insgesamt 505 g CO_2eq/pkm führt.

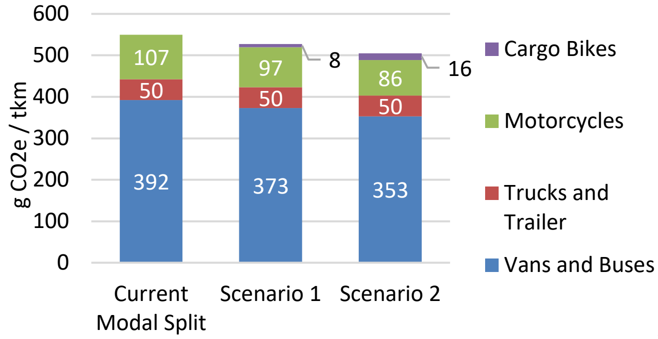

Abbildung 17: Durchschnittliche THG-Emissionen des städtischen Güterverkehrs im Großraum Accra pro Tonnenkilometer für verschiedene Verkehrsmix auf der Grundlage von Emissionsfaktoren für Motorräder, Lkw und Transporter sowie eigenen Berechnungen für die Emissionen von Lastenrädern

4. Reichen Mini-Grids zur ausschließlichen Energieversorgung der E-Fahrzeuge?

Die Energie aus dem installierten Solar-Mini-Netz reicht aus, um die leichten Elektrofahrzeuge auf dem Don Bosco Campus zu betreiben. Zum Laden der auf dem Don Bosco Campus vorhandenen E-Fahrzeuge wird ein automatisches Lastmanagement eingesetzt. Der derzeit verwendete Algorithmus bestimmt anhand des Batteriestatus, des Regensensors und der aktuellen Uhrzeit, ob die Fahrzeuge geladen werden sollen. Da die Einspeisung in das nationale Stromnetz nicht erlaubt ist, erzeugt das Don Bosco Tema Mini-Grid oft überschüssige Energie, die nicht verbraucht wird und aufgrund voller Batterien und geringer Energienachfrage nicht gespeichert werden kann. Es ist wichtig zu betonen, dass dies nicht auf eine falsche Dimensionierung der Mini-Grid-PV-Anlagen zurückzuführen ist, sondern auf die Konstruktion. Für einen vollständigen netzunabhängigen Betrieb müssen die installierten Solargeneratoren groß genug sein, um ihre Batterien in weniger als einem Sonnentag aufzuladen, damit sie auch an Tagen mit einigen Stunden Wolken oder Regen vollständig geladen werden können. An sonnigen Tagen werden die Batterien jedoch sehr früh am Tag vollständig aufgeladen (Abbildung 18), was in Verbindung mit einem geringen Verbrauch an einem solchen Tag zu einer Drosselung der PV-Erzeugung führt.

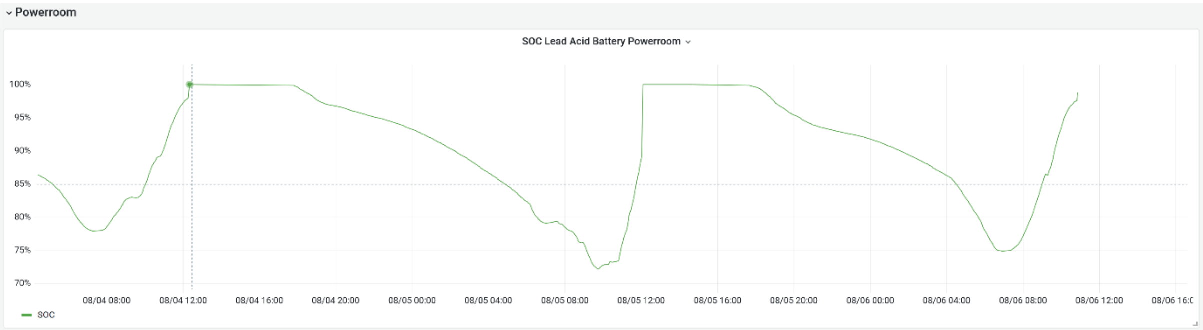

Abbildung 18: Tage mit vorzeitig voll befüllter Hauptbatterie

Die einer Drosselung der PV-Produktion ist in der folgenden Abbildung zu sehen:

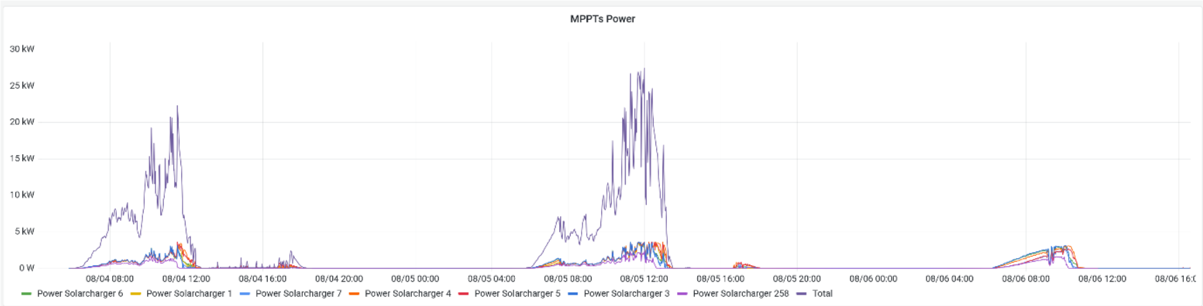

Abbildung 19: Unterbrochene PV-Produktion im Stromsystem im Kraftraum, Don Bosco Mini-Grid

Die uneingeschränkte PV-Produktion sollte an den beiden angezeigten Tagen nach dem Mittag weiterlaufen. Der starke Rückgang der gesamten PV-Erzeugung fällt mit dem Erreichen des 100%igen Ladezustand der Batterie zusammen, wie in der obigen Grafik zu sehen ist.
An solchen Tagen könnte der Strom, der von Mittag bis Sonnenuntergang erzeugt wird, sowohl aus finanzieller als auch aus ökologischer Sicht als "kostenlose Energie" angesehen werden, die in der Produktion nichts kostet und keine wirkliche Alterung der Komponenten verursacht, wenn sie produziert wird. Wird die Energie zum Aufladen von E-Fahrzeugen verwendet, kann die CO2-Belastung durch die geladene Energie als Null angesehen werden, da sie, wenn sie nicht für eine flexible Last wie ein E-Fahrzeug verwendet wird, überhaupt nicht erzeugt würde.
Der Batteriestatus ist nicht der einzige Parameter, anhand dessen bestimmt wird, wann ein E-Fahrzeug geladen werden sollte. In der ersten Testanwendung werden zwei weitere Parameter berücksichtigt: die Information des Regensensors, ob es gerade regnet oder nicht, und die Tageszeit. Ersteres verhindert das Laden bei Regen, unabhängig vom Batteriestatus. Sobald es zu regnen beginnt, muss die Hauptbatterie so gut wie möglich geschützt werden und alle aufschiebbaren Lasten müssen sofort gestoppt werden, um eine möglichst lange Laufzeit der Hauptbatterie zu gewährleisten.
Die Tageszeit unterstützt das allgemeine Ziel, bei Sonnenuntergang volle Batterien zu haben. Das Aufladen der E-Fahrzeuge sollte nicht nach 16 Uhr erfolgen, da ab diesem Zeitpunkt die Sonneneinstrahlung aufgrund des niedrigen Sonnenstandes und der häufigen Nachmittagswolken über dem Horizont, die die Sonneneinstrahlung noch weiter verringern, erheblich abnimmt.

Abbildung 20 und Abbildung 21 zeigen, dass an bestimmten Tagen die Energie, die aus dem Mini-Netz erzeugt werden könnte, mehr als ausreichend ist, um die vorhandenen E-Fahrzeuge vollständig aufzuladen, auch wenn ihre Batterien vollständig entladen sind. An Regentagen ist dies nicht gegeben und auch nicht während längerer Schlechtwetterperioden. Betrachtet man den Spitzenwert der PV-Erzeugung zur Mittagszeit in Abbildung 20, lässt sich abschätzen, dass in der Installation im Kraftraum allein und nur durch die dort installierten DC-Laderegler etwa die Hälfte der möglichen PV-Energieerzeugung tatsächlich nicht erzeugt wird.

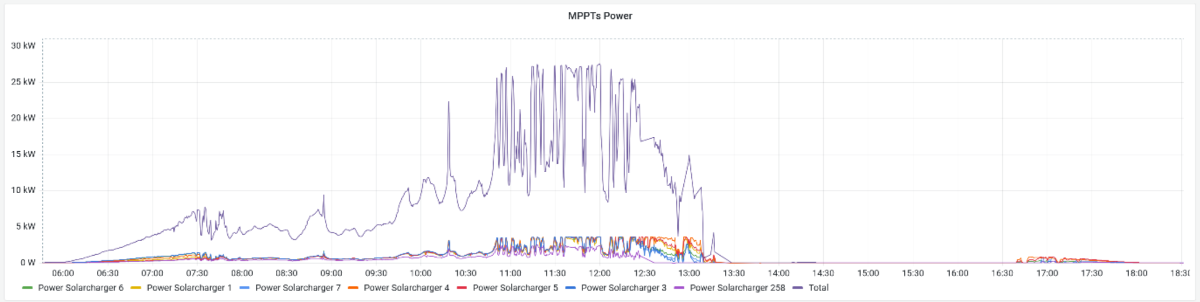

Abbildung 20: Ausgangsleistung der im Kraftraum installierten Laderegler, wobei die Produktion nach dem Mittag fast zum Erliegen kommt

In diesem Zeitraum wird von den Ladereglern, in der obigen Grafik, folgende Energie erzeugt:

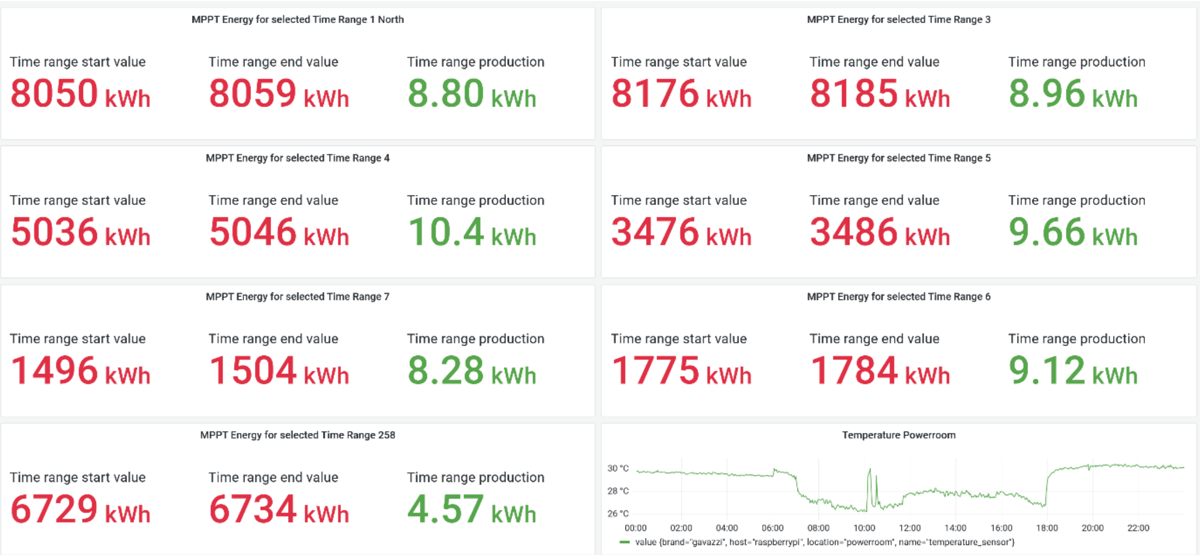

Abbildung 21: Von den im Power Room installierten Ladereglern erzeugte Leistung, am 5. August 2022

Summiert man die gesamte "Zeitspannenproduktion" in der obigen Abbildung, ergibt sich eine Gesamtenergieproduktion von 59,79 kWh. Es kann davon ausgegangen werden, dass bei günstigen Wetterbedingungen am Nachmittag desselben Tages fast die gleiche Energie erzeugt werden könnte. Diese Zahl stellt nur die gekürzte Energie eines Teils der PV-Anlage dar. In den anderen PV-Anlagen des Mini-Netzes wird mehr Energie gekürzt. Diese Zahl allein übersteigt jedoch bei weitem die Kapazitäten aller Batterien aller E-Fahrzeuge auf dem Campus, die im Rahmen des MoNaL-Projekts angeschafft wurden.

5. Welche Ersparnisse von Solar- und Batteriekapazität bietet Stromverteilung im Mini-Grid?

Die Größe des Batteriespeichers auf dem Don Bosco Campus wird durch den Energieaustausch zwischen den installierten Stromsystemen und dem Solar-Mini-Grid reduziert. Der Energieaustausch zwischen den PV-Anlagen im Don Bosco Tema Mini-Grid führt zu einer Verringerung der Größe der einzelnen PV-Anlagen. Während eine absolute Zahl immer von zu vielen Parametern abhängt, um eine konkrete Zahl nennen zu können, lässt sich der Vorteil des Stromhandels am Beispiel der Kapelle darstellen, indem man das Don Bosco Tema Mini-Grid als fiktives Dorf betrachtet, dessen PV-Anlagen über ein privates Mini-Grid verbunden sind.

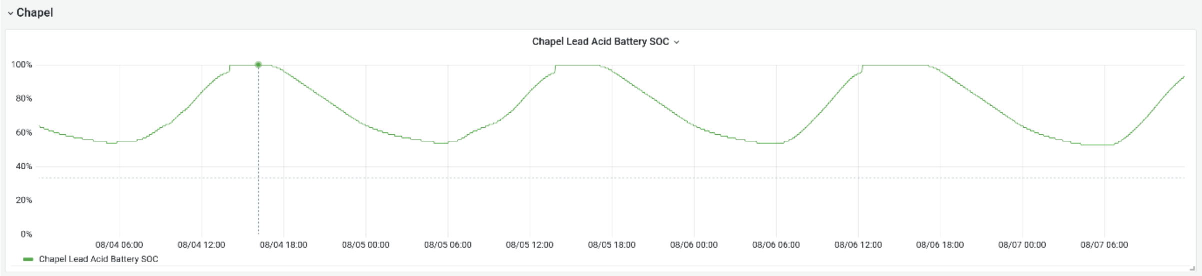

Abbildung 22: Ladezustand (SOC) der Kapellenbatterie in der gewählten Zeitspanne

Da der Verbrauch der Kapelle sehr gering ist und sie gleichzeitig über einen für ihren Bedarf überdimensionierten PV-Generator verfügt, ist die Batterie der Kapelle normalerweise am frühen Nachmittag vollgeladen (Abbildung 22).

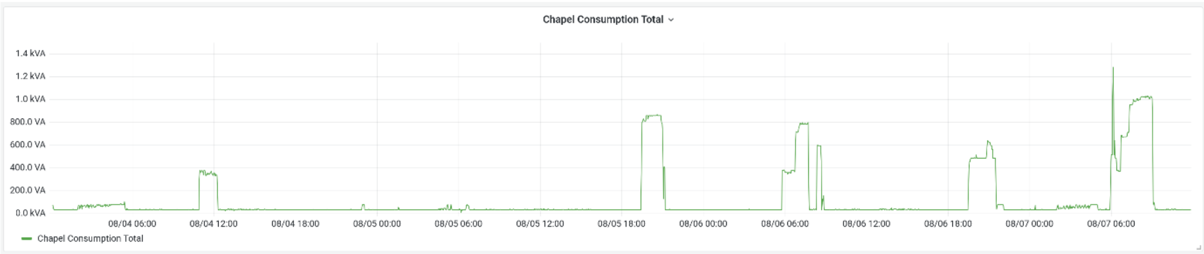

Abbildung 23: Verbrauch der Kapelle im ausgewählten Zeitraum

Nachdem die Batterie vollständig geladen ist, wird die PV-Produktion auf die eingestellte maximale Einspeiseleistung gedrosselt.

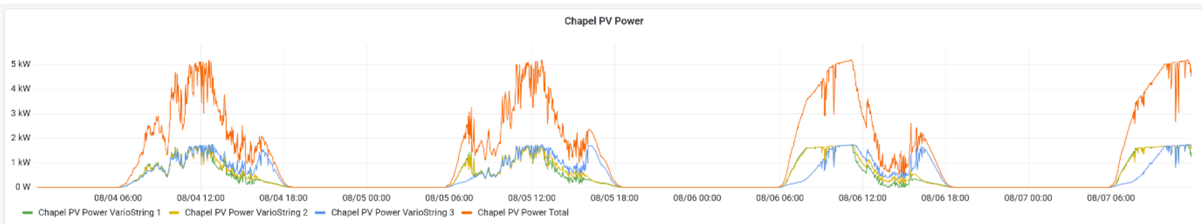

Abbildung 24: PV-Stromerzeugung in der Kapelle im ausgewählten Zeitraum

Die Zahlen in den drei obigen Abbildungen (22-24) lassen den Schluss zu, dass das Stromsystem in der Kapelle für seinen Bedarf stark überdimensioniert ist. Der Energiehandel im Mini-Netz ermöglicht dennoch eine Nutzung der gespeicherten Energie. Die in der Batterie der Kapelle gespeicherte Energie wird ab 18 Uhr in das Mini-Netz eingespeist und konstant gehalten, bis die Batterie am nächsten Morgen, meist zwischen 5 und 6 Uhr, leer ist (Abbildung 25). Diese PV-Anlage kann so zur Energieeinspeisung in den Nachtstunden genutzt werden, wenn die Energie besonders benötigt wird und teuer ist.

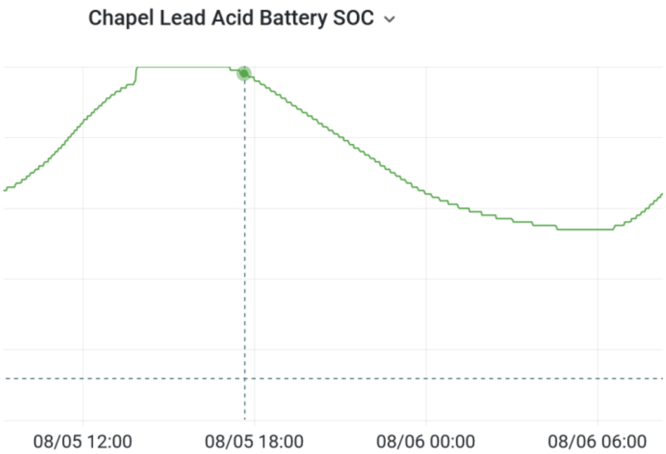

Abbildung 25: PV-Anlage der Kapelle, die nachts in das Mini-Grid einspeist

Die hier gespeicherte und eingespeiste Energie kann in Form von Produktion und Speicherung in anderen netzgekoppelten PV-Anlagen eingespart werden. Dies ist ein extremes Beispiel, welches die Bedeutung und den Flexibilitätsgewinn im Mini-Grid-Design durch den Stromhandel unterstreicht. Andere PV-Anlagen im Don Bosco Tema Mini-Grid verhalten sich ähnlich.

Nachhaltigkeitsbewertung - Kriterienkatalog

Die Gesamtbewertung der Nachhaltigkeit wurde anhand des Rahmens von Goedkoop et al. abgeleitet (Goedkoop, Indrane und de Beer 2020). Um die Nachhaltigkeitsleistung qualitativ und quantitativ zu bewerten, ist eine multikriterielle Bewertung auf der Grundlage einer Auswahl von Kennzahlen und Indikatoren erforderlich. Zu diesem Zweck wurde eine Reihe von Kriterien festgelegt und durch geeignete Kennzahlen und potenzielle Datenquellen vervollständigt. Für die Zwecke dieser Untersuchung wurde eine vereinfachte Referenzskala entwickelt und in eine dreistufige Bewertung umgewandelt, wie in der folgenden Tabelle dargestellt.

Tabelle 4: Punktesystem für den Kriterienkatalog der Nachhaltigkeitsbewertung

Punkte	Beschreibung
+1	Wünschenswerte Situation
0	Akzeptable Situation
-1	Inakzeptable Situation

Zur Bewertung der Nachhaltigkeitsleistung des Systems wird die Gesamtzahl der erreichten Bewertungen gezählt und ein Durchschnitt gebildet. Liegt das Ergebnis über Null, kann das System als insgesamt akzeptabel bewertet werden. Bleibt es unter Null, ist eine weitere Verbesserung erforderlich. Die erforderlichen Daten für die dreistufige Bewertung wurden mit unterschiedlichen Methoden und Datenquellen erhoben, wie z.B. der bereits erwähnten Fokusgruppenbefragung, Interviews oder Herstellerinformationen. Ein Überblick über den Kriterienkatalog wird im folgenden Abschnitt gegeben. Mit Hilfe des erarbeiteten Kriterienkatalogs ist es möglich, die Nachhaltigkeit eines Produktsystems über ökonomische, ökologische und soziale Dimensionen hinweg qualitativ und quantitativ nachzuweisen.

Tabelle 5: Ökologische Indikatoren des Kriterienkatalogs

Dimension	No.	Criteria	Indicator	SDG	Data Source	Results	Score
Ecological indicators	1	**End-of-life responsibility**	EoL management performed in formal and using standardized method	12; 13	Desktop Research/expert interviews	Informal recycling is the norm in Ghana with few formal recycling firms in operation	-1
	2	**Air quality**	NOX, CO, VOC, SO2 transport emissions per passenger km	3; 11; 12	LCA Analysis	No Tank-to-Wheel emissions and thus no additional air pollution in cities	+1
	3	**GHG-Emissions**	Measured in CO_2-eq./pkm (passenger-kilometre) for passenger transport, CO_2-eq./tkm (tonne-kilometre) for freight transport and CO_2-eq./kWh for electricity generation. GHG-emissions mainly include CO_2, CH4 and N2O.	3; 11; 12; 13	LCA Analysis, literature comparison	E-Cargo bikes: 184 g CO_2-eq./tkm (PV-Powered); 520 g CO_2-eq./tkm (powered by Ghanian grid mix) E-Mopeds: 16 g CO_2-eq./pkm (PV-Powered); 27 g CO_2-eq./pkm (powered by Ghanian grid mix), when batteries are swapped at the facilities; 41 g CO_2-eq./pkm (PV-Powered); 51 g CO_2-eq./pkm (powered by Ghanian grid mix), when batteries are swapped by Diesel transporters Mini-Grid: 55 g CO_2-eq./kWh	+1
	4	**Noise pollution**	$\frac{\text{Inhabitants area with noise pollution} > 65\text{ dB in m2}}{\text{total study area in m2}}$	3	objective rating	No noise from E-Vehicles	+1
	5	**Space occupancy**	Defined by space used-up by charging station ad stationary devices compared with vehicles	11	Survey Questionnaire	Space occupied by devices and charging station less than occupied by conventional vehicles	+1
	6	**Use of renewable Energy**	**Literature** review	7; 12	Literature review/pilot site scenario	Currently 100% renewable energy sourced	+1
	7	**Life span of the scooter**	Life span provided in years or km/ tkm/ pkm (for vehicles), differentiation of the lifespan of individual components when components are exchanged over life span of the product	12	LCA Analysis	E-Cargo bikes: 20 years (Batteries 4 years, Tyres: 6 years, electronics 10 years, Frame: 20 years); 6.750 tkm E-mopeds: 65.000 pkm: 50.000 km (Battery: 40.000 km, Vehicle: 50.000 km) Mini-Grid 25 years (PV-modules, cables, construction: 25 years, Batteries: 10 years, Solar Charger, Inverter and electronics: 7 years).	+1

Tabelle 6: Ökonomische Indikatoren des Kriterienkatalogs

Dimension	No.	Criteria	Indicator	SDG	Data Source	Results	Score
Economic indicators	8	**Affordability**	$\frac{\text{Fare per 5km trip within the study}}{\text{average income per month}}$	10	PC-Questionnaire /Profitability-Analysis	Fare: 12 GHC / 1334 GHC = 0,009 comparable with singular taxi transport	0
	9	**Local employment**	$\frac{\text{Number of employees hired}}{\text{total amount of employees}}$	1; 8	--		Not Applicable
	10	**Convenience**	How convenient is it for you? Survey, scale from 1-5.	10	PC-Questionnaire +Group discussion	4/5	+1
	11	**Profitability**	$\text{Break} - \text{even analysis} = \frac{\text{revenue}}{\text{costs}}$	8	Profitability Analysis.	5.9 Years with 40GHS per ride for a distance of 10km	+1
	12	**Policy framework**	The existence of a system in place to ensure that decisions regarding mobility solutions are agreed by city authorities and decisions are in line with city development plans	9; 11	Desktop Research	No Policy/legal framework on e-mobility available in Ghana	-1

Tabelle 7: Soziale Indikatoren des Kriterienkatalogs

Dimension	No.	Criteria	Indicator	SDG	Data Source	Results	Score
Social indicators	13	**Gender and social equality**	The existence of a policy that guarantees equal rights for women	5; 10	PC-group discussion	Female Participants felt safer in using shared vehicles than in public transport	+1
	14	**Accessibility**	Number of charging points/Moped	10	Pilot site inspection	4 vehicles, 1 cp	+1
	15	**Safety**	Number of fatal and non fatal accid	3	PC-Questionnaire	No safety incidents recorded	+1
	16	**Society Health**	CO_2 equiv., SO_2 equiv., PO_4 equiv.per passenger km (GWP, AP, EP) LCA	3	LCA Analysis		
	17	**Effectiveness and Comfort**	Number of Bikes/Mopeds accessible by residents walking 10 min		Site Inspection	Within site, charging stations available within 10minutes of walking	+1
	18	**Usability of the sharing app**	Objective rating		Focus Group discussion	3/5	0

Schlussfolgerung

Die Nutzer bzw. Teilnehmenden der Produktklinik, in der die Geräte unter lokalen Bedingungen getestet wurden, äußerten ihr Interesse, LEVs und Sharing-Systeme entsprechend den ermittelten Bedürfnissen und Anwendungsfällen zu nutzen. Die Bewertung von elektrischen Leichtfahrzeugen unter lokalen Bedingungen war entscheidend für das Verständnis der Probanden für die Leistung dieser Geräte. Zusätzlich zeigte die Analyse nötige Potentiale auf, welche die Leistung und soziale Akzeptanz erhöhen würden. Faktoren wie Kosten, Lärmemissionen, mögliche Reichweite, Gewichtskapazität und Sicherheit stehen bei der Akzeptanz von E-Mopeds an erster Stelle, während die Umweltverträglichkeit auf der Liste der wichtigsten Faktoren nur eine untergeordnete Rolle spielt. In Bezug auf Sharing-Systeme wurden die Lage der Abholstellen, die einfache Nutzung von Software-Anwendungen, die Verfügbarkeit, der Preis und die Vielfalt der Geräte als wichtig für potenzielle Nutzer eingestuft. Die Rentabilitätsanalyse des Produktsystems ergab für ein E-Moped eine Wirtschaftlichkeit nach 6,3 Jahren. Die lange Zeitspanne bis zur Rentabilität könnte durch die Umsetzung nationaler politischer Maßnahmen oder Gesetze verkürzt werden, die die Einfuhrsteuern auf E-Mopeds senken würden. Die Umweltvorteile der Produkte und Produktsysteme wurden im Vergleich zu Mobilitätsangeboten auf fossiler Basis nachgewiesen. Eine Umstellung auf LEVs und Mini-Netze würde sich positiv auf die nationalen Emissionen des Landes auswirken und bei der Erreichung der Emissionsziele helfen. Mit Hilfe des erarbeiteten Kriterienkatalogs ist es möglich, die Nachhaltigkeit eines Produktsystems über ökonomische, ökologische und soziale Dimensionen hinweg qualitativ und quantitativ nachzuweisen. Dies könnte sich beim Zugang zu Finanzmitteln insbesondere von ESG-sensiblen Fonds als nützlich erweisen. Mit diesen Erkenntnissen ist es möglich, Markteintrittsstrategien für leichte Elektrofahrzeuge und deren Sharing-Systeme in Schwellenländern wie Ghana zu entwickeln.

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Sustainable Energy Impact

Task Force: Mobility

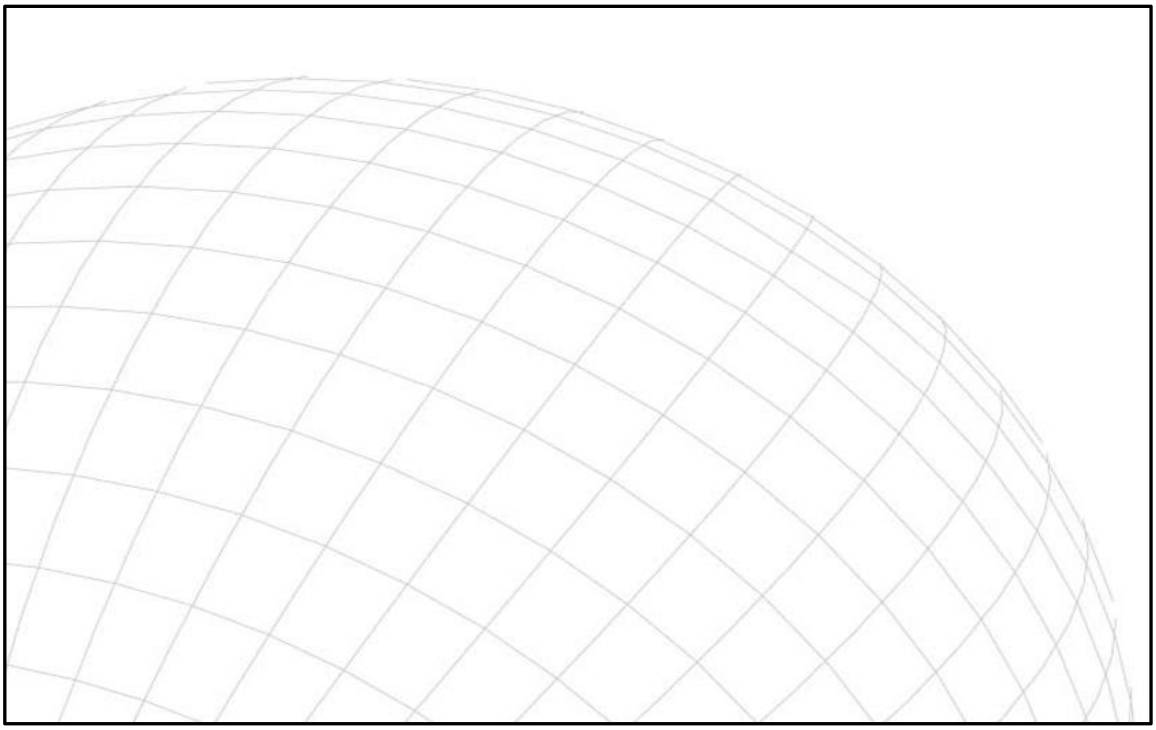
Evaluation Report: Social Acceptance and Sustainability Criteria Catalogue of Light Electric Vehicles in Ghana

Product Clinic & Track Testing

Location: Don Bosco Technical Institute, in Tema, Ghana

Date: 26.09.2022 – 28.09.2022

Authors: Tobias Pflug, Eric Mensah, Fred Adjei



1. Introduction

The demand of reliable transportation solutions is increasing in Ghana because of the urbanization and population growth experienced in the country in recent decades (World Bank 2021) . This increase of demand showed the challenges and problems of the infrastructure conditions in Ghana clearly with an increase in vehicles 6.7million in 1960 to 30.8million in 2022 on non-expanded infrastructure as showed by Ayetor et.al (Ayetor et al. 2022). Unexpanded and improved transport facilities means congestion, road safety challenges and high emissions particularly in urban centres such as the capital city, Accra (Ayetor et al. 2022). The current challenge for mobility presents an opportunity for the introduction of sustainable mobility into the local environment. The MoNaL project seeks to achieve this with a pilot project on the campus of the academic partner Don Bosco Solar and Renewable Energy Centre. Following the deployment of vehicles, a test regime is required to confirm the suitability of devices. Further to that, it is necessary to identity what factors contribute to the social acceptance such light electric vehicles in the local environment. Finally, a catalogue of criteria need to be selected and assessed in the local environment to prove the sustainability of the products introduced. The product clinic held on the Don Bosco campus set out to answer the following research questions:

Figure 1: Geographical map of Ghana

I. What is required to adapt light electric vehicles to different local environments in Ghana?

II. What factors influence the social acceptance of light electric vehicles and their sharing systems in Ghana?

III. How can the sustainable offer of light electric vehicles used in Ghana be assessed?

2. An overview of the Assessment of Light Electric Vehicles on Social Acceptance and Sustainability

Transportation in its current form remains unsustainable. The use of fossil-fueld vehicles to power mobility leads to high GHG emissions. The focus is to leverage on modes such as walking, public transport, or the use of micro-mobility devices such as Light electric vehicles (LEVs). LEVs such as electric mopeds and electric cargo bicycles are gaining prominence and use in most western societies and slowing being incorporated into transitioning economies (Adjei, Cimador, and Severengiz 2022).

Their promise of being able to substitute short trips is crucial to emissions reduction(Ewert et al. 2020). In better context, between 17%-49% of trips made and 6%-30% of distances covered by private trips can be substituted by LEVs (Hilke Fischer and Dave Keating 2021). A sustainable mobility turnaround will only be successful if the focus is also on avoiding car travel and shifting to other modes of transport(Hilke Fischer and Dave Keating 2021).A substantial part of increasing the sustainability reach of LEVs is to deploy them in a sharing system (Kumar, Lahiri, and Bahadir 2017). Sharing systems aid in the decrease in greenhouse gases emissions and decrease in exploitation of natural resources to produce raw materials due to the effect of needing less devices for larger populations and even more so when powered by renewable energy sources (Belk 2014). A study on bike sharing impact and implementation outlined benefits and some importance of bike sharing system such as reduction in travel time, improvement in the health of the population, offering other choices of transport and reduction in cost of transport(Ricci 2015). These benefits are currently primarily targeted at males and the younger generation and those that have more disposable income (Ricci 2015). Most studies on sharing systems have been targeted at developed countries with low focus on developing and transition economies (Cheng 2016). The track test and product clinic in Ghana sets out to fill the gap and provide insight into the feasibility of electromobility usage and its sharing system in Ghana using social acceptance and technology acceptance models as a theoretical framework to find factors that would impact the adoption of such devices in the local environment .

A key part of introducing technology in a sector is to ensure the use of trials and a participatory process for the use and potential adaptation of the technology to the local setting (Mirvis, Sales, and Hackett 1991). Hence it is necessary to test LEVs in Ghana across different terrain to provide data on the performance of devices and as well provide a first look for users. There is no literature known to the authors at this time of tests for LEVs in Sub-Saharan conditions. Whiles track tests tell a part of the story when it comes to assessment in the local environment, a different mode is required to assess the overall product sustainability. Goedkoop et.al provide a basis for the assessment of products on social impact (Goedkoop, Indrane, and de Beer 2020). Further research on the topic of sustainability criteria have been conducted usually with either an ecological focus or economical. For a complete picture, it is necessary to adapt existing literature to evaluate sustainability across the spectra of ecological, social and economic criteria.

3. Methodology

To achieve the objectives of the track testing and product clinic, is a mixed approach which includes focus group discussions and track testing in various terrain are used. A mixed methods approach allows the use of qualitative and quantitative questions and hence is well-suited to the research questions (Wu 2012). Social acceptance being key to the discussions are easily incorporated using such an approach. Using the theoretical framework of Schäfer et.al, the social acceptance of LEVs were assessed as part of the overall sustainability assessment using the criteria catalogue. The phenomenon of acceptance can be seen practically on the basis of three dimensions: Acceptance subject, acceptance object and acceptance context (Schäfer and Keppler 2013). Acceptance therefore infers that someone (acceptance subject) accepts something (object of acceptance) within the respective or initial conditions (context of acceptance) (Schäfer and Keppler 2013).

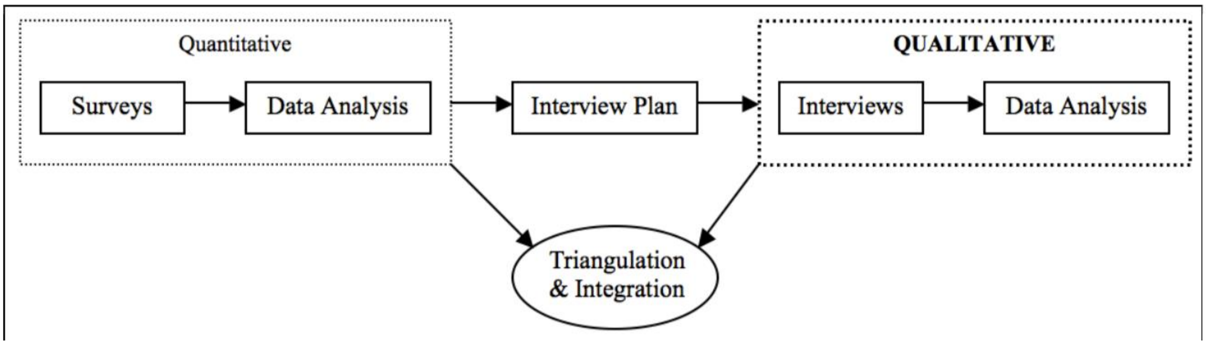


Figure 2: Mixed Method Design ´ Source: P. Fei Wu, 2012

The overall sustainability assessment was derived using the framework of Goedkoop et.al (Goedkoop, Indrane, and de Beer 2020). To evaluate the sustainability performance qualitatively and quantitatively, a multi-criteria evaluation based on a selection of key figures and indicators is required. For this, a set of criteria has been identified and replenished by appropriate metrics and potential data sources. For the purposes of this research a simplified reference scale was developed and converted to a three-stage evaluation as shown in the table below:

Table 1: Scoring system for Sustainability Assessment´s criteria catalogue

Score	Explanation
+1	Beyond generally acceptable situation
0	Generally acceptable situation
-1	Unacceptable situation

This system excludes any past or future improvement efforts, as for this a longer period of time is necessary to observe changes or evaluate past processes. To evaluate the overall sustainability performance of the system, the total number of each achieved evaluation will be counted and an average will be provided by dividing the total score sum by the number of evaluated criteria. If the result exceeds zero, the system can be evaluated as overall acceptable. If it remains below zero, further improvement will be necessary. The required data for the three-stage evaluation were collected using different methods and data sources, such as the aforementioned focus group survey, interviews or manufacturer information. An overview about the criteria catalogue is provided in the section results. An essential part of the product clinic procedure is the focus group survey that includes the questionnaire. The questionnaire is divided into 4 kinds. Social, economic, ecological and cross-cutting questions that are not specified to a specific field but answer to two or more selected criteria. The questionnaire was developed with the survey tool https://www.umfrageonline.com. The questionnaire is contained in the Appendix of this report. The structure of the focus group discussion which comprised groups of 10-25 people over 3 sets of groups is shown below:

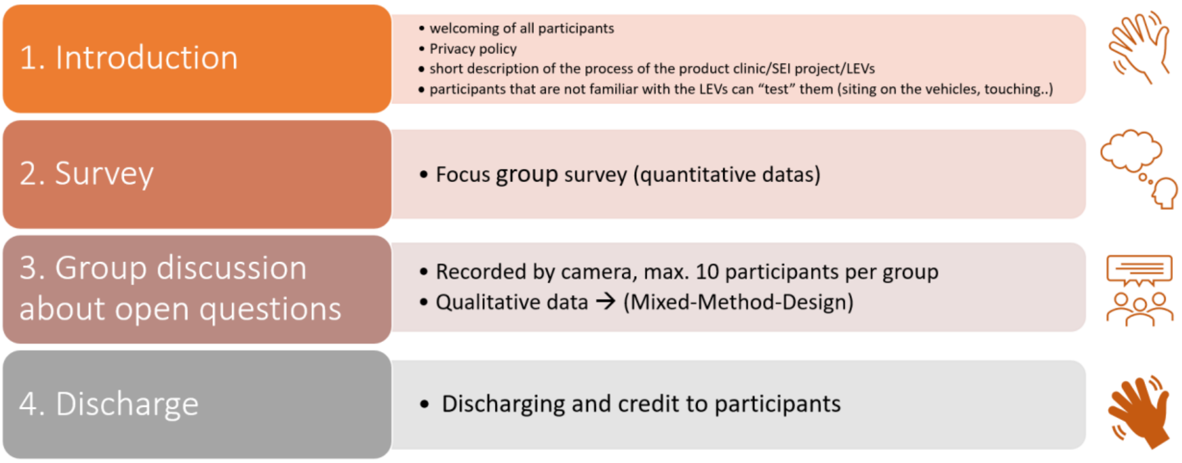


Figure 3: Format of focus group discussions for product clinic in Don Bosco

Light electric vehicles (e-moped, two-wheeler e-cargo bike, and three-wheeler e-cargo bike) installed on the campus of Don Bosco were tested on selected tracks as part of the product clinic (elaborated above). Different standard motorcycle track tests were performed to determine their performance in the local terrain based on the work of Capitani et al. (Capitani et al. 2006). Standard track tests were outlined on sandy/grassy, paved, and graveled roads. Following three continuous revolutions on the test tracks, drivers were asked qualitative questions on maneuverability and handling, stability, steering, and brake traction. A summary of recommendations and comments are presented in the results and discussions. The tests used for the assessment are presented below:

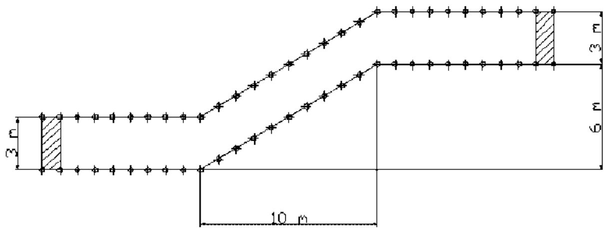


Figure 4: ISO Lane Change

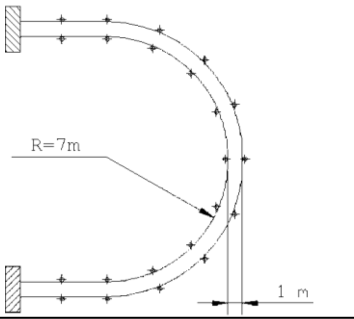


Figure 5: 900 R30 turn track

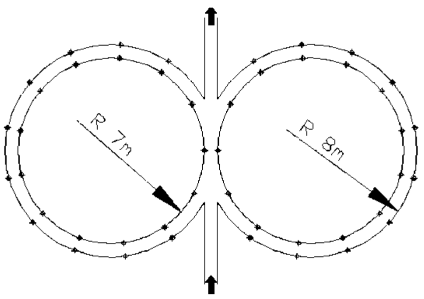


Figure 7: Constant Radius J-turn

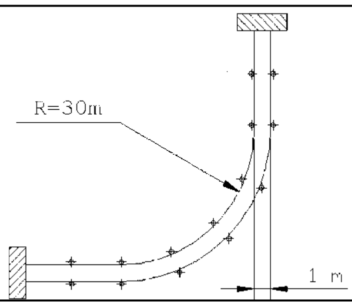


Figure 6: ´Figure-8´track test

4. Results and Discussions

4.1 Track Testing of Light Electric Vehicles

Drivers for the light electric vehicles after the track tests answered qualitative questions on manoeuvrability and handling, stability, steering, and brake traction with the aim of identifying areas of deficiency or parts requiring adaptation to the local environment. A summary of deficiencies and recommendations are elaborated below:

Table 2: Summary from track tests of LEVs on local terrain

Product	Findings/Comments/Recommendations for Improvement to the local environment
E-Moped	• Bigger vehicle tires with additional grooves for better traction. • Vehicle should have higher clearance from the ground would be better for the rough and uneven local terrain. • Vehicle is heavy especially in the back leading to curvature during sharp turns. • Speed is continuous when the throttle is released
Two-Wheeler e-cargo bike	• Difficulty in sharp turns, poor performance on gravel particularly in terms of stability. • Lights should be connected to main batteries instead of the use of replaceable AA batteries. • Placement of electronics and batteries in loading bay inconvenient. • Loading bar should have a cover for security and protection from elements such as rain. • Reflective materials should be placed on various areas of the vehicle to ensure visibility for improved safety.
Three-Wheeler e-cargo bike	• Difficulty in sharp turns, poor performance on gravel particularly in terms of stability. • Lights should be connected to main batteries instead of the use of replaceable AA batteries. • Placement of electronics and batteries in loading bay inconvenient. • Loading bar should have a cover for security and protection from elements such as rain. • Reflective materials should be placed on various areas of the vehicle to ensure visibility for improved safety.

Figure 8: MoNaL and Don Bosco team perform various track test on different terrain

4.2 Factors influencing social acceptance of LEVs

In evaluating factors that influence social acceptance of Light Electric Vehicles (LEVs) in Ghana. Respondents were made to rank factors deemed very important to them when using a sharing system and e-mopeds. Respondents had e-mopeds as well as e-bicycles on site and hence could familiarize themselves with the use of both devices. The factors for influencing the adoption of e-mopeds are therefore similar if not the same for the adoption of e-bicycles. The factors influencing the social acceptance of e-mopeds and sharing systems are elaborated in the tables below.

The Kendall's Coefficient of Concordance was also used in analyzing factors important to the purchase and or use of an e-moped as mentioned above. The Kendall's Coefficient (W) was found to be 0.013 and significant at 1% level. The null hypothesis (i.e., Ho: No agreement among respondents ranking) was rejected in favor of the alternate hypothesis (i.e., Ha: There is agreement among respondents ranking) in the factors considered important when purchasing or using an e-moped. The Kendall's 'W' implies that there was 13% agreement among the respondent rankings. Because of incomplete data, 50 responses were used in this analysis.:

Table 3: Ranking of factors important to respondents in the purchase and use of e-moped

Factors	**Mean Score**	**Rank**
Acquisition Cost	5.31	1st
Low Noise	5.32	2nd
Possible distance	5.34	3rd
Weight Capacity	5.37	4th
Safety	5.38	5th
Repairability	5.46	6th
Power	5.53	7th
Environmental sustainability	5.57	8th
Maintenance Cost	5.77	9th
Design	5.95	10th
Diagnostics		
Number of Observation	50	
Kendall's W	0.013	
Degree of Freedom	9	
Chi-square	5.806	
Asymptotic Significant	0.000	

The ranking of factors for the social acceptance of sharing systems for LEVs as well was done using a Likert scale from 1-5 (1= very important, 2= important, 3= neutral, 4= not important, and 5= not very important). The Kendall's Coefficient of Concordance was used to analyze agreement in the ranking of these factors by respondents. The Kendall's Coefficient (W) was found to be 0.20 and significant at 1% level. The null hypothesis (i.e., Ho: No agreement among respondents ranking) was rejected in favor of the alternate hypothesis (i.e., Ha: There is agreement among respondents ranking) in the factors considered important in using the sharing system. The Kendall's 'W' implies that there was 20% agreement among the respondent rankings. Because of incomplete data, 49 responses were used in this analysis.

Table 4: Ranking of factors important to respondents in using the sharing system

Factors	**Mean Score**	**Rank**
Location	2.89	1st
Easy Usage	2.94	2nd
Availability	2.95	3rd
Price	2.97	4th
Variety	3.26	5th
Diagnostics		
Number of Observation	49	
Kendall's W	0.20	
Degree of Freedom	4	
Chi-square	3.867	
Asymptotic Significant	0.000	

The results elaborated above offer concrete insights into the social acceptance of LEVs and their sharing systems in societies such as Ghana and other transitioning economies. The results confirm or agree with earlier work done by Adjei et. al, where conventional motorbikes were used instead of LEVs due to their unavailability in the country at the time (Adjei, Cimador, and Severengiz 2022). It is clear that environmental sustainability is not the driving factor for a switch to a more sustainable transport mode for the given society. An entry strategy for future suppliers or service providers would need to focus on the core needs or purposes for transport as opposed to an inference to planet protection or climate change. Cost appears to be the main factor and this is reflective of the current economic conditions in the country. Further factors such as distance, weight/load capacity reflect the need of these devices to their specific use cases: short distance travel and the transport of people and materials.

4.3 Sustainability Criteria catalogue of LEVs in Don Bosco Ghana

The results from surveys and interviews were used to populate a criteria catalogue designed in the conceptual planning of the MoNaL project to assess and provide a larger overview of the sustainability of the product system installed on the campus of Don Bosco. The criteria catalogue is provided below:

Table x: Scoring system for Sustainability Assessment´s criteria catalogue

Score	**Explanation**
+1	Beyond generally acceptable situation
0	Generally acceptable situation
-1	Unacceptable situation

Dimension	No.	Criteria	Indicator	SDG	Data Source	Results	Score
Ecological indicators	1	**End-of-life responsibility**	EoL management performed in formal and using standardized method	12; 13	Desktop Research/expert interviews	Informal recycling is the norm in Ghana with few formal recycling firms in operation	-1
	2	**Air quality**	NOX, CO, VOC, SO2 transport emissions per passenger km	3; 11; 12	LCA Analysis	No Tank-to-Wheel emissions and there Thus no additional air pollution in cities	+1
	3	**GHG-Emissions**	Measured in CO_2-eq./pkm (passenger-kilometre) for passenger transport, CO_2-eq./tkm (tonne-kilometre) for freight transport and CO_2-eq./kWh for electricity generation. GHG-emissions mainly include CO_2, CH4 and N2O.	3; 11; 12; 13	LCA Analysis, literature comparison	E-Cargo bikes: 184 g CO_2-eq./tkm (PV-Powered); 520 g CO_2-eq./tkm (powered by Ghanian grid mix) E-Mopeds: 16 g CO_2-eq./pkm (PV-Powered); 27 g CO_2-eq./pkm (powered by Ghanian grid mix), when batteries are swapped at the facilities Mini-Grid: 55 g CO_2-eq./kWh	+1
	4	**Noise pollution**	$\frac{\text{Inhabitants area with noise pollution } > 65 \text{ dB in m2}}{\text{total study area in m2}}$	3	objective rating	No noise from E-Vehicles	+1
	5	**Space occupancy**	Defined by space used-up by charging station ad stationary devices compared with vehicles	11	Survey Questionnaire	Space occupied by devices and charging station less than occupied by conventional vehicles	+1
	6	**Use of renewable Energy**	**Literature** review	7; 12	Literature review/pilot site scenario	Currently 100% renewable energy sourced	+1
	7	**Life span of the scooter**	Life span provided in years or km/ tkm/ pkm (for vehicles), differentiation of the lifespan of individual components when components are exchanged over life span of the product	12	LCA Analysis	E-Cargo bikes: 20 years (Batteries 4 years, Tyres: 6 years, electronics 10 years, Frame: 20 years); 6.750 tkm E-mopeds: 65.000 pkm: 50.000 km (Battery: 40.000 km, Vehicle: 50.000 km) Mini-Grid 25 years (PV-modules, cables, construction: 25 years, Batteries: 10 years, Solar Charger, Inverter and electronics: 7 years).	+1

Dimension	No.	Criteria	Indicator	SDG	Data Source	Results	Score
Economic indicators	8	**Affordability**	Comparison to the price of local alternative means of transportation	10	Uber Technologies Inc. 2022; World Taximeter 2022	GHS 26-47 for a Uber/Taxi per ride for a distance of 10km	0
	9	**Local employment**	$\frac{\text{Number of employees hired}}{\text{total amount of employees}}$	1; 8	--		Not Applicable
	10	**Convenience**	How convenient is it for you? Survey, scale from 1-5.	10	PC-Questionnaire +Group discussion	4/5	+1
	11	**Profitability**	$\text{Break} - \text{even analysis} = \frac{\text{revenue}}{\text{costs}}$	8	Profitability Analysis	5.9 Years with GHS 30 per ride for a distance of 10km	+1
	12	**Policy framework**	The existence of a system in place to ensure that decisions regarding mobility solutions are agreed by city authorities and decisions are in line with city development plans	9; 11	Desktop Research	No Policy/legal framework on e-mobility available in Ghana	-1

Dimension	No.	Criteria	Indicator	SDG	Data Source	Results	Score
Social indicators	13	**Gender and social equality**	The existence of a policy that guarantees equal rights for women	5; 10	PC-group discussion	Female Participants felt safer in using shared vehicles than in public transport	+1
	14	**Accessibility**	Number of charging points/Mopeds /study area	10	Pilot site inspection	4 vehicles, 1 cp	+1
	15	**Safety**	Number of fatal and non fatal accidents/passenger	3	PC-Questionnaire	No safety incidents recorded	+1
	16	**Society Health**	CO_2 equiv., SO_2 equiv., PO_4 equiv.per passenger km (GWP, AP, EP) LCA	3	LCA Analysis		
	17	**Effectiveness and Comfort**	Number of Bikes/Mopeds accessible by residents walking 10 min		Site Inspection	Within site, charging stations available within 10minutes of walking	+1
	18	**Usability of the sharing app**	Objective rating		Focus Group discussion	3/5	0

5. Conclusions

The assessment of light electric vehicles in the local condition was crucial to understanding the performance of these devices and revealed adaptions that would increase performance and adoption. Users and participants in the product clinic expressed willingness to use LEVs and their sharing systems with the needs identified. It is crucial to note the key factors that would enhance the social acceptance of LEVs and their sharing systems. Factors such as costs, low noise, possible distance (range), weight capacity and safety are at the fore front for the acceptance of e-mopeds with environmental sustainability low on the list of ranked factors. With regards to sharing systems, location of pick-up points, easy usage of software applications, availability, price (cost), and variety of devices were ranked as significant to potential users. With the aid of the elaborated criteria catalogue, it is possible to qualitatively and quantitatively prove the sustainability of a product system across economic, ecological and social dimensions. With these insights, it is possible to device entry strategies to transitioning economies such as Ghana for light electric vehicles and their sharing systems.

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Appendix 1: Questionnaire for the product clinic

I.Part - Demographic questions

1.What is your gender?

- a.Male
- b.Female
- c.I don't want to answer

2.What is your age?

- a. 15-25 years
- b. 26-35 years
- c. 36-45 years
- d. 46-55 years
- e. 56-65 years
- f. Older than 65 years

3.What is your occupation?

- a. Teacher
- b. Student
- c. Other

I.Part – Illustration of the current situation

4.Have you used Light Electric Vehicles (LEVs)*1 on or around the Don Bosco campus?

- a. Yes
- b. No

4.2 If yes, how often have you used an e-moped/cargo bike of the sharing system in a day?

- a. 0 times
- b. 1-3 times
- c. 4-5 times
- d. 5-8 times
- e. More than 8 times

4.3 If you answered no to question 4.1, please state why?

5.What problems did you encounter when using the LEVs?

- a. Software application problems
- b. Mechanical problems, please explain what exactly you encountered
- c. Battery problems
- d. Driving problems
- e. Other problems, please explain

6. What problems did you encounter when using the vehicle rental/sharing system?

- ◯ a. Software was too slow
- ◯ b. Problems with the internet connection
- ◯ c. Software could not run on my phone
- ◯ d. Software language was difficult to understand
- ◯ e. Further

7. In your opinion, how suitable are the vehicles for Ghanaian roads?

We will discuss this questions in the 3.part of the product clinic (open discussion), so **you don't need to answer this question here**. If you like to make some notes already, feel free to do so.

8.Did you ever have an accident while using an LEV? (CC quest. no.18/22)

- ◯ a. If yes, what happened? (answer in 8.2)
- ◯ b. No

8.2 Answer, if you have chosen 8.a.

9. On a scale of (1-5) rate how easy is it to use the following in the sharing system.

	1 - not very easy	2 - not easy	3 - neutral	4 - easy	5 - very easy

Unlocking the system	○	○	○	○	○
Using the bikes	○	○	○	○	○
Locking the bikes	○	○	○	○	○
Battery indication	○	○	○	○	○
Handling of the bikes	○	○	○	○	○

10.What are the 4 biggest advantages for you, in case of using the system?

We will discuss this questions in the 3.part of the product clinic (open discussion), so **you don't need to answer this question here**. If you like to make some notes already, feel free to do so.

11.How likely are you to recommend us to a friend or colleague?

- ○ a. Strongly disagree
- ○ b. Disagree
- ○ c. Neither agree or disagree
- ○ d. Agree
- ○ e. Strongly agree

12.To which of these places do you often need transportation?

You can select multiple options.

- ☐ a.Work
- ☐ b.Education

- [ ] c.Shopping
- [ ] d.Travel
- [ ] e.Private appointments
- [ ] f.Other

12.2 How many kilometers do you drive in a month, for going to...?

	0-10km	11-20km	21-40km	41-70km	71-100km	101-150km	151-250km	251-500km	more than 500km
Work	◯	◯	◯	◯	◯	◯	◯	◯	◯
Education	◯	◯	◯	◯	◯	◯	◯	◯	◯
Shopping	◯	◯	◯	◯	◯	◯	◯	◯	◯
Travel	◯	◯	◯	◯	◯	◯	◯	◯	◯
Private appointments	◯	◯	◯	◯	◯	◯	◯	◯	◯

12.3 How comfortable is the transportation to... for you?

	1 - not very comfortable	2 - not comfortable	3 - neutral	4 - comfortable	5 - very comfortable	no answer
Work	◯	◯	◯	◯	◯	◯
Education	◯	◯	◯	◯	◯	◯
Shopping	◯	◯	◯	◯	◯	◯
Travel	◯	◯	◯	◯	◯	◯
Private appointments	◯	◯	◯	◯	◯	◯

13. How much do you pay for transportation in a month?

- a. 0-50 GHC
- b. 51-100GHC
- c. 101-150GHC
- d. 151-200GHC
- e. 201-250GHC
- f. More than 250 GHC

II.Part - Further improvement and development

14.Are you fine with your current transport situation, or would you like to improve your situation with a sharing system?

- a. I am fine
- b. I would like to improve my situation.

14.2 If the answer was b, what do you want it to be changed or improved? (e.g. get faster to your destinations, more comfort, more space in the vehicle ...)

We will discuss this questions in the 3.part of the product clinic (open discussion), so **you don't need to answer this question here**. If you like to make some notes already, feel free to do so.

15. How much do you currently pay to drive 5km within the study area?

- a. 0-12GHC
- b. 13-25GHC
- c. 26-50GHC
- d. 51-75GHC
- e. 76-100GHC
- f. More than 100 GHC

16. Do you think, you can save costs using the sharing system (compared to car, bus, trotro, taxi)?

We will discuss this questions in the 3.part of the product clinic (open discussion), so **you don't need to answer this question here**. If you like to make some notes already, feel free to do so.

16.2 What is your preferred payment method?

- ◯ a. Cash
- ◯ b. Mobile money
- ◯ c. Debit card

17.Do you prefer using the e-moped or the cargo-bike *1?

- ◯ a. E-moped
- ◯ b. Cargo-bike
- ◯ c. No preference
- ◯ Very dissatisfied

17.2 For which transports would you use the cargo-bike?

- ◯ a. Work
- ◯ b. Education
- ◯ c. Shopping
- ◯ d. Travel

- e. Free time
- f. Else

17.3For which transports would you use the e-moped?

- a. Work
- b. Education
- c. Shopping
- d. Travel
- e. Free time
- f. Else

18.Do you think people feel more comfortable because they are using a more ecological mobility solution?

- a. Yes
- b. No
- c. I don't know

19.What do you think of how many people in Accra region would pay (at least a bit) more for this ecological solution?

- a. 0%-20%
- b. 21%-40%
- c. 41%-60%
- d. 61%-80%

e. 81%-100%

20.Which of these factors is important for you in using a sharing system (Rate from 1-5)

(1. not very important 2. not important 3. neutral 4. important 5. very important)

	1	2	3	4	5
a. Easy usage	◯	◯	◯	◯	◯
b. Price	◯	◯	◯	◯	◯
c. Location	◯	◯	◯	◯	◯
d. Variety of bikes	◯	◯	◯	◯	◯
e. Availability	◯	◯	◯	◯	◯
f. Other	◯	◯	◯	◯	◯

21.Which of these factors is important to you, should you want to purchase and use an e-moped? (rate each factor on scale 1-5)

(1. not very important 2. not important 3. neutral 4. important 5. very important)

	1	2	3	4	5
a. Safety	◯	◯	◯	◯	◯
b. Design	◯	◯	◯	◯	◯
c. Power	◯	◯	◯	◯	◯
d. Possible distance	◯	◯	◯	◯	◯
e. Weight capacity (load capacity)	◯	◯	◯	◯	◯
f. Low noise	◯	◯	◯	◯	◯
g. Acquisition costs	◯	◯	◯	◯	◯
h. Maintenance costs	◯	◯	◯	◯	◯
i. Repairability	◯	◯	◯	◯	◯

j. Environmental sustainability	◯	◯	◯	◯	◯
k. Other	◯	◯	◯	◯	◯

25.Do you think the space occupancy for the LEVs (charging points etc.) is managed effectively?

Very ineffective — Very effectively

1	2	3	4	5

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A generic GHG-LCA model of a smart mini grid for decision making using the example of the Don Bosco mini grid in Tema, Ghana

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Abstract

Ghana's population is in a steady growth, which is accompanied by increasing energy demand. At the same time a significant proportion of the population lack access to the electricity grid. Within the framework of the United Nations Sustainable Development Goals (SDGs) access to energy shall be available for everyone (SDG 7). Solar Mini Grids can be used to meet this growing energy demand and give environmentally friendly access to energy in remote regions. Since Solar Mini Grids can be complex systems that require many components such as photovoltaic modules, charge controllers, cables, and battery storage it is crucial to analyze the environmental impacts of these Mini Grids considering the full life cycle. For this purpose, a generic Excel based LCA model has been created to show the optimization potentials of individual system components of Solar Mini Grids and analyze the most environmentally friendly construction. Results for the first case study at the Don Bosco Mini Grid in Tema show that the emissions are highly dependent on the technology and capacity of the energy storage as well as the utilization rate. The utilization rate describes the ratio of the consumed electricity to the produced electricity for cases where a feed in to the national grid is not possible. Therefore, it is important to design the Mini Grid and the energy storage beforehand considering local conditions in a way the environmental impact over the Solar Mini Grid life cycle can be optimized. This can be achieved by using the generic LCA model developed in this paper.

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Keywords: Sub-Saharan Africa; Solar Energy; Mini Grid; Life Cycle Assesment

1. Main text

The Sustainable Development Goals (SDGs) aim to achieve access to affordable and reliable, sustainable energy for all by 2030 [1]. This goal is particularly important for regions like Sub-Saharan Africa where only 82 percent of the population had access to energy in 2018. Rural areas in specific are poorly supplied, with only 67 percent of the population having access to energy at all [2]. Ghana with its growing population is one example of the increasing demand for electricity as economic growth always goes hand in hand with growing requirements e. g. for more electricity. However, the access to electricity does not mean that a constant supply can be guaranteed: Power supply is mostly unstable, inefficient, and often expensive. Moreover, it is based on fossil fuels, such as diesel generators, which are preferred but have a significant environmental impact [3]. As a result, environmentally friendly energy that enables constant supply must be ensured to achieve the SDGs [4].

Environmentally friendly energy supply can be provided through off-grid solutions such as Mini Grids, that are primarily supplied with renewable energy [5, 6]. Mini Grids in general are defined as decentralized energy systems combining different energy and storage technologies for optimizing the output of the individual components [7–10]. Since Mini Grids operate independently, a high efficiency energy storage is needed. Electrochemical storage systems such as batteries play a key role. The performance of these batteries mainly depends

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on their lifetime and energy efficiency [11, 12]. Both lithium-ion and lead-acid batteries can be used for this purpose, whereby lead-acid batteries are the cheapest rechargeable energy storage which are widely used. But if the lead-acid battery is operating close to its low state of charge (SoC) more losses occur and result a shortened lifetime. Lithium-ion batteries are lasting longer and have a higher energy density [13]. Thus, they lead over the entire life cycle of use to more favorable power storage costs despite the higher initial investment [14, 15].

To have a constant supply, Mini Grids in general are optimized for the lowest season where the solar radiation is reduced. Energy storage therefore is needed to ensure that the intermittencies do not interrupt supply [16, 17]. This requires both more PV modules and more storage capacity, so overall an over dimensioned design of the Mini Grid as it is designed for the season with the lowest electricity output leading to an oversupply of energy in summer. The surplus energy can neither be stored nor fed into the grid as grid-feed is expensive in Ghana. Mini Grids therefore are mostly off-grid solutions, even if they could act otherwise [8]. This results in special conditions for those Mini Grids which are optimized for stand-alone functionality under all circumstances. To minimize the environmental impact, it is crucial to assess the impact during the planning process. Currently, most environmental impact assessments are carried out for existing PV systems, buildings, Mini Grids or batteries [18–22]. To make the consideration possible a generic Life Cycle Assessment (LCA) model will be presented in this paper.

2. Materials and Methods

A generic LCA model was generated to design Mini Grids as environmentally friendly as possible in terms of its greenhouse gas (GHG) emissions. LCA is a methodology for quantification of products, processes, or services at all stage of life. The methodology is standardized and described in ISO 14040 and ISO 14044 [23]. LCA is the most suitable tool to get information about environmental performance and improvement of products and components. LCA therefore analyses the different parts of products, processes and services and helps to select relevant indicators of environmental performance, including measurement technique. If the LCA considers all aspects from raw materials acquisition and manufacturing (cradle) to recycling and disposal (grave) it is therefore called “cradle-to-grave”. There are four phases which are processed one after the other: Goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation [23].

Decisions can be made based on the results and products can be marketed as environmentally friendly, e. g. through labeling. Decision processes based on the information can be very comprehensive [23]. Thus, extensive decision-making processes and therefore the optimizing of product design is called Life Cycle Engineering (LCE) [24, 25].

2.1. Goal and Scope of the study

The goal description of a LCA shows the intended application, the reason for the study and the intended audience for the results. System boundaries as well as the assumptions made are defined here. The definition of cut off criteria is important due to the complexity of inputs and outputs [23].

The overall goal of this study was to develop a generic model that enables decision makers to design a Mini Grid as environmentally friendly as possible. The focus is on GHG emissions as these are important to reduce global warming and reach the global goals to be climate neutral until the mid of the century [26]. Moreover, with this focus it is possible to minimize the impact from developing countries which need more time to reduce their emissions and prevent them from making the same mistakes as industrialized countries. To achieve this, the components used in the model should be variably interchangeable. The LCA of the Mini Grid is based on a cradle-to-grave analysis. The functional unit is the consumed kilowatt hour (kWh). The use phase and the associated transport and maintenance measures are not considered as the ecological impact here is adopted as not significant [27, 28] . The general system boundaries are shown in Figure 1.

The LCA process along the system boundaries and the associated structure of the model is explained below.

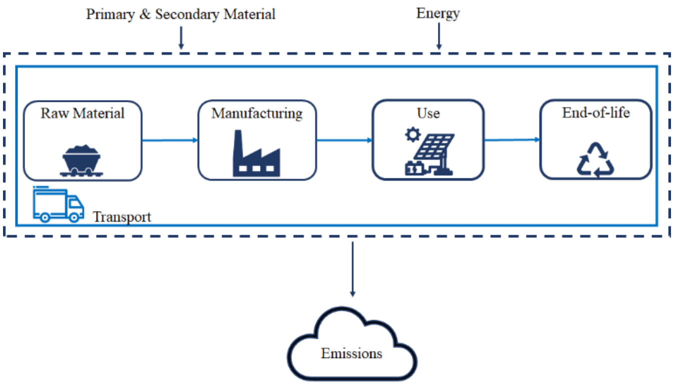


Fig.1. system boundary diagram for the life cycle assessment of the Mini Grid

2.2. Manufacturing

To evaluate the sum of GHG emissions for the Mini Grid a lifetime analysis of the components has been made. The lifetime of the Mini Grid is scaled according to the maximum lifetime L_{pv} of the PV modules which is assumed to be 25 years. The other components were adjusted accordingly to this lifetime. For this purpose, the maximum lifetime

$$L_{pv} = j = 25\ years \tag{1}$$

is used to set the main assumptions of the individual component's lifetime L_x into relation to the maximum L_j as

$$Units\ over\ L_j = \frac{L_j}{L_x} \tag{2}$$

The amounts are free parameters while the units over lifetime are derived from the ratio of the lifetime of individual parameters to the Mini Grid. In combination with the individual data of the actual consumption of x the requirement of materials over the whole lifetime L_{xj} can then be calculated as

$$L_{xj} = x \cdot Units\ over\ L_j \quad (3)$$

These calculations can then be used to generate the GHG emissions for every component x, if the manufacturing GWP from the GaBi database GWP_m is calculated with L_{xj}:

$$GHG_{Manufact} = \sum_{x=1}^{n}(GWPm_x \cdot L_{xj}) \quad (4)$$

2.3. Transportation

It is assumed that the materials are manufactured and brought to the point where they are needed and used. Three options are possible here: The sea route with subsequent transport by truck, the route by truck and the route by plane. The transport after the use phase to the Accra Waste Recycling & Recovery Park is also considered. For the calculation, the transport processes were also modeled in GaBi and the output of the transport processes GWP_t was considered. The GHG emissions for transport in general can be calculated with ton kilometers s traveled:

$$GHG_{Transport} = \sum_{x=1}^{n}(GWP_{t,x} \cdot s) \quad (5)$$

2.4. Use Phase

Although there are no significant emissions in the use phase, it is important to have a look on the difference between the produced and consumed energy. Specific emissions are higher, if produced energy needs to be stored. At the point where the batteries are full, and the surplus energy cannot be consumed, the PV production must be reduced, if a grid feed-in is not available, resulting in a deteriorating environmental impact. This leads to a low utilization rate that describes the ratio of the amount of the energy consumed to the maximum utility. To solve this problem demand-side-management is a viable option [29]. Also, the consideration to expand the Mini Grid with individual components can be done. To find the ideal way at this point, the functional unit contains the consumed kilowatt hour. This means, that every GHG emissions are set in relation to the kilowatt hours consumed.

2.5. End-of-Life

For end-of-life the components are transported to the Accra Waste Recycling & Recovery Park and shredded. No credits are accounted for recycling. The electricity consumption for this is 15 kWh [12] per kg of the components. The total emissions can be calculated with:

$$GHG_{Recycling} = \sum_{x=1}^{n}\left(GWP_{r,x} \cdot L_{xj}\right) \quad (6)$$

To calculate the total GHG emissions GWP_{total} of a planned Mini Grid the individual aspects are added together as

$$GHG_{total} = GHG_{Manfufact} + GHG_{Transport} + GHG_{Recycling} \quad (7)$$

2.6. Inventory Analysis

For modeling purposes, the individual components of the Mini Grid were identified with the GaBi database [30] and literature and added to an Excel file. The Excel file is used to ensure that non-experts can use the generic model in future use cases without knowledge of GaBi. The installed devices were divided into eight categories as shown in Table 1:

Table 1. Bill of components for the Mini Grid

Device	Unit	Source
PV module	[kg] / [kW_p]	[31]
Inverter	[kg]	[30]
Electronic / Controller	[kg]	[30]
PV mounting	[kg]	[30]
Lead Acid battery	[kg] / [kW]	[30]
Lithium-ion battery	[kg]	[30]
Aluminum cable	[kg]	[30]
Copper cable	[kg]	[30]

The inventory modeling was mainly done with the GaBi software of Sphera Solutions Inc [30] with factors from CML – Department of Industrial Ecology (2016) [32].The emissions of the PV modules had to be researched from the literature and the Global Warming Potential (GWP) according to 100 years was added to the model database [32]. As the different batteries, lead acid and lithium-ion, and the cables, copper, and aluminum, have different CO_2eq emissions a subdivision was necessary.

To make the construction and therefore the electricity supply as sustainable as possible, decisions based on a generic Life Cycle Assessment model of a smart Mini Grid can be used to adapt various scenarios of the environmental impact and take regional conditions into account. For example, it can be examined to what extent the purchase of already used batteries in a second life application has an impact on the GHG emissions of the Mini Grid or to what extent the dimensions of individual components, such as adding individual modules, affect the emissions and the standard components of the Mini Grid. The individual parameters can be exchanged variably, and different expansion scenarios can already be considered in the planning phase. This enables decision makers to compare different configurations according to defined target values. Is the Mini Grid for example over dimensioned due to local conditions, the impact of the overall balance can be estimated. This setup additionally allows a real time monitoring of the emissions. Especially the optimizing of the generic model due to specific conditions in case studies is important to use this approach for the most environmentally friendly construction of Mini Grids. This requires a constant evaluation of the model through case studies. In order to demonstrate the model a case study on Don Bosco Technical Institute in Tema, Ghana was conducted to test the potential of the model

3. Case study on Don Bosco Technical Institute in Tema, Ghana

The Don Bosco Mini Grid is a Mini Grid at the campus of the Salesian's of Don Bosco site in Tema, Ghana. An overview of the campus and of the Mini Grid is shown in Figure 2. There are 13 buildings on the site, all connected to the local Mini Grid. The Mini Grid itself consists of four different power systems, connected into a single Mini Grid. The buildings on site can be divided into pure consumers buildings, which only use power from the Mini Grid and prosumers, a combination of consumers and producers, being equipped with photovoltaic power systems which produce energy. With the four power systems, there are four prosumer buildings and nine consumer buildings. The prosumers are: the Provincial House (3), the Solar Training Center with its Power Room (7 and 8), the Hostel (4) and the Container (6). The facility at the Church (1) is not yet operating. Two of the prosumers, the Provincial House (3) and the Power Room (7) are equipped with batteries for power storage. During nighttime, these two prosumers supply power to the whole Mini Grid.

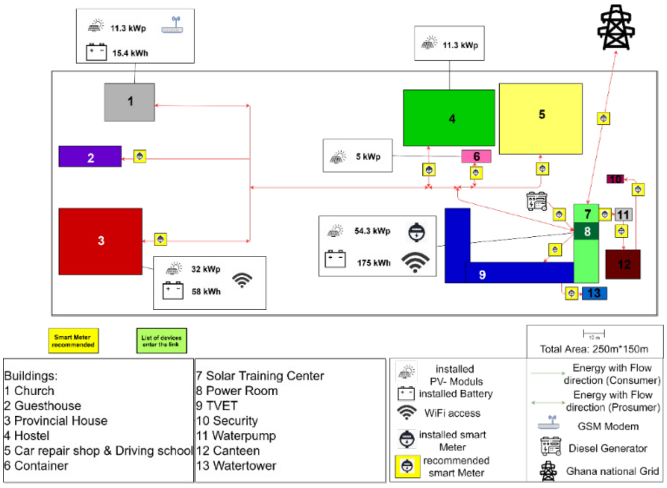


Fig. 2: Sketch of the Don Bosco Mini Grid

The power storage is dimensioned to supply power for one night. Once the batteries have reached a certain depth of discharge, they are charged using grid power. This usually happens at the end of the night or during periods of bad weather, when the sun is not shining in the morning. A diesel generator which was used to provide power during cutouts before the solar systems have been installed is still integrated into the Mini Grid as a safety aspect and is available when batteries are discharged and the grid is down. Currently the solar self-sufficiency of the campus has reached 85%, only 15% of the total power consumed coming from the national grid. The long-term goal is a 100 % self-sufficiency. Reaching total self-sufficiency is however financially very challenging, having to enlarge both production and storage to serve all the loads during worst case weather scenarios. A bill of components for this special Mini Grid is shown in table 2.

Table 2. Bill of components for the Don Bosco Mini Grid

Device	Amount of Devices	Total weight	Weight over Lifetime
PV modules	313 pcs.	5,947 kg	5.947 kg
Inverter	16 pcs.	619 kg	2.211 kg
Electronic/Controller	8 pcs.	36 kg	129 kg
PV mounting	698 pcs.	698 kg	698 kg
Lead Acid battery	72 pcs.	5.863 kg	24.430 kg
Lithium-ion battery	0 pcs.	0 kg	0 kg
Aluminum cable	2,150 m	7 kg	7 kg
Copper cable	25 m	665 kg	665 kg

For the transport it is assumed that the various components are transported from China by ship and subsequently trucked from the port to the Don Bosco Technical Institute in Tema,

Ghana. The lead-acid batteries come from Germany and are transported by ship completed with the 11 km transport by truck to the location. The lithium-ion battery is mentioned in the results event though there is none in the case study, because they might have no relevance for this specific case, but are relevant for future evaluations

4. Results

The results show that the total GWP of the Mini Grid amounts 235,304 kgCO_2eq. Figure 3 shows the share of the life cycle environmental impact for each phase. 86.8 % of the emissions are attributable to the manufacturing, 12.9 % are from transportation and 0.3 % are from recycling. A breakdown of the components in manufacturing shows that the PV modules account for 37.9 % of the emissions and thus the largest share of the total emissions, followed by the inverters with 33.7 %, which is together nearly two thirds of the whole construction. The lead acid batteries follow with 17.1 %. The other components electronics, controller, PV mounting, cables and the lithium-ion battery are combined and form the last 11.3 % of the emissions.

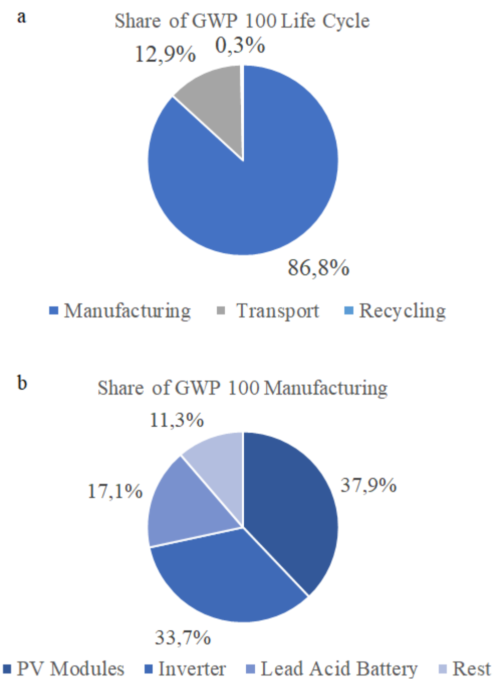
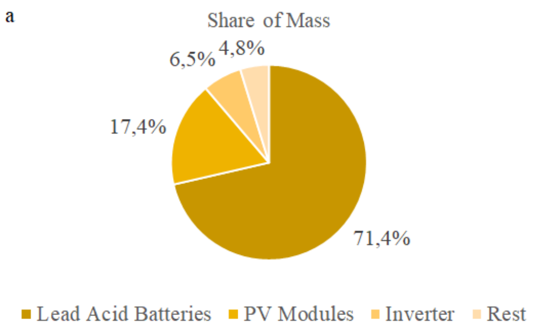


Fig. 3. (a) total amount of GWP emissions; (b) share of GWP for the Don Bosco Mini Grid

Figure 4 shows the share of emissions for the components during transport. These results demonstrate that the distance is not that relevant, but the weight and the number of the components which are used in the Mini Grid. Due to the high weight of the lead acid batteries which are 71.4 % of the total mass, they have the highest impact with 15,364.7 kgCO_2eq. This is 50.8 % percent of the whole transport, followed by the PV modules with 29.9 %. 11.5 % of the emissions during transport are from the inverter, and the electronics, controller, PV mounting and the cables together account for the rest of 8.2 %.

To evaluate the environmental impact of the Mini Grid, it is compared with the utility grid in Ghana and a diesel generator. The production for the Mini Grid is calculated with the theoretical production of 4.5 full hours per day which results in 1,643 full load hours per year. Multiplied by the available capacity of 103 kW the electricity production for the entire life cycle is 4,241 MWh. Derived from the total GWP the Mini Grid has relative emissions of 0.055 kgCO_2eq / kWh consumed. According to the Ghana Energy Commission the emission factor for the grid energy is 0.460 kgCO_2eq / kWh [31] and [32]. For the diesel generator the emission factor is 1.65 kg kgCO_2eq / kWh [33].

The savings over 25 years amount 1,713 tCO_2eq compared to the utility grid and 6,769 tCO_2eq compared to the diesel generator when accounting for the full 25-year life cycle of the Mini Grid.



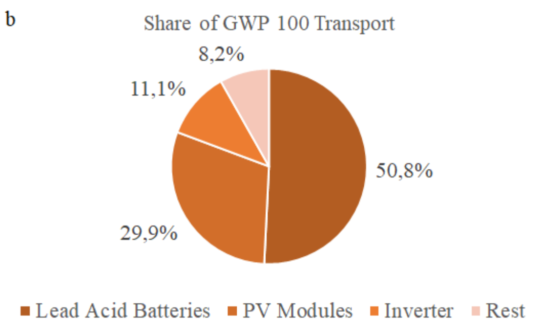


Fig. 4. (a) total share of the GWP for associated mass; (b) total share of transport

5. Discussion

The example of the Don Bosco Campus shows that the Mini Grid can only save emissions if the energy produced is used to a large extent. Therefore, it is important to compare the results with the actual consumption, because of the discrepancy between production and consumption which will probably raise the kgCO_2eq emissions because not all the energy produced can be used as grid feed-in is not available. In order to keep the environmental impact as low as possible it makes sense to fully utilize the installed capacity, i.e., to consume all the electricity produced and increase the utilization rate. Ideally this would happen without external influences and further control mechanisms in which electricity is always consumed as soon as it is available. The batteries would be charged only for the night in their optimal SoC, extending their lifetime and minimizing the environmental impact. Through smart control, i.e., through demand-side-management, consumption can be adapted to electricity production and thus ensure that a hundred percent purchase of the electricity produced and a targeted storage in the batteries can be made possible. In this way, resources can be conserved, and power purchase can also be guaranteed.

If individual elements need to be replaced during the Mini Grids lifetime the decision can be made based on LCA values. Energy storage can be targeted by using this model to scale the Mini Grid according to the local conditions and the optimal SoC of the batteries. For example, it is possible to consider whether replacing the lead acid batteries after their life cycle with lithium-ion batteries would make sense or not. This is important due to the fact, that the lead-acid batteries in this case have the highest environmental impact of all components in the transport phase even though they have the shortest transport distance which is over 10,000 km less than those of the other components. However, no consideration is given to whether this implementation would be possible. As mentioned before, lithium-ion energy storage is not used because of the associated high costs. A consideration of the costs therefore can be useful in comparison to find the right way for the rural areas and find the cheapest and most environmentally friendly alternative for people living in these areas and enable a long-term change. Therefore in a next step the exact production and consumption data for the Don Bosco Mini Grid should be collected over a year and modelled with HOMER [34] to calculate the associated emissions and relate them with the associated costs.

The model would be helpful if it is used to influence political decisions supporting the stabilization of production and consumption e.g. through expansion of the electrification network, expansion of demand-side-management or efficient and inexpensive grid feed-in. Smart networking of such systems would be also possible to ensure that every kilowatt-hour produced could also be consumed and thus keep the environmental impact as low as possible. However, this will require more far-reaching influence and political decisions that make the models solutions truly effective. Further solutions, such as electromobility devices in sharing systems, for the synchronization of produced and consumed energy can also be evaluated in terms of their environmental impacts. Over dimensioned scaling of Mini Grids could be used sensibly and emergency suppliers as diesel generators only retain for critical infrastructure such as hospitals, so that the overall environmental impact in rural areas could be downsized.

6. Conclusions

The results of the case study demonstrate the applicability of the generic model which was created to analyze the most environmentally friendly Mini Grid related to the consumed kilowatt hours. The life cycle inventory is divided into the sections of manufacturing, transport, use phase and end-of-life. The case study for the Don Bosco Mini Grid results in a total GWP of 235,304 $kgCO_2eq$ which is mostly from the manufacturing. Over two thirds from these emissions are from the PV modules and the inverters which are better not increased due to the high impact. During the transport lead-acid batteries have the highest amount even if they have the shortest transport route. Reducing the number of lead-acid batteries is an effective way to minimize emissions here, especially because of the high impact of the PV modules which are necessary because they cannot be used fully during Harmattan season. However, a financial feasibility depends on local conditions and still needs to be considered. It is crucial that emissions are highly dependent on the individual components which can be variably adjusted in this model.

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Life Cycle Assessment on Electric Cargo Bikes for the Use-Case of Urban Freight Transportation in Ghana

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Abstract

The population and economic growth in African countries such as Ghana and the resulting increase in the need for mobility are raising unsolved challenges. An increasing number of people and goods have to be transported within an inadequate energy supply and transport infrastructure. However, the increasing number of vehicles also cause challenges such as air pollution or traffic congestion. Electrified cargo bikes are considered a space-efficient and eco-friendly alternative for freight transportation in cities. Due to their low energy demand and battery capacities, they also offer the potential to be supplied with electricity via the mini-grids commonly used in African countries, as a full-coverage electricity supply is not yet available everywhere. The growth of electric cargo bikes for the delivery of parcels, groceries and other goods in urban regions raises the question of how environmentally friendly they are compared to other urban transport modes, considering the whole life cycle, and which modal share is required to have a significant impact on the overall transport system. This paper aims to answer this question by conducting a Life Cycle Assessment on the use case of an electric cargo bike used in Ghana based on different operating and dissemination scenarios. The design of the analyzed cargo bike is adapted, e.g. in terms of the used suspensions and tires, for a usage on Ghanaian roads and climatic conditions.
The results show that cargo bikes have a smaller environmental impact on global warming potential in terms of ton-kilometers as diesel vans, especially if long product lifetimes are realized. The most important parameters for the reduction of greenhouse gas emissions are the use of renewable energies for the charging of the batteries, the utilization of the payload capacity and the production of the battery. It could be shown that the GHG emissions over the life cycle are significantly lower when the batteries are powered by solar energy. Including solar powered e-cargo bikes in the modal split for freight transport in the accra region would result in greenhouse gas emission savings of 4-8%.

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Keywords: Electric Mobility; Life Cycle Assessment; Electric Cargo Bikes; Freight Transport; Sustainable Development; Micromobility

1. Introduction

Freight transportation is increasing in urban areas due to “urbanization, population growth, and changes in goods’ demand patterns” [1]. Due the common use of fossil fuels in transport this increase is connected to emissions of greenhouse gases (GHG) such as CO_2 along with other air pollutants as particulate matter and NO_x. In fact, the global transport sector accounts for a quarter of the global GHG emissions [2].

These emissions lead to several challenges. GHG emissions contribute to global warming while other air pollutants cause the prevalence of respiratory illnesses [3]. Moreover, large diesel vans, which carry out freight transport in most cities, do frequent stops contributing to congestion [1] and using a rather scarce resource in crowded cities – space [4].

The future economic development and population growth is expected to amplify the aforementioned challenges. The United Nations forecast that the world population will increase to 9.2 billion by 2050 with an increasing share of the population living in cities. Many of so-called megacities, emerging mainly in Asia, Africa, and Latin America, will face high levels of traffic congestion, pollution, and noise. [5]

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Due to the challenges described above, it is particularly important to develop and analyze possible solutions for the transport of goods in the cities of developing countries. Light electric vehicles (LEVs) and in particular electrified cargo bicycles (e-cargo bikes) are emerging as a popular solution.

LEVs are low-speed, small, lightweight vehicles with a mass of less than 350 kg, a design speed up to 45 km/h and are powered by batteries, fuel cells, or a hybrid system [6]. The term LEV covers different vehicle types like e-cargo bikes, e-mopeds and small electric cars [7]. Cargo bikes are defined as single or multi-track transport bicycles with a maximum width of 1 m and a permissible total weight of up to 250 kg, also with electric motor assistance or as a serial hybrid (up to a speed of 25 km/h) for transporting goods and people, according to the German Road Traffic Licensing Regulation [8].

Previous studies have already well explored the potential of LEVs. For example, studies exist on the life cycle environmental impact of electrified mopeds [9,10] or stand-up scooters [11,12]. Existing studies on e-cargo bikes focus on the emission reduction potential of substituting conventional delivery vans with e-cargo bikes in urban areas for case studies in Europe [1,13–16], the United States [17–20] and Singapore [21]. However, those studies only consider well-to-wheel-emissions. Currently, there are no acclaimed studies that assess the environmental impact of e-cargo bikes considering their whole life cycle. Furthermore, no study has yet addressed the potential of cargo bikes for developing countries.

Therefore, his paper aims to answer the question of how environmentally friendly e-cargo bikes are compared to other urban transport modes and which modal share is required to have a significant impact on the overall emissions of the freight transport system in Ghana considering the whole life cycle. We conduct a Life Cycle Assessment (LCA) on the use case of an e-cargo bike in Ghana based on different operating and dissemination scenarios. This study is part of a research project which aims to evaluate the potential of LEV based on a pilot project in the Greater Accra region. Therefore, we base our assumptions on the situation in this region.

We first present the current state of research on the potential environmental impact of e-cargo bikes and the situation of the mobility sector in Ghana to derive a possible effect of e-cargo bikes on a modal shift. Subsequently, we describe the methodology, assumptions, and results of the conducted LCA for e-cargo bikes. We discuss the results in comparison with alternative transport modes and in relation to the potential impact on modal shift before drawing a conclusion.

1.1. Freight Transport with e-cargo bikes

Potential benefits of LEVs and cargo bikes are their lower energy demand for production and operation compared to vehicles with internal combustion engines resulting in lower GHG emissions [7]. Furthermore, cargo bikes require less traffic space compared to conventional trucks and vans and can use designated bike paths if available [1]. These benefits are widely recognized and evaluated in different studies summarized in table 1.

A study of Melo & Baptista simulated the impact of replacing delivery vans with e-cargo bikes in different traffic scenarios in Porto, Portugal. The results suggest that substituting diesel delivery vans for e-cargo bikes reduces CO_2 emissions by up to 73%. It also emphasizes that only 10% of delivery vans can be replaced with e-cargo bikes. [1]

Some simulations consider the impact of implementing e-cargo bikes in transshipment facilities in German urban areas in a hybrid model with vans [13,14]. Both studies conclude that the implementation of e-cargo bikes will reduce GHG emissions. Another simulation evaluates the integration of e-cargo bikes in Frankfurt, Germany. According to the study's results, the adoption of e-cargo bikes is both environmentally and financially beneficial. [15]

Table 1. Summary of studies on implementation of e-cargo bikes in urban areas. Own illustration based loosely on Elbert & Friedrich (2020). Green marks indicate the presence of, while red marks indicate the absence of, the designated argument or method.

Authors	Location	Type	Incl. LEV impact on emissions	Methods incl. cradle-to-grave LCA	Notes
Melo & Baptista (2017) [1]	Porto, Portugal	Urban	● (green)	● (red)	Substituting diesel delivery vans for e-cargo bikes reduces CO_2 emissions by up to 73% (746 kg CO_2 emissions avoided)
Assmann, Lang, & Müller (2020) [13]	Germany	Urban	● (green)	● (red)	CO_2 emissions reduced by 50% when e-cargo bikes are used in conjunction with diesel vans
Llorca & Moeckel (2020) [14]	Munich, Germany	Urban	● (green)	● (red)	NO_2 emissions decrease as substitution of vans with e-cargo bikes increases
Elbert & Friedrich (2020) [15]	Frankfurt, Germany	Urban	● (green)	● (red)	Discusses integrating e-cargo bikes into urban consolidation concepts with a simulation-based study
Arnold, et al. (2018) [16]	Antwerp, Belgium	Urban	● (green)	● (red)	Compares efficiencies of conventional delivery vans and e-cargo bikes through a simulation; cargo bikes may be more efficient in highly congested areas
Boston Transportation Department (2021) [17]	Boston, Massachusetts	Urban	● (green)	● (red)	Considers e-cargo bikes as a solution to transportation challenges the city of Boston faces, including emissions
Sheth, et al. (2019) [18]	Seattle, Washington	Urban	● (green)	● (red)	Concludes that e-cargo bikes are most cost-effective for short-range deliveries
Urban Freight Lab (2020) [19]	Seattle, Washington	Urban	● (red)	● (red)	Compares traditional truck deliveries with e-cargo bike deliveries; cargo bike efficiency rate improved over time
Choubassi et al. (2016) [20]	Austin, Texas	Urban	● (green)	● (red)	Compares different e-bicycles based on assessment factors, (life span, payload, etc.) via a case study
Chiara et al. (2020) [21]	Singapore	Urban	● (green)	● (red)	Concludes that cargo cycles can reduce travel time and distance travelled

Similar case studies have been conducted for urban delivery systems in other European cities, such as Antwerp [16], and outside of Europe – namely in Boston, Massachusetts [17], Seattle, Washington [18,19], Austin, Texas [20], and Singapore [21]. These studies find that the implementation of e-cargo bikes decreases GHG emissions. Most studies recommend using e-cargo bikes in conjunction with conventional vehicles. By implementing hybrid solutions GHG emissions will still be decreased, but feasibility, efficiency, and overall cost will not be negatively affected.

Another commonly researched topic is the effect of cargo bikes on user travel behavior. Studies of Thomas [22] and Riggs [23] emphasize the need for proper infrastructure and terrain. This indicates why most studies focus on well-developed areas with urban delivery centers, paved roads, and designated bike paths. There are no acclaimed studies on e-cargo bike implementation in rural or less developed areas.

1.2. Mobility situation in Ghana

Ghana is a developing country in western Africa, located off the coast of the Gulf of Guinea at the Atlantic Ocean. The country consists of urban areas, such as its capital city, Accra, and rural areas. With a share of 95% road transport is the primary form of transportation in Ghana, according to the Ministry of Transport. Most communities, including rural towns and villages, can access this form of transportation. [24]

In 2015, 6,819 Mt CO_2 were emitted by the transportation sector in Ghana, accounting for 25% of all CO_2 emissions. The growth in transportation emissions is averaging 11.1% per year. According to a case study conducted in Ghana, "poor fuel quality, aging vehicle fleet, and lack of mandatory roadworthy emission tests" resulted in this increase in emissions. [25] Therefore Ghana may especially benefit from replacing environmentally unfriendly petrol and diesel-fueled vehicles with sustainable vehicles like e-cargo bikes.

Only few data is available on the modal split of freight transport in cities in Ghana. One case study analyzed the Greater Accra region based on interview guides, personal observations and questionnaires [26]. It shows 69% of vehicles used for freight transport in the city are vans and buses, 21% trailers and trucks and 2% motorcycles as depicted in figure 1.

1.3. Potential effect of e-cargo bikes on a modal shift.

We decided to use the modal split recorded by Srabah et al. [26] as a reference value to calculate the modal shift and emission reduction potential of e-cargo bikes in the Greater Accra region in Ghana. According to previous studies for the use case in Europe, cargo bikes can replace up to 10% of vans [1]. As the substitution potential of cargo bikes strongly depends on the quality of the bicycle infrastructure [4], we assume that the value in Ghana is probably lower (5%) in our scenario 1 as shown in figure 1. However, we see potential for cargo bikes to additionally substitute 10% of the freight transport of motorcycles as they have a similar transport volume. In scenario 2 we assume a substitution potential of 10% and 20% respectively for both transport modes.

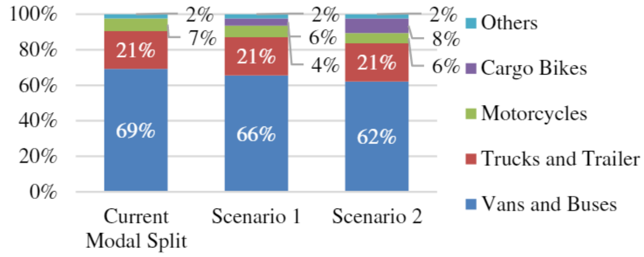

Figure 1: Modal split of freight transport in the Greater Accra region according to [28] and different scenarios for a modal shift after the implementation of e-cargo bikes. Own illustration.

2. Methodology

Life Cycle Assessment is a method for quantifying the environmental impact of products or services throughout their life cycle. Therefore, it considers all life phases, from raw material extraction, production, transport, and use to end-of-life. According to the ISO standards 14040/44, LCA consists of four phases: Goal and Scope Definition, Life Cycle Inventory, Impact Assessment and Interpretation [27,28].

The goal of this study is to examine the lifecycle impact of e-cargo bikes on the GHG emissions of urban freight transport in Ghana. Therefore, the impact category global warming potential (GWP 100) developed by the IPCC was chosen [29]. Although other environmental impact categories such as particulate matter pollution are relevant in transport as well, the focus of this study is to present the potential impact of e-cargo bikes on the GHG emissions of urban freight transport. The scope includes impacts caused by the production of primary and secondary materials, components and spare parts as well as transport, energy consumption in use, and end-of-life. An evaluation of local pollutant emissions and costs of cargo bikes is out of the scope of this study. The functional unit is one ton-kilometer (tkm). This indicates that cargo with the weight of a metric ton is transported over one kilometer.

The assessed e-cargo bike is an off-road capable model with large wide tires and a lithium-ion battery. For the assessment of production, the bill of materials was analyzed jointly with the manufacturer. Other assumptions such as range or lifetime of individual components were also determined in consultation with the manufacturer unless otherwise stated.

2.1. Production phase

The manufacturing processes of the individual components were first modeled in the software GaBi [30], considering the manufacturing location and the associated transport routes. This is followed by the final assembly in Germany. The overall weight of the bike is 60 kg. The major components are the steel frame (18.8 kg), the tires (9.5 kg) and the battery (8.5 kg). Most components come from China including the battery, all electronics, the rubber parts and most steel-, plastic- and aluminum parts, excluding the steel frame. The steel frame is a mixture of Finish and German pipes with Finish pipes making up 54% and German pipes 46%. The tires are from Japan and the remaining parts are from Germany including some steel-, plastic- and aluminum parts as well as the seat and the 3D printed parts. The weight shares can be found in detail in Table 2 where they are compared with the respective GHG emissions.

Table 2: Material composition and GHG Emissions for materials and parts of one e-cargo bike.

	Weight in kg	GWP in kg CO_2e
Steel Frame	18.8	44
Tires	9.5	47
Battery	8.5	79
Aluminum Parts	6.4	137
Engine	6.3	73
Steel Parts	3.1	13
Electronics	2.2	31
Polymers	2.0	8
Seat	1.8	3
Rubber Parts	1.4	9
Manufacturing	-	3
Total	60	446

2.2. Transportation

The transportation of the cargo bikes from Germany to Ghana is modelled using diesel vans (Euro 4), container ships for transport and electricity driven rail transportation. All vehicles are modelled with the country's specific diesel and heavy fuel oil mix from the reference year 2016. For the shipping, a heavy fuel oil driven ocean-going containership with a payload capacity of 43,000 dwt, representing an industry average, was assumed. The rail transportation is modelled with the region-specific electricity mix.

2.3. Use phase

For the utilization phase, the lifetime of individual components was considered, especially of the battery, as well as the charging of the cargo bike. The battery has both a calendrical and a cyclical lifetime, for which 1000 charging cycles over a period of 4 years were assumed. Furthermore, a capacity loss of 10% over 1000 cycles was assumed which was based on the provided data sheet. The electricity consumption for one charging cycle was assumed to be 1,1 kWh based on the estimation of the manufacturer. The calculated value from the battery data sheet is 0,96 kWh. The estimation of the manufacturer based on their experience was used for the calculations, since it was assumed that it better represents the actual energy demand. The electric motor and other electrical components have a lifetime assumption of 10 years and the tires of 6 years. The tires are extra thick comparable to motorcycle tires and can thus last longer than conventional bicycle tires, even on unpaved roads which explains this long manufacturer's specification. The lifetime must be validated by operation on site over a longer time span. For the steel frame and the other components of the e-cargo bike, a lifetime of 20 years was assumed. This means that on average 5 batteries, 2 electric motors and 3.5 sets of tires are to be credited per life cycle of the e-cargo bike.

For charging two different scenarios were compared. One is the charging with the Ghanaian utility grid mix and the other is the charging of the battery using photovoltaic (PV) electricity. The GHG emissions per kWh for the Ghanaian electricity mix were calculated according to the IGES List of Grid Emission Factors [31] and for the charging with PV electricity, the data set for PV electricity in Indonesia from the database of GaBi [29] was used, since no region-specific PV dataset is available and Indonesia has similar climatic conditions.

To compare the e-cargo bike with other cargo vehicles, the transport performance must be determined, considering the parameters range, maximum payload and load capacity. The maximum payload of the e-cargo bike is 120 kg. A utilization of 50% is assumed accounting for empty runs as well. According to the manufacturer, the range of the e-cargo bike with a full battery charge is between 25 and 30 km, depending on the riding style and terrain. The lower end of the spectrum was used to account for the terrain in sub-Sahara Africa.

To calculate the transport performance the range per charging cycle is multiplied by the number of charging cycles, taking the degradation of the battery into account. The resulting kilometrage is then multiplied by the effective load (i.e. the maximum payload multiplied with the utilization). This results in the number of ton-kilometers accumulated over the life cycle. To calculate the GHG emissions per tkm, the GHG emissions over the life cycle are divided by the ton-kilometers.

2.4. End-of-Life

The end-of-life comprises the dismantling of the vehicle and the energy demand of the subsequent shredding process. Excluded from this is the seat made of wood and natural fiber, for which an incineration is assumed.

2.5. Alternative transport modes

For the comparison with alternative transport vehicles, the GWP per tkm was determined for a van, a motorcycle and a truck with data provided by the German Environmental Agency [31], due to the lack of data for the Ghanaian use case. We had to convert the data for motorcycles, as these were only available in relation to one passenger kilometer. Therefore, we first calculated the GHG emissions over the lifetime by multiplying the GHG emissions per passenger kilometer by the indicated kilometrage of the vehicle of 60,000 km. Afterwards, we calculated the transport performance of the motorcycle by multiplying the lifetime kilometrage by an assumed effective load of 80 kg. Finally, we calculated the GHG emissions per ton-kilometer by dividing the GHG emissions over the life cycle by the transport performance.

3. Results

Figure 2 shows the share of the different life phases and spare parts in GHG emissions of the cargo bike over its life cycle per ton-kilometer in two scenarios.

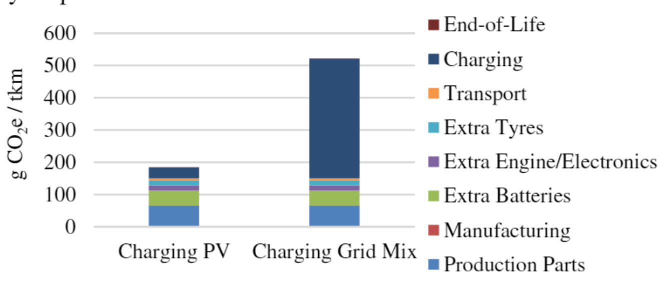

Figure 2: Life cycle GHG emissions per passenger-kilometer of e-cargo bikes used in Ghana for different scenarios. Own illustration.

It shows the use phase and thus the charging is highly relevant for the GHG emissions. Charging with PV electricity results in emissions of about 184 g CO_2e per tkm, while using Ghana's electricity mix, which is mainly based on natural gas and hydropower [33], results in emissions of over 520 g CO_2e per tkm.

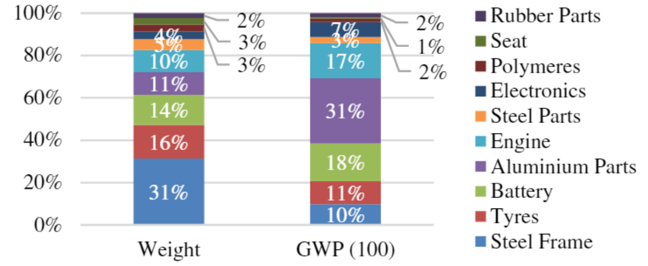

Figure 3: Share of GHG emissions of different materials in the production of one e-cargo bike compared to their weight shares. Own illustration.

Figure 3 shows the share of different components in GHG emissions of the production of one e-cargo bike in comparison to their weight share.
The steel frame, despite its considerable weight, does not make a significant contribution. The largest shares are in the aluminum parts, the battery, and the engine. In this context, it is important to consider the entire life cycle. The battery has a share of 18% of the GHG emissions of the production of one vehicle. However, this share increases when the entire life cycle is considered, as 4 additional batteries are needed over the life cycle of the e-cargo bike. The battery's share of GHG emissions for production including spare parts is thus 40%. This share could be even higher, as the climatic conditions in Ghana are difficult for the battery due to the frequent heat and early battery losses can occur. Other high shares of GHG emissions are in the production of the aluminum, and in the tires, which are particularly large due to their off-road suitability and must be replaced frequently when used on unpaved roads in Ghana. The shares for transport, final assembly in Berlin and End-Of-Life are low compared to the other life phases.

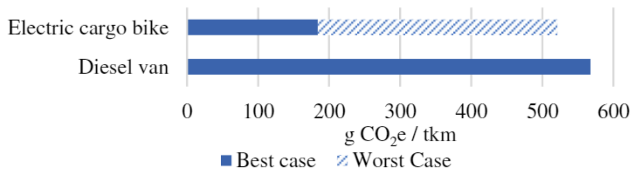

Figure 4: Comparison of GHG emissions per ton-kilometer of a diesel van [31] and an electric cargo bike for transportation in Ghana. Own Illustration.

Figure 4 illustrates the comparison of electric cargo bikes with a diesel van (3,5-7t payload) in Ghana. The results show that operation with solar energy results in significant emission savings compared to the diesel van. However, if the e-cargo bike is charged with the country's electricity mix, the GHG emissions in relation to the cargo transported are at a similarly high level as those of a small van. The main reason for this is the lower transport volume of the cargo bike compared to the van. This means that more cargo bikes would be needed to transport the same amount of goods. In the case of the cargo bike, the emissions from vehicle production are therefore related to a lower number of ton kilometers.

To calculate the effect of cargo bikes on GHG emissions from urban freight transport, we used the model split of the Accra region as shown in section 1.3. We multiplied the share of the different transport modes in the modal with their emissions per ton-kilometer. We considered the modal split in the status quo as well as our developed scenarios for the implementation of e-cargo bikes. Thereby we can see the average emissions of urban freight transport in the Greater Accra region per ton-kilometer for different modal splits.

Figure 5 shows, that a 4% share of cargo bikes in the modal split (scenario 1) can reduce the GHG emissions by 4% from 549 g CO_2e per tkm to 528 g CO_2e per tkm, whereas a share of 8% (scenario 2) results in a reduction of 8% and a total of 505 g CO_2e per tkm.

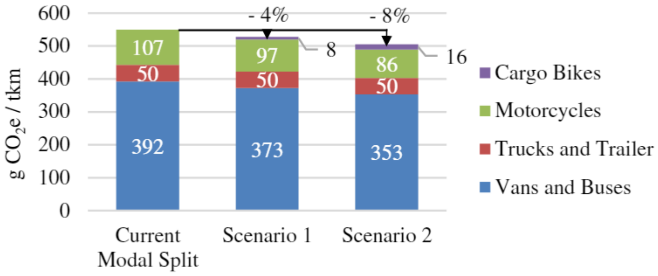

Figure 5: Average GHG emissions of urban freight transport in the Greater Accra region per ton-kilometer for different modal splits based on emission factors of [31] for motorcycles, trucks and vans as well as own calculations for the emissions of cargo bikes. Own illustration.

4. Conclusion and Discussion

The Life Cycle Assessment of electric e-cargo bikes shows that in case of intensive use, especially the charging of the batteries is the main contributor to GHG emissions. If e-cargo bikes are charged with solar energy, the GHG balance is positive also in comparison to other transport methods such as a diesel van. When discussing the calculated GHG emissions of the cargo bike, it should be noted that due to poor data availability, we compared them to the emissions of a German diesel van. When comparing with a Ghanaian van, the evaluation would probably shift in favor of the cargo bike, as on average older vehicles with higher emission values are used in Ghana. Furthermore, it is recommended that future studies and comparisons of cargo bikes and diesel vans also consider NOx and particulate matter emissions, as electromobility offers advantages especially with regard to these local emissions [34]. Another possibility for future research is the analysis of the cost reduction potential of cargo bikes. For the use in Ghana, besides charging, the lifetime of the lithium battery is also of high importance, as it is quite short compared to the rest of the e-cargo bikes when used intensively and there can be more dropouts when the heat is intense. Since the energy-intensive production of the battery is a major hotspot in manufacturing, the use of more robust batteries such as solid-state batteries should be considered. There is a need for further research on the actual lifetime of different battery types under the climatic conditions in Sub-Saharan Africa.

Another hotspot in manufacturing is aluminum, which is produced in China in the case of the e-cargo bike under consideration. Another emission hotspot in manufacturing is aluminum, because of the CO_2-intensive power mix used in China as well as the high energy demand of the production of primary aluminum. Next to the use of renewable energies in aluminum production it could be an alternative to use a higher proportion of secondary aluminum. However, it has to be considered, that even if the usage of secondary aluminum for extrusions part is common [35], possible limitations due to the alloy composition and quality need to be considered.

The data availability for the life cycle inventory analysis was limited, especially regarding the use phase in Ghana. The PV electricity mix, for which no country-specific values were available, was approximated with a data set for Indonesia. The range of the 36 region-specific datasets of the used database for GHG emissions of PV electricity spans between 31 g and 69 g CO_2e per kWh and depends mainly on solar irradiance [30]. The selected electricity mix from Indonesia is at the lower end of this range at 31 g, due to high solar irradiance comparable to solar irradiance in Ghana. The countries have similar proximity to the equator and similar climatic conditions. In addition, the assumptions regarding the life span of the different components need to be tested by long-term studies in the field.

We have shown e-cargo bikes can represent an environmentally friendly relief for the urban freight transport system in Ghana with a potential reduction of 4-8% of GHG emissions per ton-kilometer if they can claim a significant share in the modal split. However, further research will be needed to investigate the effect on the Ghanaian urban transport system in more detail. This should focus on the empirical analysis of the current modal split in Ghanaian urban freight transport and the life cycle GHG emissions of alternative transport modes such as vans and trucks. In addition, well-founded scenarios for a potential share of e-cargo-bikes in the modal split should be collected within the framework of user surveys or simulations.

Acknowledgments

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Converted and shared Light Electric Vehicles in Ghana: A technical and economic analysis based on converted ICE motorbikes and e-mopeds.

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Abstract. This paper sets out to examine the economic and technical viability of LEVs in Ghana as a business model. It further examines the profitability of converted motorbikes which are adapted from ICE motorbikes. The business model is built on technical requirements of the ICE conversion in Ghana. The authors used a case study approach to analyze an exemplary business model based on 40 e-mopeds and 20 stand-alone solar charging stations deployed on the campus of KNUST until December 2021. A further analysis was also done on the process of converting an ICE motorbike to create a minimum viable product which runs on electricity. The business model examines the profitability of such converted motorbikes taking into account production and assembly costs whiles also considering fixed costs. The results of the analysis prove that a single e-moped deployed in the model was profitable after 6.3 years and a converted motorbike was profitable compared to a conventional motorbike between 22500Km to 32500Km of use depending on the purchase scenario. The discussion and results provide a good basis for further research and give support to sustainable business models and manufacturing of LEVs.

Keywords: Electromobility; Sharing Systems; Sustainable Business Models

1 Introduction

Ghana has posted robust pre-pandemic economic growth over the past two decades. GDP per capita grew by an overage of 3% over the period. With poverty alleviation programs initiated and continued by successive governments, poverty rates have halved between 1998 and 2016 [1]. The economic performance is further supported by the discovery of oil in the Ghanaian sector of the gulf of Guinea which elevated the country to middle income status[2]. Figures from the Ghana Statistical Service indicate a post-independence population growth of 6.7million in 1960 to 30.8million in 2022 [3]. However increasing population and economic growth have a direct correlation to increased mobility needs as noted by Ayetor et.al[4]. Out of the 72 million vehicles in use in Africa, Ghana accounts for 2.5 million[4]. Mobility needs in Ghana until now has been fossil-fuel based with limited research and implementation of sustainable mobility options. This paper seeks to assess the profitability of a business model based on Light Electric Vehicles (LEVs) in a shared environment based on the campus of the Kwame Nkrumah University of Science and Technology (KNUST). It also assesses a business model based on a converted Internal Combustion Engine (ICE) motorbike for the city of Sunyani where a minimum viable product was developed with the University of

Energy and Natural Resources and the local startup Solar Taxi. A cursory analysis of the technical requirements for the conversion of a converted ICE motorbike is also provided whiles respecting the proprietary information of Solar Taxi, the private partner involved in the research. The objective of such a sustainable mobility solution would be to provide transportation access whilst minimizing resource consumption and traffic congestion utilizing a sharing system for LEVs. Questions to be answered by this paper are elaborated as follows:

I. Can business models on a university campus based on shared light electric vehicles be operated economically?

II. What are the technical requirements for the conversion of an ICE motorbike to an electrically powered model?

III. Can a business model based on converted ICE motorbike be operated economically?

2 An overview of sustainable business models, LEV sharing systems and the conversion of ICE motorbikes to e-motorbikes

The sustainable business model draws on the tenets of the traditional business model. The business model concept gained prominence in the early days of the internet, the so-called dot.com era[5]. On a general level it is a statement[5], a description[6], a representation[7], a conceptual tool or model[8], a structural template[9][5], and a framework[9], to name a few. It is assumed that innovations on a business model level tend to yield higher returns when compared to product or process innovations[9]. The Business Model Canvas presents a framework for visualizing and structuring business models on an organizational level or on a unit basis[9]. For organizational decision-making and academic research in the context of emerging industrial phenomena, like Industry 4.0 or Re-Distributed Manufacturing[9][10], the business model concept allows firms to elaborate the potential customer and value chain benefits and compare or generate the required configuration and implementation of the other business model elements or units [9], [11].

The canvas is geared toward economic benefit only, hence to transition to a sustainable model, amendments would be required. The definitions in various literature see sustainable business models as a modification of the conventional business model concept, with certain characteristics and goals added to it; and, they either 1) incorporate concepts, principles, or goals that aim at sustainability; or 2) integrate sustainability into their value proposition, value creation and delivery activities[9]. Geissdoefer et al. concretely define the sustainable business model as a business model that incorporates pro-active multi-stakeholder management, the creation of monetary and non-monetary value for a broad range of stakeholders and hold a long-term perspective [9], [11].

The use of light electric vehicles (LEVs) is slowly gaining prominence with efforts made to introduce such devices in Ghana in various international development programs [12]. In general terms, between 17% and 49% of trips made and 6% to 30% of the distance covered by private trips can be substituted by LEVs[13]. A study by Schelte et al. found that e-moped sharing resulted emissions of 20–58 g CO_2-eq./pkm which is comparable to emissions from electric buses (27–52 g CO_2-eq./pkm)[14]. As 81% of trips can be can be substituted by the use of e-mopeds, this statistic is significant [14] in reducing Ghana´s GHG emissions. Sustainable mobility is aided by the sharing of LEVs in a closed system[15]. About 8% of households reported surveys by the Ghana ministry of roads and transport that owning between one and four motorbikes which were in good condition for private use[16]. In total there was a stock of approximately 2.4 million conventional motor bikes in year 2012[16]. With a current estimated population of 30,8 million people [3]and an assumption of a constant share of conventional motorbikes per person there could be a stock of 2.86 million conventional motorbikes in 2022. With such an estimation, current potential demand for e-motor bikes is 2.8 million e-motor bikes, as this is the calculated and estimated current number of conventional motor bikes in Ghana. A research gap exists on the viability of a sustainable business model based on e-mopeds, the business potential for converted ICE motorbikes and the environmental impact of such a substitution of conventional ICE motorbikes.

3 Methodology

3.1 Profitability of a shared LEVs on a Campus

The possibility of an e-moped sharing system at the KNUST University in Kumasi is imagined as an example that can be scaled up to similar institutions in Ghana. Assumptions have been estimated based on one-on-one interviews and email correspondence with experts in the field of EV sharing systems (Russ P., Tier Mobility GmbH, 2021) , findings after reviews of the Ghanaian tax and business registration systems (Aryee M.A., MEK Consult and HR Essentials LLC, 2021), and the business model of the private e-mobility service provider, Solar Taxi Ghana. Details of correspondence is included in the appendix.Detailed cost considerations can be found in the appendix giving greater context to the profitability analysis. An average drive on campus from takes eight minutes based on existing campus shuttle service, speed limits and a survey of students and staff on the KNUST campus to understand transport needs and dynamics[17]. 10 cents per minute was set as the fee per ride based on current costs on the campus. A business model canvas for the operation is provided below:

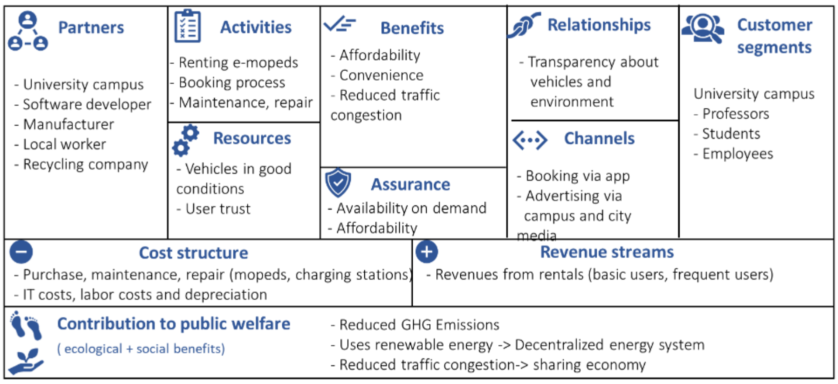

Fig.1. Business Model Canvas for campus sharing system based on the work of Osterwalder & Pigneur [11], [18]

Table 1. Assumptions for shared LEV business model on a university campus.

Description	Assumption
Number of e-mopeds	40 e-mopeds with an LEV available every 500m
Number of rides	10 rides per LEV a day
Replacement of e-mopeds	1,5 new e-mopeds per year needed compensate for the loss caused by theft, vandalism, and total damage

3.2 Conversion and profitability analysis of an ICE motorbike

Technical feasibility of conversion of an ICE motorbike is proven by the creation of a minimum viable product (MVP) of a converted motorbike. Due to protection of proprietary information and protection of trade secrets of the private firm Solar Taxi, a basic overview of the conversion process and its key components are provided. The components of electric motorbike that require modifications include the original frame, swingarm, brushless DC motor, electronic speed controller (ESC), lithium-ion battery pack, power transmission, DC–DC converter. Parts that were replaced are; the engine, starter battery, throttle, clutch lever and dashboard. These parts were replaced with: 5kW chain driven motor, 50Ah Li-ion battery pack, motor controller, hall sensor throttle, and an electronic dashboard. Mechanical fabrication involved creating a platform to seat the electric motor, creating a housing for the battery pack a platform to mount the motor controller. The former location for the engine now contains the electric motor and the battery pack. The former location for the battery that powers the starter now houses the motor controller which translates actions such as turning the throttle into forward or backward movement. The battery used in the conversion is the HYSJ 21700E. This cell has a 3.7V nominal voltage and capacity of 17.76Wh. It has a nominal capacity of 4800mAh, has a maximum charge current of 3A and a maximum discharge current of 15A continuous and 25A short term. Determination of the potential pricing model for the converted motorbike was done by analyzing the cost implications of commercial production and market entry scenarios. Both analysis is based on information and interviews with the private sector firm Solar Taxi. There are two different business models when it comes to conventional motorcycle conversion. In the first scenario, the company buys conventional used motorcycles, converts them into e-motorcycles and sells them to customers who do not yet own a motorbike. In second scenario, the customer brings his own conventional motorbike to the company and the company converts it into an e-motorbike. Costs are presented in the excel appendix and used for the profitability analysis.

Fig.2a. Conventional motorbike stripped internal combustion engine (top right, Model: Haojin 125-32, 150cc)
Fig.2b. Rewired conventional motorbike linked to a battery pack (top left)
Fig.2c. Fully converted ICE motorbike at the campus of UENR (Left)(original model was Haojin 125-32, 150cc)
Fig.2d. E-mopeds and stand-alone solar charging stations on the campus of KNUST (Right)

4 Results and discussions

Figure 4 shows the plotting of revenue vs known costs and shows an approximate break-even point after 2.300 days and thus 6.3 years. Since the exact costs for the software development are currently unknown, it can be assumed that the calculation will shift, and that profitability will occur sooner. An overview of costs and assumptions used in the analysis is elaborated below.

Table 2. Costs and revenue overview per e-moped.

Cost type	Description	Cost	Cost/e-moped
Onetime costs	e-mopeds, solar charging stations, equipment	387.760€	9.694,€
Fixed monthly costs	Wages, rental and operational costs	2.968€	2,44€
Variable monthly costs	Replace, theft, software use, update	313,38€	1,83€
Cost per ride	Credit card, insurance fees, repair, city permits	6.393,23€	0,53€
Revenue per ride	fixed fee and minimum 8mininute ride		1,40€

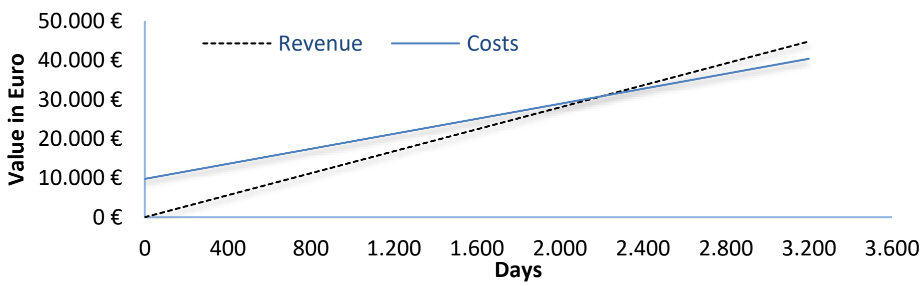

Fig. 3. Days until one e-moped is economical.

The cost of a converted motorbike in scenario 2 is less than a brand-new converted electric motorbike as defined in scenario 1 and the product might be more suitable for the local environment. In addition, the converted motorbike also has ecological advantage in that it is in fact a reuse case. An assessment of the price of the converted motorcycle from scenario one, the sales price is even higher and exceeds the price of a new electrically powered-motorbike. Graphs of operating costs of converted bikes vs ICE motorbikes for both scenarios 1 and 2 are generated to demonstrate the profitability of the converted motorbike as there is insufficient data for a full business case analysis. It can be observed the rising costs of ICE motorbikes in both instances compared to a steady slow rise in cost for the converted motorbike with break-even achieved after about 32.500km of operation in scenario 1 and 22.500Km in scenario 2. It is assumed that the converted motorbikes will be powered by solar charging stations whose cost is counted once as part of equipment costs hence no further costs are incurred for electricity supply. Solar charging stations used in the analysis are designed to power two e-mopeds at a time.

Table 3. Costs and sales overview of converted motorbike vs ICE motorbike.

Cost type	Description	Cost
Onetime equipment costs	Cost of fabrication equipment, specialized tools, etc.	4.305€
Cost of ICE motorbike	Cost of traditional motorcycle purchase	672€
Sales cost for converted motorbike (Scenario 1)	Sales cost based on imagined business model scenario 1 as elaborated above	2.856,43 €
Sales cost for converted motorbike (Scenario 2)	Sales cost based on imagined business model scenario 2 as elaborated above	2.148,32 €

Table 4. Costs considered for operational costs of converted motorbike vs ICE motorbike.

Cost type	Description
Purchase	converted motorbike is dependent on the scenario whiles ICE motorbike is purchased once
Engine oil	Cost for engine oil change considered as 2,80€ per month
Fuel	Costs for ICE motorbike fuel considered as 2,80€ per 100km
Maintenance	Costs for ICE motorbike assumed to be 14,00€ ; costs for converted motorbike assumed at 2,80€

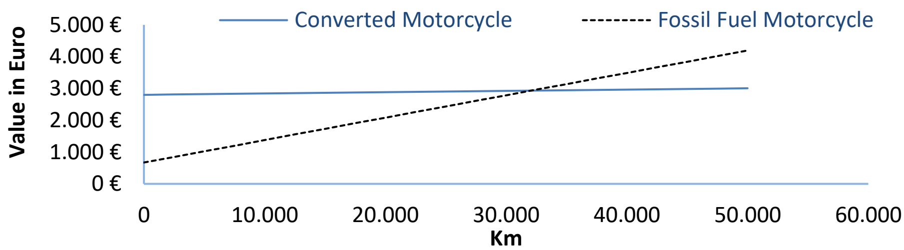

Fig. 4. Kilometers until the converted motorcycle is economical (scenario 1)

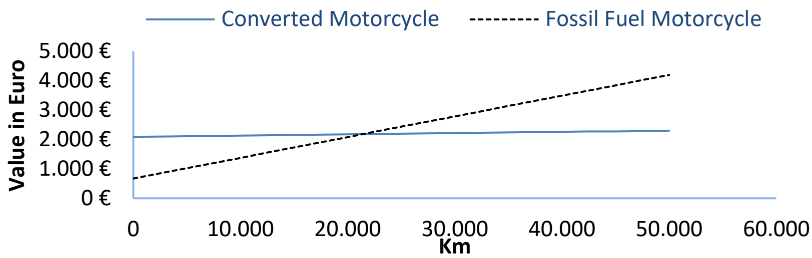

Fig. 5. Kilometers until which the converted motorcycle is economical (scenario 2)

5 Conclusions

Comparing the elaborated business models of LEVs on KNUST campus and the models for converted motorbikes with literature shows that these models do fall under the structures defined by Zott et. al[5] in that they are sustainable in terms of emissions reduction and innovative being adapted to the local environment and pricing constraints. They are also well within the definitions of Geissdöfer et. al[9],sitting between sustainable business models and circular business models due to the replacement of used ICE motorbikes with converted e-mopeds. The results elaborated proves from the pilot of shared devices on campus of the Kwame Nkrumah University of Science and Technology and as well the development of the prototype converted motorbike that these business models are indeed feasible despite long periods to profitability. Consumers in Ghana usually use mobility devices for a long period of time opting for repair and maintenance as opposed to newer models. Proving the economic viability of one e-moped is necessary to extrapolate that the business model as a whole would be profitable. In both scenarios of a business model based on a converted motorbike, it was observed that lower operating costs made these models cheaper over the lifetime compared to ICE motorbikes and present a valid business case. The sales prices indicated are based on pilot projects and prototypes and hence are on the higher-end of cost pricing. These costs should reduce further with higher production rates dues the principles of economies of scale. This represents a limitation of the paper as well as these benefits are not explored to reduce sales costs. Further analysis in operating costs are needed to provide a deeper insight into lifetime costs and end-of-life costs for the converted motorbike. Finally, whiles this paper lays out the technical feasibility of conversion, a performance review of the minimum viable product is needed to compare with e-mopeds and ICE motorbikes. Emissions reduction potential are well documented in literature internationally, however further research on the specific emissions reduction for these business models need to be investigated by means of a life-cycle assessment taking into account the local Ghanaian environment.

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Appendix

The authors provide a cloud folder with raw data from profitability analysis to provide further context for graphs and figures.

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