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Locally Manufactured Small Wind Turbines: Sustainability Assessment integrating Life Cycle Assessment and Multi-Criteria Decision Analysis

MSc Thesis

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Abstract

Locally Manufactured Small Wind Turbines (LMSWTs) are small-scale wind turbines that can be constructed by non-experts using simple tools and techniques, and whose designs are developed collaboratively by a global community of designers-users-manufacturers. In this study, LMSWTs have been assessed from a sustainability perspective, in comparison with a commercial small wind turbine, for off-grid applications in rural areas. The compared alternatives differ not only in terms of size and technology, but also in the "delivery model" under which they are employed, ranging from conventional to increased participation models, where users are empowered to maintain the systems themselves. The influence of the local context was taken into account through a parameter reflecting the dispersion of settlements in the studied area. Life Cycle Assessment was used to assess the environmental impacts and a life cycle approach was taken to estimate a variety of techno-economic, social and institutional sustainability indicators. The sustainability indicators were then used as criteria in Multi-Criteria Decision Analysis, using the PROMETHEE method to rank the alternatives from two stakeholder viewpoints: investors and policy makers. For both viewpoints, it was found that local manufacture combined with participative delivery models was ranked first, unless the Institutional burden became the most significant criterion for the policymaker. In this respect, we observed significant impact of different preferences translated to different sets of weights. Thus, expert elicitation is needed to define the weight of this criterion for policymakers, as well as to quantify the performance of the alternatives in it, taking into account existing conditions in each local context.

Keywords: Sustainability assessment, LCA, MCDA, PROMETHEE, stakeholders, small wind, rural electrification, life cycle, delivery models

Περίληψη

Οι Τοπικά Κατασκευασμένες Μικρές Ανεμογεννήτριες (ΤΚΜΑ/Γ) είναι ανεμογεννήτριες μικρής κλίμακας που μπορούν να κατασκευαστούν από μη ειδικούς χρησιμοποιώντας απλά εργαλεία και τεχνικές και τα σχέδια των οποίων αναπτύσσονται συνεργατικά από μια παγκόσμια κοινότητα σχεδιαστών/κατασκευαστών/χρηστών. Σε αυτή την εργασία, οι ΤΚΜΑ/Γ έχουν αξιολογηθεί από πλευράς βιωσιμότητας, σε σύγκριση με μια μικρή εμπορική ανεμογεννήτρια, για εφαρμογές αυτόνομων συστημάτων σε αγροτικές περιοχές. Οι υπό σύγκριση εναλλακτικές λύσεις διαφέρουν όχι μόνο ως προς το μέγεθος και την τεχνολογία, αλλά και ως προς το «μοντέλο παράδοσης» (delivery model) με το οποίο υλοποιούνται, το οποίο κυμαίνεται από συμβατικά έως πλήρως συμμετοχικά μοντέλα, όπου οι χρήστες είναι εξουσιοδοτημένοι να συντηρούν οι ίδιοι τα συστήματα. Η μέθοδος της Ανάλυσης Κύκλου Ζωής χρησιμοποιήθηκε για την εκτίμηση των περιβαλλοντικών επιπτώσεων, ενώ υιοθετήθηκε γενικότερα μια προσέγγιση κύκλου ζωής για την εκτίμηση ποικίλων δεικτών τεχνοοικονομικής, κοινωνικής και θεσμικής βιωσιμότητας. Οι δείκτες βιωσιμότητας στη συνέχεια χρησιμοποιήθηκαν ως κριτήρια για την εφαρμογή Πολυκριτηριακής Ανάλυσης, χρησιμοποιώντας τη μέθοδο PROMETHEE, προκειμένου να ταξινομηθούν οι εναλλακτικές λύσεις εκ μέρους δύο ομάδων ενδιαφερομένων: α) των επενδυτών-χρηστών της τεχνολογίας και, β) των φορέων χάραξης πολιτικής. Και για τις δύο ομάδες, οι ΤΚΜΑ/Γ συνδυαζόμενες με συμμετοχικά μοντέλα ήταν η προτιμητέα επιλογή, εκτός όταν το Θεσμικό κόστος αποκτούσε πολύ μεγάλη βαρύτητα για τους φορείς χάραξης πολιτικής. Από αυτή την άποψη, παρατηρήσαμε σημαντική επίδραση διαφορετικών προτιμήσεων που μεταφράζονται σε διαφορετικά σύνολα βαρών. Συνεπώς κρίνεται απαραίτητη η διαβούλευση με εμπειρογνώμονες προκειμένου να προσδιοριστεί το βάρος αυτού του κριτηρίου για τους φορείς χάραξης πολιτικής, καθώς και να ποσοτικοποιηθεί η απόδοση των εναλλακτικών λύσεων σε αυτό, λαμβάνοντας υπόψη τις υπάρχουσες συνθήκες σε κάθε τοπικό πλαίσιο.

Λέξεις-κλειδιά: Ανάλυση βιωσιμότητας, Ανάλυση Κύκλου Ζωής, Πολυκριτηριακή ανάλυση, PROMETHEE, μικρές ανεμογεννήτριες, αγροτική ηλεκτροδότηση

Ευχαριστίες

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List of Abbreviations

AEP	Annual Energy Production
AHP	Analytic Hierarchy Process
CED	Cumulative Energy Demand
CML	Centrum voor Milieuwetenschappen (Centre for Environmental Studies)
DM	Delivery Model
EDI	Energy Development Index
FP	Fixed Parts
GWP	Global Warming Potential
IAEA	International Atomic Energy Agency
ICT	Information and Communication Technologies
IEA	International Energy Agency
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
LGC	Levelized Generating Cost
LM	Locally Manufactured
LMSWT	Locally Manufactured Small Wind Turbines
MAMCA	Multi-Actor Multi-Criteria Analysis
MCDA	Multi-Criteria Decision Analysis
MCDM	Multi-Criteria Decision Making

MP	Moving Parts
O&M	Operation & Maintenance
PROMETHEE	Preference Ranking Organization METHod for Enrichment of Evaluations
R&D	Research & Development
RES	Renewable Energy Sources
SETAC	Society of Environmental Toxicology and Chemistry
SWT	Small Wind Turbine
UNEP	United Nations Environment Programme

1. Introduction

In rural areas where grid connection is technically and economically unfeasible, small scale renewable energy technologies can provide a viable solution for many of the 1.1 billion living today without electricity [1], allowing them to generate electricity in a sustainable way [2].

The alternative in this context, which is usually found among low-income communities in developing countries, is using unhealthy, insecure and fossil-intensive energy sources, such as kerosene, wood or candles. In other rural contexts, higher-income users can afford to use diesel generators, which is of course a highly fossil-intensive technology.

In most of these cases, small-scale solar power is applicable but usually needs to be paired with other energy sources in order to provide energy consistently, through the day and throughout the year. Small-scale hydropower has many advantages and is often the preferred choice [3] when hydro resource is available. When this is not the case, small wind turbines are another choice that can be combined well with solar panels, especially in areas where the weather is windy during the less sunny seasons. Very often however, even in areas with high wind resource, small wind turbines are not preferred due to their high maintenance requirements which are usually ineffectively addressed [4].

Small wind turbine manufacturers are usually located thousands of kilometres away from the sites where the wind turbines are installed, which makes the maintenance process slow and costly. Also, in not so few cases [5], manufacturing companies have stopped operating, leaving their customers without spare parts and technical support.

An alternative to conventional small wind turbines, has emerged that aspires to overcome the barrier of ineffective maintenance by producing the wind turbines locally, thus making their maintenance easier and less time- and capital- consuming. Additionally, these turbines have lower capital cost than their conventional counterparts, which makes them much more accessible to low-income rural communities. These wind turbines- discussed in detail below- can provide a function that in specific contexts is not sufficiently covered by other technologies, and for this reason it was deemed interesting to further examine and improve them in terms of their sustainability.

Locally manufactured small wind turbines

The term locally manufactured small wind turbines (LMSWTs) has been used in literature [3], [6], [7], [8], [9], [10], [11], to describe small-scale wind turbines that can be manufactured, installed and maintained by non-experts using basic workshop facilities, and whose designs are open, in the sense that they are not patented and can be further developed.

LMSWTs are being made by practitioners around the world in different sizes, ranging in rotor diameters from 1.2 to 7 m [7]. Amongst different designs, the most widespread, with others deriving from it, is that of Hugh Piggott, a widely acknowledged small wind expert who has developed a design that is efficient and can be manufactured with simple tools and techniques and mostly locally-sourced materials. His manual for constructing a small wind turbine, "A Wind Turbine Recipe Book" [12], has been translated in more than 10 languages, facilitating the dissemination of this technology in different parts of the world. Piggott's designs are not patented and can be modified and replicated by anyone and for any use [9]. Due to these open designs, a growing global community of designers, manufacturers and users has evolved, which continues to develop the designs collaboratively through a bottom-up innovation process, resembling "an open-source hardware community in the making" [7].

A previous study [9] has compared a LMSWT with a commercial SWT in a rural off-grid application and found that the LMSWT, despite having higher O&M costs and shorter lifespan, has significantly lower capital costs, lower Net Present Cost and lower Levelized Generating Cost (LGC), with costs spreading more evenly throughout the turbine's lifetime.

In other studies, the social aspects of LMSWTs have been emphasized: their potential to boost local economy, build local capacity and create employment in contexts where it is most needed [3], [6], [10], as well as their flexibility, scalability and adaptability to better suit different environments and applications, arising from the open nature of their designs [7], [11].

Open design and local manufacturing in the developing and developed world

Locally manufactured small wind turbines (LMSWTs) constitute an alternative model of production that aspires to meet the needs of low-income, rural, off-grid communities with renewable and sustainable technology. This model of production is related to "Appropriate technology" [13], which is characterized by being "small-scale, decentralized, labour-intensive, energy-efficient, environmentally sound, and locally autonomous" [14]. As time is normally a resource more abundant than capital in the developing world, intermediate technology has been argued to be a better fit for the sustainable development of these countries, especially when it is based on open designs [15].

At the same time, the more and more widespread use of technologies like 3-D printing and computer-aided manufacturing, as well as the emergence of several makerspaces in neighbourhoods around the world, are enabling the rapid manufacturing of products locally, giving meaning to distributed production models in developed countries as well. These local makerspaces (where digital and benchtop manufacturing technologies are shared) are often inspired by the commons movement and are affiliated with open design and open source technologies. Thus, a new dynamic is being created, combining the advantages of open knowledge/design –which has no geographical limits- with local production, which has the potential to be more environmentally and socially sustainable. This alternative model of production, based on the convergence of the digital commons of knowledge, software and design with local manufacturing technologies has been tentatively called by scholars "Design Global, Manufacture Local" [16].

Is it possible that distributed production can serve the needs of the world better than mass production and economies of scale when all aspects of sustainability –environment, economy, society and more- are concerned? This study is not aiming to answer this question but may potentially shed some light towards the comparison of these two different approaches, in the case of a specific application -small wind turbines- applied in a specific context -rural, off-grid areas of developing countries.

2. Goal and Objectives

The main objectives since the beginning of this work have been:

- To perform an extensive Life Cycle Assessment of LMSWTs compared with a commercial SWT

This has been mentioned as a request for future research in previous studies [3], [11]. Especially because LMSWTs have been used in very different contexts and with very different models of production/operation/maintenance (delivery models), some of which have been characterized as inefficient, it has been suggested that an environmental Life Cycle Assessment could help avoid cases where a low carbon technology is used in an inefficient way.

- To integrate the results of LCA in a sustainability assessment framework, using MCDA to rank alternative small wind turbine solutions for a variety of sustainability criteria and from different stakeholder viewpoints

Since locally manufactured and commercial SWTs represent not only different technologies but also different models of manufacturing and O&M, it was expected that they could imply quite different lifecycle impacts in social and economic dimensions as well. Thus, performing a comparative sustainability assessment was deemed interesting and integrating MCDA techniques would allow to encompass a variety of criteria and the viewpoint of different stakeholders in such a complex decision problem.

To sum up, this work intends to comparatively assess locally manufactured and a commercial SWT for rural, off-grid applications in developing countries from an integrative sustainability perspective and from the point of view of different stakeholders.

The ultimate goal is to understand the strong and weak points of LMSWTs against commercial SWTs for rural electrification in developing countries, in order to support decision makers to decide whether -and choose which- locally manufactured small wind alternatives better suit a specific context and should be promoted on sustainability grounds.

3. Literature review

Literature review on the subject of Locally Manufactured Small Wind Turbines has been presented in the Introductory session. The present chapter details on the one hand, a review of published papers on the subject of Life Cycle Assessment of small wind turbines and secondly, a review of sustainability assessment frameworks that have been used to assess small-scale rural electrification energy systems.

Life Cycle Assessment for small wind turbines

There is a limited number of studies performing Life Cycle Assessment for small or micro wind turbines in literature. For LMSWTs no such study has been published and only a Bachelor thesis could be obtained on the subject [17].

The assessed small wind turbines in these studies range in rotor diameters from 1.3 to 9 m and in rated power from 250 W to 7.5 kW. It should be noted that their Annual Energy Production (AEP) is calculated at very different wind conditions, while many papers do not provide information about the conditions at which the AEP has been calculated. As most impacts are expressed per kWh generated, this difference or uncertainty in the calculation of the turbines' generation creates an incomparability of results in the various papers[1]. Besides, results should not be compared because the system boundaries and considered components are very different between the studies.

Most papers include the wind turbine's rotor, generator and tower in the assessment, while some also consider the electric and electronic components and the foundation. The most common materials used for the wind turbines are glass fibre, resin, steel, copper, aluminium, cast iron and several kinds of plastic. Steel and concrete are used for the tower and foundation of the wind turbines in off-grid mode. In many cases, rare earth magnets have not been considered in the inventories, even though the majority, if not all of these wind turbines are using them. Instead it is possible that the amount of other metals in the inventory has been increased to substitute for the absence of magnets -as has been the case in other LCA studies [18].

Regarding the system boundaries, some of the reviewed studies perform a Cradle-to-Grave LCA, while others a Cradle-to-Gate, excluding O&M and Disposal form the assessment. However, even in Cradle-to-Grave studies, Maintenance was often not considered (or only an amount of Lubricating oil was considered but not transportation for maintenance) as it was assumed to be insignificant compared to the other lifecycle stages.

Out of the twelve reviewed studies, half of them assess wind turbines in off-grid mode and half of them connected to the grid. Finally, environmental impacts are assessed mainly as far as energy consumption and CO_{2eq} emissions are concerned, often using the payback time index. Some

[1] A direct comparison would be unjust for wind turbines assumed to be operating at low wind conditions.

studies assess impacts in a variety of additional categories, such as Acidification, Ozone layer depletion and Abiotic resource depletion among others.

Concerning the LCA study for the LMSWT [17], the author performs a cradle-to-gate[2] LCA for a 500 W LMSWT in off-grid application, including in the assessment the rotor, the generator and the structure of the wind turbine. LCA is performed with OpenLCA software and results are presented for various mid-point impact categories using CML method, as well as endpoint impact categories through the Eco-Indicator. Unfortunately, results are presented aggregated for the whole lifetime of the wind turbine without specifying how long is the lifetime or how much is the total lifetime generation of the wind turbine. Therefore, results cannot be translated to impacts per kWh generated in order to be compared with the results of the present study.

The reviewed LCA studies are summarized in Table 1 below.

[2] Transportation for Installation is not considered

Reference	Operating mode	Rated power (kW)	Manufacturer /Model	Rotor diameter (m)	AEP (kWh)	at average wind speed (m/s)	Lifetime (years)	Materials	Considered components	System boundaries	Impact categories
Barnes M. (2017) [17]	Off-grid	0.5	Locally Manufactured (WindAid)	1.7	870	-	-	fiberglass, steel	blades, generator, structure	Cradle-to-gate. Raw materials, Manufacturing, Installation (O&M, Disposal, Transportation not considered)	Various CML midpoint impact categories, Eco-indicator
Wei-Cheng Wang, Heng-Yi Teah (2017) [19]	Off-grid	0.6	Digisine Energytech CO., LTD	1.3	101	4	1	NdFeB magnets, epoxy resin, mild steel, carbon steel, ABS, aluminium alloy, copper, semi-conductor	Rotor, generator, electronic components, tower	Cradle-to-grave (no Maintenance considered)	Energy payback time, GWP payback time
Smith et al. (2015) [20]	Off-grid	5	5 kW Fortis Montana	5	-	5.93	20	Copper, Fiberglass, various types of steel, Concrete	Wind turbine, tower, foundation	Cradle-to-grave (No maintenance considered)	Acidification, GWP, Human toxicity, Abiotic resource depletion (Sb)
Md. Shazib Uddin, S. Kumar (2014) [21]	Grid-tied	0.5	-	1.7	1782	9.83	20	fiberglass plastic, aluminium, permanent magnets, steel	blades, nacelle, tail rod, tower, switchboard, inverter	Cradle-to-grave (Maintenance not considered)	Embodied energy, various air emissions, Energy and CO2 intensity and payback time
Ardente et al. (2010) [22]	Grid-tied and Off-grid	1	-	2.7	372	-	20	Reinforced carbon fibre, aluminium, steel, copper, plexiglass, concrete	Blades, hub, nacelle, tail, cables, tower, foundation, batteries, inverter	Manufacturing, Installation O&M, End-of-Life, Transportation	Air, water and soil emissions, GWP, Energy consumption, Energy and CO2 payback time
Greening, Azapagic (2013) [23]	Grid-tied	6	Proven 11	5.5	7800	5	20	fiberglass, cast iron, stainless steel, low-alloyed steel, rubber, aluminium, copper, epoxy resin, lubricating oil, polyethylene, polyvinylchloride, tin, lead, polypropylene	rotor, nacelle, tower, foundation and electronics	Cradle to grave	All CML 2 Baseline 2001 impact categories

Reference	Operating mode	Rated power (kW)	Manufacturer /Model	Rotor diameter (m)	AEP (kWh)	at average wind speed (m/s)	Lifetime (years)	Materials	Considered components	System boundaries	Impact categories
Kabir et al. (2012) [24]	Grid-tied	5	Endurance 5kW	5.5	-	-	25	Fiberglass, epoxy resin, steel, copper, aluminium, polyester, stainless steel, concrete, steel rebar	Rotor, nacelle, tower, foundation	Manufacturing, Installation, O&M, End-of-Life, Transportation	Energy intensity, GWP, ozone depletion, acidification
Tremeac B., Meunier F. (2009) [25]	Off-grid	0.25	Windside WS-0.3C (VAWT)	3	120	-	20	Aluminium, fiberglass, copper, steel	Blades, Nacelle, Tower, Foundation	Cradle-to-grave (Maintenance not considered)	Impact 2002+ categories, Payback time and Intensity index for energy and CO2 emissions
Fleck B., Huot M. (2009) [18]	Off-grid	0.4	Southwest Wind power's Air X (US)	1.17	588	-	20	Stainless steel, aluminium, copper, steel, plastic	Turbine, tower, battery bank, inverter	Cradle-to-gate (Installation, Electricity distribution, O&M not included	GWP
Allend, Hammond, Mcmanus (2008) [26]	Grid-tied	0.6	-	1.7	164 (urban), 870 (open)	2.3 - 5.2 (urban), 2.8 - 7.8 (open)	15	Aluminium, copper, steel, rare earth magnets	Rotor, nacelle, tail, electronic parts	Cradle-to-gate	GWP, Ozone layer, acidification, eutrophication, heavy metals, carcinogens, winter smog, summer smog, energy resources
Celik, Muneer, Clarke (2007) [27]	Grid-tied	7.5	Windka	9	5000 - 49000	2.6 - 4.9	25	Steel, copper (no inventory provided)	Wind turbine, Inverter, battery	-	GWP, Energy and CO2 payback time
Rankine, Chick, Harrison (2006) [28]	Grid-tied	1.5	Renewable Devices Ltd, SWIFT Rooftop wind turbine	2	1000 – 4000	4 - 7.2	20	Aluminium, carbon fibre, epoxy resin, copper, mild steel, stainless steel, polymers	Rotor, nacelle, mast, electronic components	Cradle-to-grave	Energy consumption, CO2 emissions, payback time

Table 1: Literature review table for LCA of small wind turbines

Other dimensions of sustainability

As far as the environmental dimension of sustainability is concerned, Life Cycle Assessment is the widely accepted and standardized [29] methodology to assess environmental impacts. For other dimensions of sustainability, however, not only there is no universally accepted methodology, but there is not even agreement about which dimensions should be addressed and eventually, how sustainability is defined. On the one hand, this is a conflict of perception, as to what sustainability should comprise; what purposes it should serve. On the other hand, even when there is agreement of perception, there is a confusion of terminology and methods used in different scientific fields [30].

The 1992 UN Conference on Environment and Development in Rio emphasized the need to develop indicators to measure Sustainable Development. More than 500 indicators have been developed since then [30]. The most commonly addressed dimensions of sustainability are the Environmental, Social and Economic dimensions, also known as The Three Pillar Model. Additional dimensions addressed in literature are the technical and institutional dimensions.

In the energy field, guidelines and a comprehensive list of thirty energy-based indicators for sustainable development have been published by the International Atomic Energy Agency (IAEA) [31]. Another index defined to assess sustainability of energy at an aggregated national level is the Energy Development Index (EDI), developed by the International Energy Agency (IEA).

However, country-level indicators are often broad in nature, may hide inequities, are not customized for each local context and have thus been considered inappropriate for the evaluation of projects at local level [32], [33].

Aspiring to overcome such issues, Ilskog [34] developed a practical manual for evaluating the sustainability of rural electrification projects, based on 39 indicators in five dimensions of sustainability: Technical, Economic, Social/Ethical, Environmental and Organizational/ Institutional. Another study [35] defined a set of 43 sustainability indicators based on Ilskog's five dimensions, in order to evaluate three small-scale rural electrification projects in Nepal, Peru and Kenya.

Doukas et al. propose a set of indicators for the evaluation of the energy sustainability of rural communities that can be used for the calculation of an Energy Sustainability Index for rural communities. Finally, Mainali and Silveira [36] introduce a rural Energy Sustainability Index for evaluating the sustainability performance of rural electrification technologies, aggregating 11 indicators in technical, economic, social, environmental and institutional dimensions.

Methodologies

As far as methods for Sustainability Assessment are concerned, different tools and methodologies have been used in order to assess alternatives in one dimension, usually techno-economic or environmental. However, it seems that an integrated approach combining different tools and methods is gaining acceptance as the most appropriate way to assess multiple dimensions of sustainability.

For example, Bhattacharyya [37] reviews several studies that assess the performance of off-grid electrification systems using different methods. The author categorizes the used methods into five categories: worksheet-based tools, optimization-based tools, MCDM tools, participatory systems approach and hybrid tools combining two or more of the above methods. After examining the different methods, he finally argues that most academic literature has focused on technical, economic and environmental dimensions of the problem, while social and institutional aspects have mostly been addressed through MCDM, which however he deems insufficient by itself to analyse the system design and its viability in detail. He therefore recommends a hybrid approach which as he supports, could complement the strengths and weaknesses of each approach.

Sala et al. [38] provide a detailed overview of methodologies used to perform sustainability assessment. A summary of these methods is presented in Figure 1. Some methods in this figure are designed to address a single dimension of Sustainability, either economic, environmental or social, while others are integrated methodologies, combining two or more dimensions.

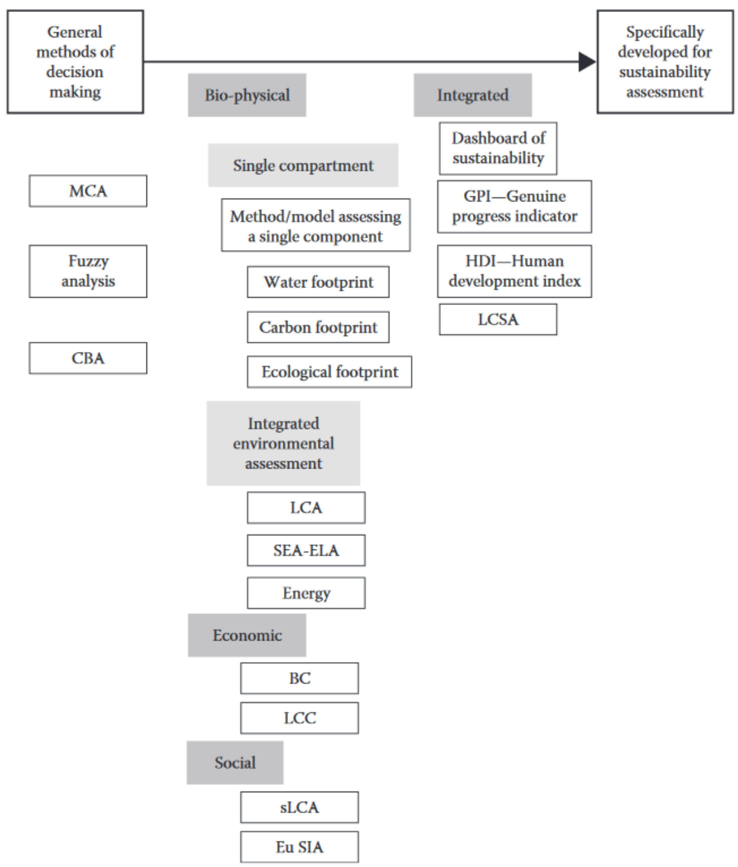


Figure 1: Overview of sustainability assessment methodologies [38]

Life Cycle Assessment belongs to the first group, assessing impacts from a lifecycle perspective but only in the environmental dimension. However, an integrated methodology combining Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Social-LCA has also been developed, under the name Life Cycle Sustainability Assessment (LCSA).

Institutional guidelines have also been published for LCSA by the UNEP/SETAC Life Cycle Initiative [39], however until today no standardization exists and there is no obligation to follow a specific methodology.

Another common integrated approach is to combine LCA with Multi-Criteria Decision Analysis (MCDA) in order to support decision making for results interpretation, but also in other phases of the assessment, i.e. to define impact categories during the LCIA phase. Zanghelini [40] provides a review on papers that have applied LCA and have used MCDA to interpret results, assessing one or more dimensions of sustainability. According to the results of this survey, depicted graphically in Figure 2, most papers (26) have assessed the three basic pillars of sustainability (environmental, social, economic), while 7 more have integrated as well the technical dimension.

Figure 2: Sustainability dimensions covered by studies combining LCA with MCDA for interpretation of results [40]

Sustainability assessment of rural electrification projects

As mentioned before, small-scale rural electrification has special characteristics and is depending on non-technical variables, much more than large-scale energy projects. Especially in remote areas, for achieving sustainability in such unfavourable environments, it is necessary to study the local context and to engage local community and stakeholders throughout the implementation of the project. More particularly, Yadoo [35] describes different "delivery models" that should be devised in order to address the variety of influential parameters and achieve sustainability in rural electrification projects.

A limited number of integrated sustainability assessments of rural electrification solutions have been found in literature and are presented in Table 2 below. It should be noted that as far as dimensions of sustainability are concerned, most of these studies cover at least four dimensions of sustainability and all of them take into account the social dimension.

In general, it seems that there is no universally accepted assessment framework or indicators and most of these studies actually propose a methodological framework and/or a set of indicators. This is probably due to the fact that rural contexts are very different when examined in a small-scale, so methods have to be customized each time based on the existing conditions and with the direct and continuous participation of local stakeholders.

Reference	Description	Context	Alternatives	Definition of criteria and weights	Criteria/Indicators	Evaluation of alternatives in criteria/indicators	Assessment method
Domenech et al. (2014) [2]	Selection among different RES technologies for electrification of rural communities in Peru	Rural communities, Peru	Wind microgrid, micro-hydro, PV micro-grid, individual PV	Group of experts	14 indicators in 2 dimensions: Social and Techno-economic	On a scale 1-10, assigned by group of experts	Weighted sum
Vaisanen et al. (2016) [41]	LCA and AHP were used to assess the sustainability of three distributed energy scenarios	Municipality of 220 inhabitants in Western Finland	3 scenarios: a) wind and hydro, b) hydro and solar, c) CHP and solar. Biogas used to cover shortages	Criteria: Hacatoglu et al. (2013). Weights: expert elicitation (AHP)	21 indicators in 5 dimensions: Environmental, Technical, Economic, Social, Institutional	Environmental: LCA (GaBi), Other criteria: literature	AHP
Bhandari R, Saptalena L. G., Kusch W. (2018) [42]	Sustainability assessment model for micro-hydro plants	Application for a 26kW plant in a remote, rural, mountainous region of Nepal	No comparison of alternatives	Literature review and Questionnaires to relevant stakeholders, Semi-structured interviews	54 assessment indicators in 4 dimensions: Economic, Social, Environmental, Technical	1-5 scoring system, scores assigned by evaluators based on field visit, interviews and questionnaires	A single overall score by a weighted aggregation of the dimensions
Lhendup (2008) [43]	Indicator-based assessment method to choose between distributed generation systems	Rural communities in Bhutan	Only methodology proposed - no application	Subjectively assigned by decision maker	Technical, Regulatory and Socio-environmental	Qualitative evaluation	Weighted sum

Lillo et al. (2015) [33]	Sustainability evaluation of energy and sanitation technologies in rural communities	Remote rural areas, application in Pucara community, in Peruvian Andes	Micro-hydro, PV, Biodigesters, Improved cookstoves, Tromble walls, Solar water heaters	Based on relative literature, with participation of community members	34 indicators in 5 dimensions: Technical, Economic, Social/ethical, Environmental, Organizational/Institutional	Scoring system. Scores assigned by evaluators and users based on data through multiple sources: transect walks, semi-structured interviews with stakeholders, specific surveys, observation, photographic evidence.	No ranking - Direct comparison of absolute values - Spider web diagrams used
Mainali B., Silveira S. (2015) [36]	Method for evaluating the sustainability performance of energy technologies applied in rural electrification, using Principal component analysis (PCA)	For illustration purposes, the case of India is used	Hydro, PV, wind, biogas, biomass gasification, and conventional fossil based, in different configurations (off-grid or mini-grid)	Literature review, adaptation for rural electrification, feedback from multi-disciplinary scholars	11 indicators in 5 dimensions: Technical, Economic, Social, Environmental, Institutional	Based on data found in literature	Normalization of data with PCA and Calculation of a single composite indicator: Energy Technology Sustainability Index (ETSI)
Kumar et al. (2018) [44]	Methodological framework combining decision analysis and optimization models for the design of a reliable/robust/economic microgrid system for rural communities in developing nations	Application on a rural microgrid for a remote community in the Himalayas, India	12 alternatives combining wind and/or PV in different configurations (off-grid or grid-tied)	Criteria: Based on available data, expert advice, available literature. Weights: Software based on decision analysis or MCDA	18 criteria in 4 dimensions: Technical, social, economic, environmental	Referring to help from experts and reports from governmental authorities	Selection of appropriate decision analysis method based on nature of problem and available data. Application: AHP

Table 2: Review of Sustainability assessment studies on Rural electrification

4. Methodology

To achieve the aforementioned objectives the following steps have been followed:

1. Selection and specification of the compared SWT alternatives and context under study
2. Selection of appropriate indicators to assess the sustainability of the alternatives
3. Extensive application of the Life Cycle Assessment methodology to assess the environmental impact of the alternatives
4. Calculation of the sustainability indicators for the alternatives, following a lifecycle approach
5. Integration of these indicators as criteria in Multi-Criteria Decision Analysis (MCDA)
6. Ranking of the alternatives from different stakeholder viewpoints
7. Performing sensitivity analysis where necessary
8. Reaching conclusions

Initially, the studied context and the alternative small wind turbine solutions were specified, based on available literature and feedback from experts on the field of rural electrification. Multi-disciplinary knowledge was used to define a set of sustainability indicators, covering environmental, social, economic, technical and institutional categories.

The methodology of attributional Life Cycle Assessment was implemented to assess environmental impacts, following the standards of ISO 14040 and ISO 14044 and using the SimaPro software. A lifecycle approach was then taken to estimate the social, economic, technical and institutional sustainability indicators, while the environmental indicators are already calculated through LCA.

Finally, the decision problem was set up in two variants related to the viewpoint of two groups of stakeholders: investors and policymakers. PROMETHEE method [45] was considered appropriate to use in order to rank alternatives and perform sensitivity analysis.

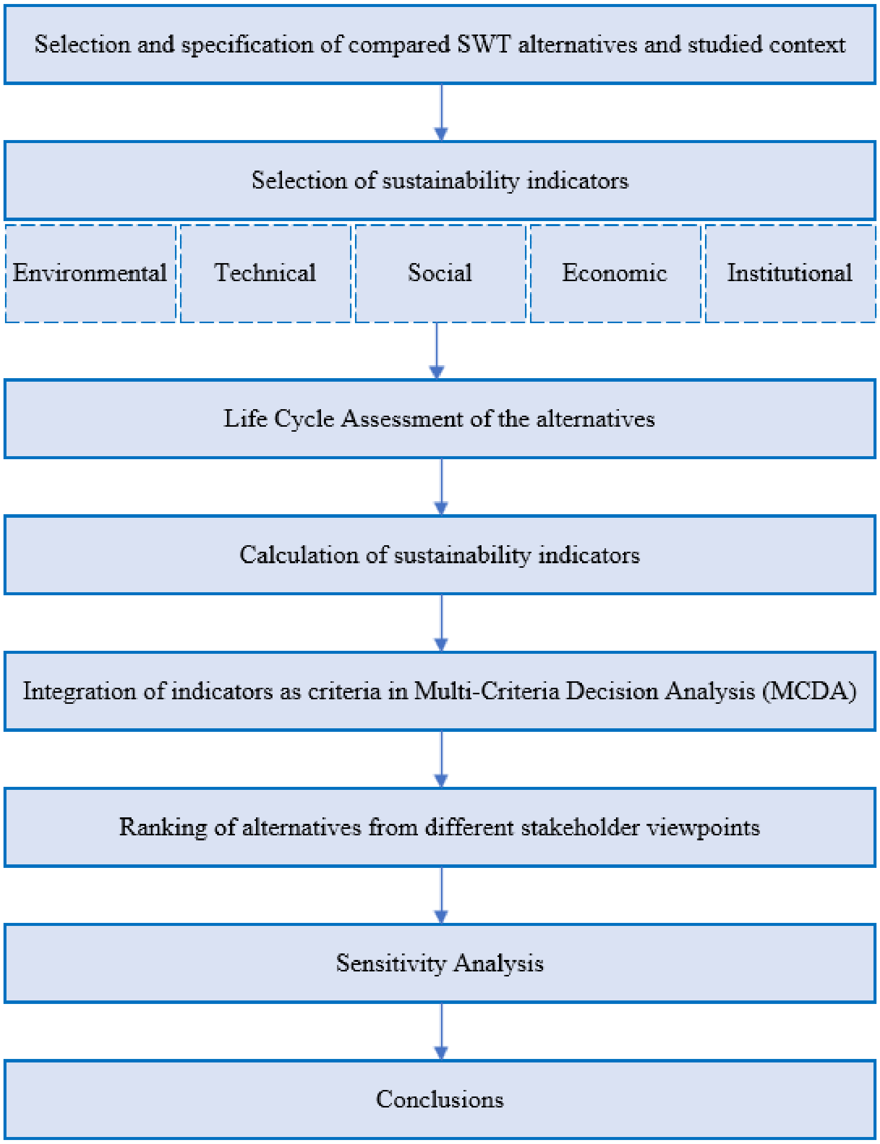


Figure 3: Description of the methodological framework

5. Specification of context and compared alternatives

5.1. Specification of context

In order to compare the lifecycle impacts of the wind turbine alternatives, the context in which they operate should be taken into account. For this assessment, it is assumed that the wind turbine is installed near a community building (i.e. school, health center or coffee shop) of a rural, off-grid community in a developing country [46], [10]. This has been a typical application in many rural electrification projects of the past decades [2], [3], [47], [48], and, as was explained in the introduction, this is a context where small-scale wind turbines have a potential to be sustainable.

The wind turbine will be used to cover a maximum load of 500 W, which comprises a small 50 l fridge, a laptop charger, multiple mobile phone chargers and 10-20 LED lights. Excess electricity will be stored in a battery bank and diverted to a dump load if batteries are fully charged.

Figure 4: LMSWT installed for rural school in Playa Blanca, Peru (Source: WindAid)

It is also necessary to define the wind resource in the assumed generic scenario. Of course, the wind resource will differ significantly from site to site, directly affecting the electricity generation of the wind turbine. However, within the conventions of this study it was assumed that the wind has an average annual value of 5 m/s and follows a Rayleigh distribution (Weibull distribution with the shape parameter k=2). For this specific wind resource, reliable measurements for the wind turbines' AEP were available [7], [49] and average wind speeds between 4-5 m/s are generally considered representative in rural contexts where small wind turbines have been used: high enough to justify the use of a small wind turbine and low enough to be found in many rural, residential areas.

Finally, it is assumed that technical support for the system can be found at a service center 100 km away from the community. We also performed a sensitivity analysis for this distance between the installation site and the service center, as this parameter is recorded to have significant influence in the turbine's lifecycle [46], [3]. Besides the base value of 100 km, values of 20 and 200 km were also assigned to the distance, to reflect the level of dispersion of settlements in the studied context.

5.2. Specification of compared alternatives

5.2.1. Specification of wind turbines

Two sizes of LMSWTs, with a 2.4 m and a 4.2 m rotor diameter respectively, which are manufactured according to Hugh Piggott's Recipe Book, have been compared with a machine from Bergey Windpower, a commercial manufacturer with reputation of high reliability. The specifications of the compared technologies are presented in Table 3.

		LM 2.4 m	**LM 4.2 m**	**Bergey XL.1**
General	Turbine topology	3-blade, Horizontal Axis Wind Turbine (HAWT)		
	Generator topology	Axial flux permanent magnet	Axial flux permanent magnet	Radial flux permanent magnet
	Rotor diameter (m)	2.4	4.2	2.5
	Rated power (kW)	0.525	2.5	1
	Annual yield at 5 m/s Rayleigh, at 12m tower (kWh)	1271 [7]	3432 [50]	1849 [49]
	Lifetime of moving parts (years)	15	15	20
	Lifetime of fixed parts (years)	30		
Materials	Blades	wooden	wooden	fiberglass
	Magnets	neodymium	neodymium	neodymium
	Tail	wooden	wooden	aluminium
	Nacelle	-	-	fiberglass

Table 3: Specifications of the compared wind turbines

(a) (b) (c)

Figure 5: The compared small wind turbines: a) LM 2.4m, b) LM 4.2m, c) Bergey XL.1

The components included in the assessment were the moving parts (blade rotor, generator, mounting frame, yaw system) and fixed parts (tower and foundation) of the wind turbines.

Each of the three turbines is assumed to be mounted on a 12 m, guyed tubular steel tower and to have a foundation of concrete and reinforcing steel. However, the 4.2 m turbine, due to its larger size, is assumed to use tubes of larger cross-section in the tower and bigger amounts of concrete and steel in the foundation.

In a typical rural application, the small wind turbine would be combined with PV, to form a hybrid system, and would be connected with the necessary electric components, power electronics and batteries [7]. In this study, these components are not considered further in the assessment, due to limited time and resources, but also because they are assumed to be similar for the three wind turbines, thus not adding value to the comparison. If these wind turbines were to be compared with another type or scale of energy source, then it would be more interesting to also include the electric and electronic components in the comparison.

5.2.2. Specification of delivery models

Another aspect to consider when comparing the lifecycle of the alternative wind turbines is the business model or "delivery model" with which they are applied. In the energy access terminology, "delivery models" are defined as strategies used to overcome barriers and achieve sustainability and scale-up of rural electrification projects [35]. For the LMSWTs, a range of delivery models have been applied in past projects to employ the technology in a particular context [48]. These delivery models address a series of important parameters in the wind turbine lifecycle, such us the the Ownership and Management model, the Maintenance strategy and the Finances. Especially the adopted maintenance strategy has been reported to have a critical impact on the viability of LMSWTs [46].

In this study, three delivery models (DM1-DM3) were examined for local manufacture and a conventional delivery model (DM-C) for the commercial turbine. DM1-DM3 assume that the wind turbines are manufactured at a regional workshop, 100 km from the community, with materials supplied from the closest major city, 200 km from the workshop. On the contrary, the commercial turbine is imported from the manufacturer's country (US) and shipped overseas. All turbines are assumed to be installed by local technicians.

The three delivery models for local manufacture differ mainly concerning their assumed maintenance strategy and particularly in the level of engagement of the end users to do part of the maintenance themselves. They vary from the fully-participative model DM1 where users (or community members) are trained to perform both preventive and corrective maintenance themselves to the non-participative DM3 where all maintenance is carried out at the regional service center. These models represent typical maintenance strategies recorded in case studies [3]. Finally, for the commercial SWT, a conventional model with a non-participative maintenance strategy is assumed.

The four delivery models and their consequence on maintenance parameters are further described in Table 4.

Delivery Model (DM)	Failures in lifetime	Maintenance trips in lifetime	Downtime[3] (days)
DM-1: Community empowerment One or two people from the community are trained and are capable of doing frequent condition monitoring and annual preventive maintenance. This way failures are minimized. In most cases, these people are also capable of doing corrective maintenance. A local stock of spare parts is available. This way, downtime is minimized to 4 days. If extra spare parts or specialized technical support is needed, these are sourced from the closest service center.	15	5	4
DM-2: Partial empowerment with external support Members of the community are trained to lower the turbine and do the annual preventive maintenance. This way failures are minimized. There is a stock of spare parts in the service center. In case of failure, the community contacts a technician to come from the closest service center. If the technician cannot fix the failure on site (e.g. the root cause was not identified correctly by the community or the defective part can be repaired but needs machinery that is not locally available), the turbine is transferred to the service center, fixed and then transferred again to the site.	15	15	15
DM-3: External support No specific training is provided and the community does not have the skills and tools to lower the turbine. Preventive as well as corrective maintenance is done by the closest service center. This results in more (and more serious) failures occurring because the users cannot lower the turbine in case they notice something abnormal. In case of failure, the community contacts a technician to come from the closest service center. Most of the times the failure cannot be fixed on site. The turbine has to be transferred to the service center to be repaired, then transferred back to the community in another trip and lifted to the tower by the technician. This way downtime is significantly increased and km are doubled.	20	40	30
DM-C: External support and imported materials No specific training is provided and the community does not have the skills and tools to lower the turbine. Preventive as well as corrective maintenance is done by the closest service center. In case of failure, the turbine has to be transferred to the service center, wait for the spare parts to be shipped from the manufacturer (US), repaired, transferred back to the community and lifted to the tower by the technician. This way downtime is significantly increased and km are doubled.	10	20	45

Table 4: Description of the examined delivery models (DM) and their consequence on maintenance parameters

[3] The average time needed for the system to come back to operation after a failure.

Table 5 then presents the subsequent calculation of the total kilometres covered for maintenance per delivery model and per value of the distance parameter, according to the following equation:

$$Total\ Maintenance\ km = (Total\ Maintenance\ trips \times Distance\ from\ service\ center \times 2$$

In the above equation, distance from service center is multiplied by two, to indicate that a return trip is needed for each maintenance trip.

Distance from service center (km)		**20**	**100**	**200**
Delivery Model	Number of maintenance trips in lifetime	Total maintenance km	Total maintenance km	Total maintenance km
DM1	5	200	1000	2000
DM2	20	800	4000	8000
DM3	40	1600	8000	16000
DM-C	20	800	4000	8000

Table 5: Maintenance parameters calculated for the examined delivery models and distance assumptions

5.2.3. Final alternatives

The two LMSWTs combined with the three delivery models shape six alternative solutions, while the commercial turbine with the conventional delivery model forms the seventh alternative of our comparison.

The seven alternatives, presented in Table 6, will be comparatively assessed in the following chapters, first for their lifecycle environmental impacts, and then for a variety of other sustainability indicators.

#	ALTERNATIVES
1	LM 2.4m, DM-1
2	LM 2.4m, DM-2
3	LM 2.4m, DM-3
4	LM 4.2m, DM-1
5	LM 4.2m, DM-2
6	LM 4.2m, DM-3
7	Commercial, DM-C

Table 6: The seven small wind turbine alternatives

6. Selection of sustainability indicators

In order to assess the sustainability of the alternatives, a set of indicators were selected taking the following aspects into account:

- Coherence with sustainability assessment frameworks in literature
- Relevance of indicators to the goal and scope of the assessment
- Indicators' sufficiency to highlight aspects that are different between the alternatives
- Availability of reliable data and calculation methods for the selected indicators
- Sufficiency of addressing different aspects of sustainability from different viewpoints

With the above considerations in mind and by acquiring feedback from a multi-disciplinary group of experts, a set of ten sustainability indicators was defined, addressing the following aspects of sustainability: Environmental, Technical, Economic, Social and Institutional. These indicators are presented in Table 7.

Category	**Sustainability issue**	**Indicator**	**Unit**
Environmental	Climate Change	1. Global Warming Potential	gCO_{2eq}/kWh
	Energy Demand	2. Non-renewable primary energy	MJ/kWh
	Abiotic resource depletion	3. Metal depletion	gFe_{eq}/kWh
Technical	Operability	4. Availability factor	%
Economic	Investment cost	5. Initial investment	€
	Operating cost	6. Annual O&M costs	€/year
	Levelized cost of generation	7. LGC	€/kWh
Social	Provision of local employment	8. National to total expenses rate	%
	Support of national economy	9. Local to national labour rate	%
Institutional	Institutional requirements	10. Institutional burden	Qualitative

Table 7: List of the indicators used for assessing the sustainability of small wind turbine alternatives

7. Life Cycle Assessment

This chapter details the implementation of attributional Life Cycle Assessment methodology to assess the environmental impacts of the seven small wind turbine alternatives. SimaPro software was used and the LCA framework described in ISO 14040 [29] and ISO 14044 [51] was followed, which comprises four phases: Goal and Scope definition, Life Cycle Inventory, Life Cycle Impact Assessment and Interpretation of results.

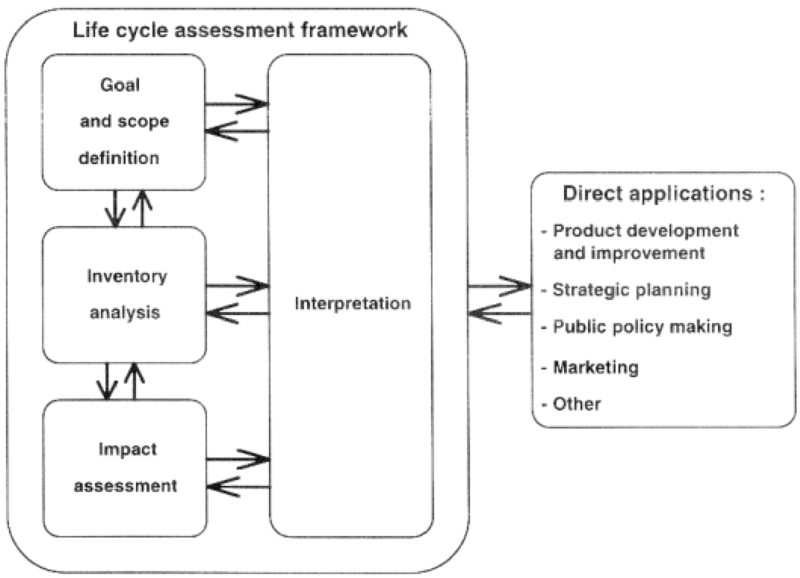


Figure 6: Phases in a Life Cycle Assessment [29]

7.1. Goal and Scope

The goal of this Life Cycle Assessment is to comparatively assess the environmental impacts of the seven small wind turbine alternatives, specified in Chapter 5, from cradle-to-grave.

Functional Unit

The function of the product under study (small wind turbine) is the provision of electricity, thus the functional unit is chosen to be "1 kWh of electricity generated at the generator's output before being distributed for consumption" within the scope described in chapter 5.

System Boundaries

The components included in the assessment were the moving parts (blade rotor, generator, mounting frame, yaw system) and fixed parts (tower and foundation) of the wind turbines. Excluded components were the power electronics, the battery bank and the cables, as they were considered to be invariable when comparing locally manufactured and commercial small wind turbines.

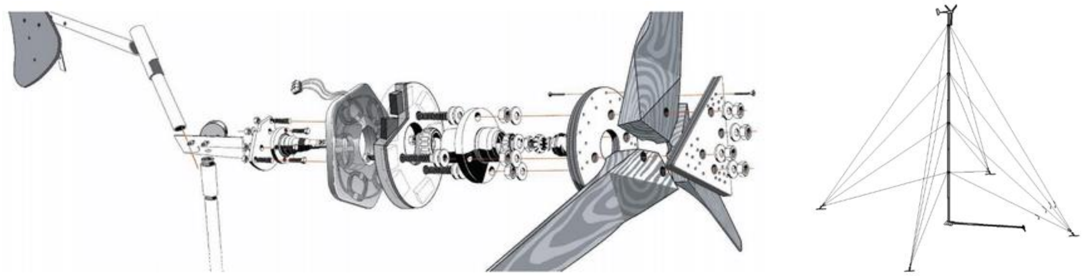


Figure 7: Breakdown of a LMSWT's moving parts (left). A guyed tubular wind turbine tower (right).

The wind turbine lifecycle stages included within the system boundaries were the Manufacturing, Installation, Operation & Maintenance, End-of-Life and Transportation between these stages in the foreground; and the upstream processes of Materials, Fuel and Energy Acquisition in the background. A stage that was not included was the R&D phase, since it consists mainly of labour and use of ICT, which were considered to be low in energy consumption. The system boundary is summarized in Figure 8.

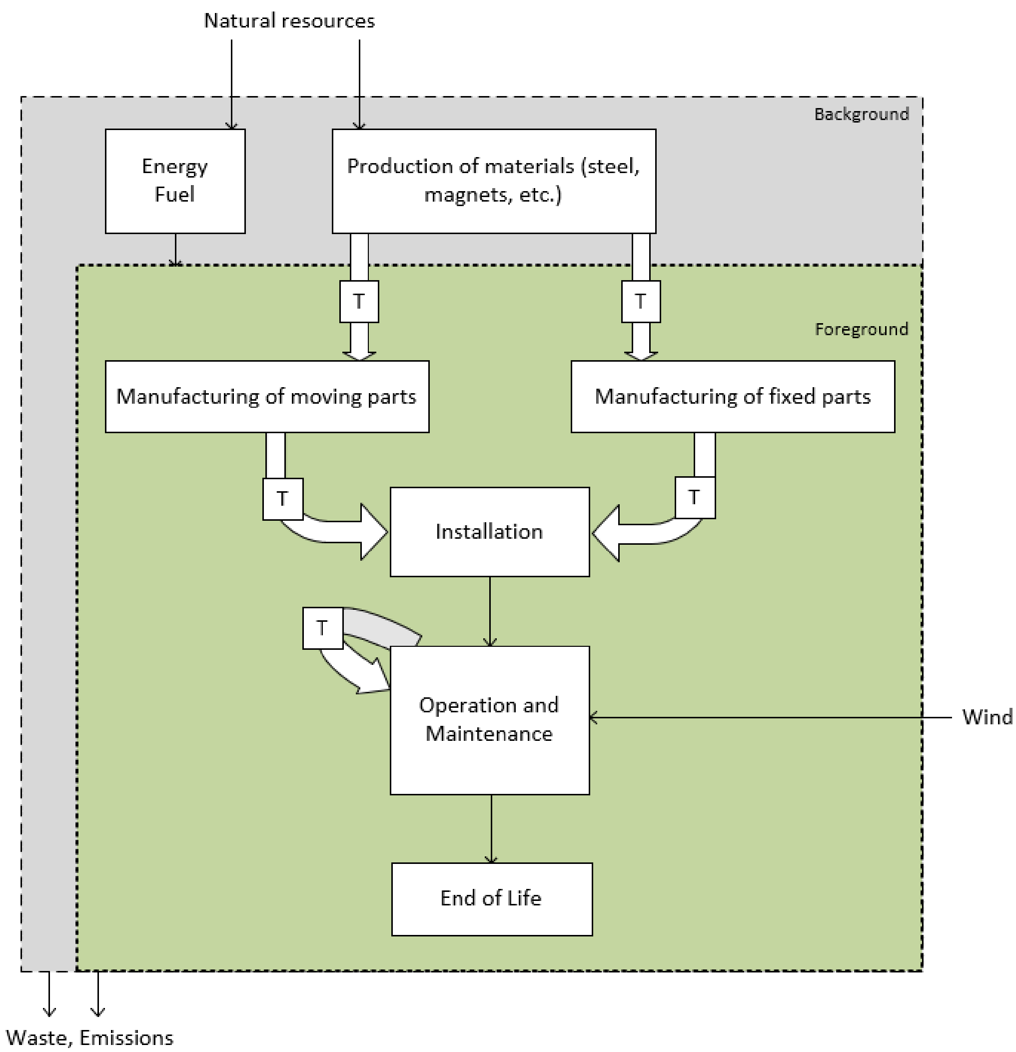


Figure 8: Flowchart of the foreground and background processes considered for the small wind turbine lifecycle

To emphasize the differences between the lifecycle of locally manufactured and imported (commercial) wind turbines, Figures 9 and 10 depict in yellow colour the stages that occur within the country of installation; for LM and imported wind turbines respectively.

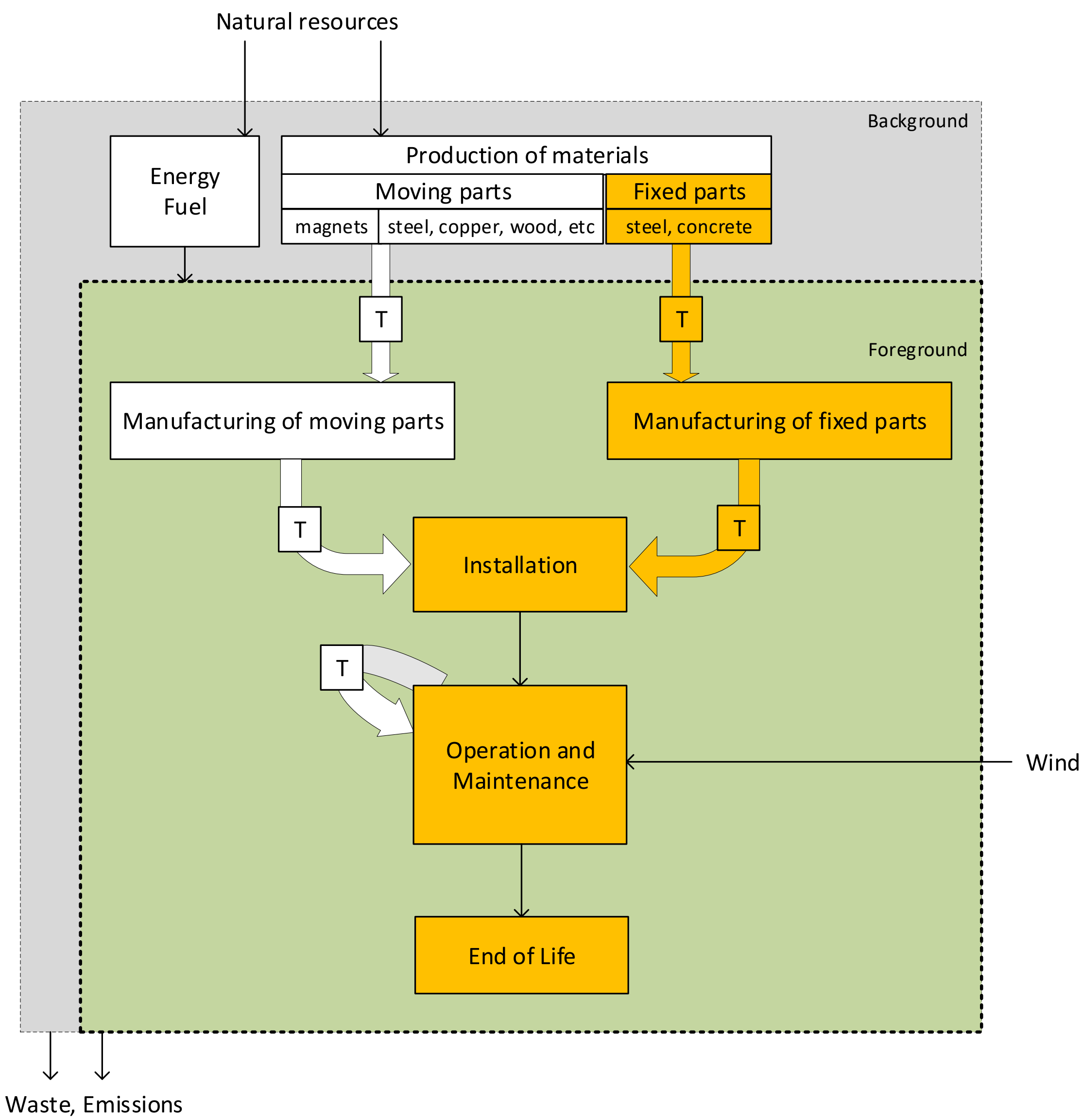


Figure 9: Lifecycle stages of a commercial SWT, taking place within the country of installation (depicted in yellow)

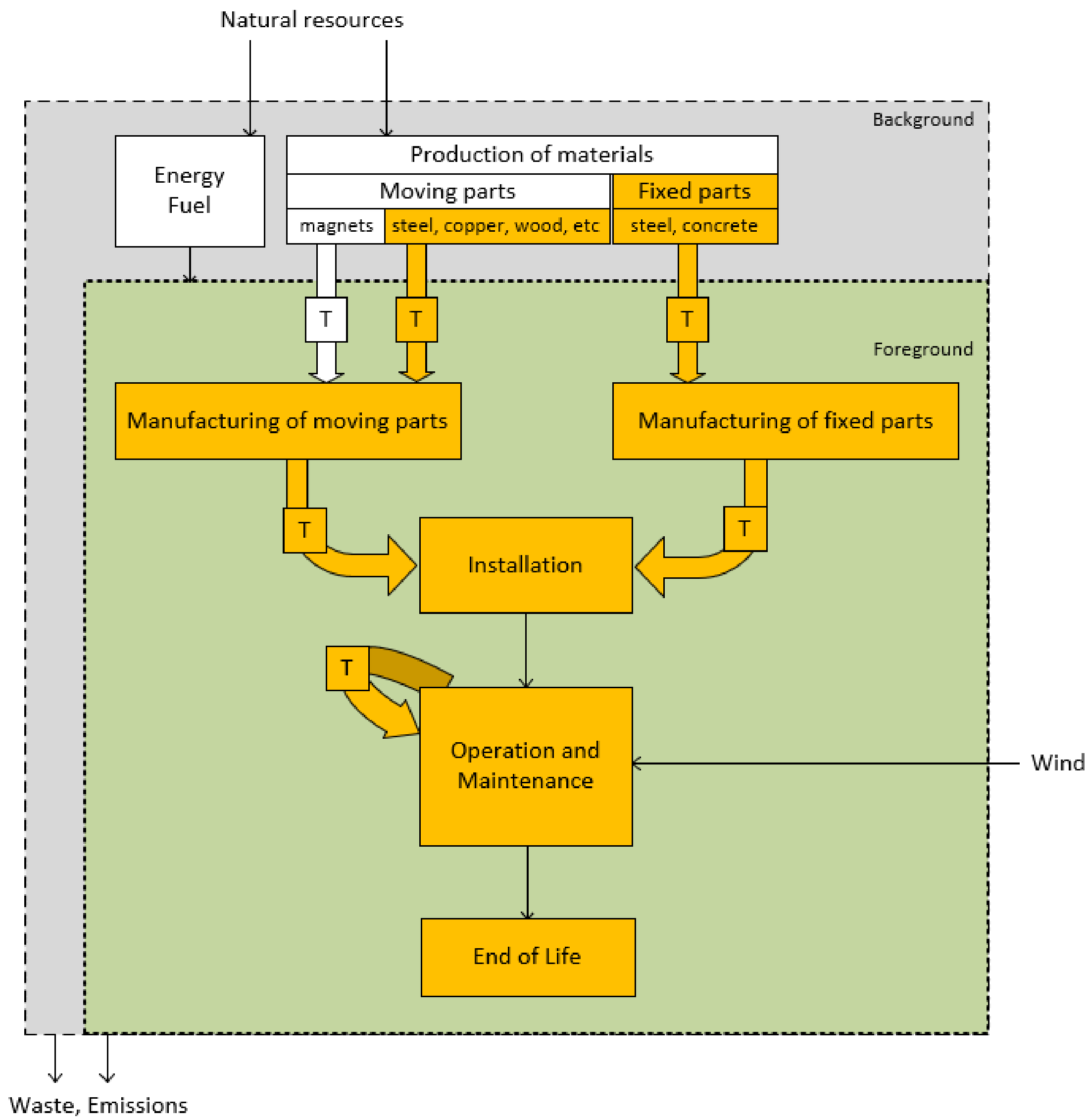


Figure 10: Lifecycle stages of a LMSWT, taking place within the country of installation (depicted in yellow)

7.2. Lifecycle Inventory

Inventory data for the materials and energy consumed for the 2.4 m turbine were acquired from LMSWT practitioners through the Wind Empowerment association [52]. For the 4.2 m turbine, these data were scaled up by a factor $S = \frac{4.2}{2.4}$.

Inventory data for the Bergey XL.1 could not be acquired from the manufacturer. Instead, the inventory of a commercial 5 kW horizontal axis wind turbine [24] was scaled down to 1 kW based on the 'economies of scale' method [23]. This inventory did not include permanent magnets and it is supposed that -as in other LCA studies- the permanent magnet impact was represented by increasing the amount of copper and aluminium in the inventory.

All data for upstream processes have been sourced from the Ecoinvent database, except for the production of neodymium magnets, for which a new process was created according to the inventory published by Sprecher [53].

The inventories for the lifecycle of the three wind turbines, which were put together and entered in the SimaPro software, are presented in detail in Tables 8, 9 and 10.

Input	Quantity for LM-2.4m	Quantity for LM-4.2m	Unit
Moving parts			
Plywood	0.0433490568	0.0758608494	m3
Planed pine wood	0.01845	0.0322875	m3
Vinyl ester resin	3	5.25	kg
Talcum powder	3	5.25	kg
Fiberglass	0.3	0.525	kg
Sheet rolling (chromium steel)	4.717	8.25475	kg
Section bar rolling (steel)	23.07	40.3725	kg
Neodymium magnets	2.4	4.2	kg
Epoxy metal glue or super glue	0.03	0.0525	kg
Copper	3	5.25	kg
Wire drawing	3	5.25	kg
Stainless steel	4.717	8.25475	kg
Cast iron	23.07	40.3725	kg
Galvanization of cast iron	1.39496	2.44118	m2
Electricity	1.775	3.10625	kWh
Transport, lorry > 28t	10.2	17.85	tkm
Transport, rail	15.4	26.95	tkm
Transport, aircraft	14.4	25.2	tkm
Transport, passenger car	600	1050	pkm
Disposal, Wood, Incinerated	39.93	69.8775	kg
Disposal, Glass, Incinerated	0.3	0.525	kg
Fixed parts			
Cast iron	93.85	164.2375	kg
Reinforcing steel	91.84	160.72	kg
Drawing of pipes	82.15	143.7625	kg
Section bar rolling (steel)	13.17	23.0475	kg
Galvanization of cast iron	5.09	8.9075	m2
Welding	5	8.75	m
Concrete	1.7	2.975	m3

Electricity	1.7	2.975	kWh
Transport, lorry > 16t	1260	2205	tkm
O&M – DM1			
Lubricating oil	3	3	kg
Paint	5	5	kg
Transportation by car (20 km)	200	200	pkm
Transportation by car (100 km)	1000	1000	pkm
Transportation by car (200 km)	2000	2000	pkm
O&M – DM2			
Lubricating oil	3	3	kg
Paint	5	5	kg
Transportation by car (20 km)	800	800	pkm
Transportation by car (100 km)	4000	4000	pkm
Transportation by car (200 km)	8000	8000	pkm
O&M – DM3			
Lubricating oil	3	3	kg
Paint	5	5	kg
Transportation by car (20 km)	1600	1600	pkm
Transportation by car (100 km)	8000	8000	pkm
Transportation by car (200 km)	16000	16000	pkm

Table 8: Inventories of the LM-2.4m and LM-4.2m small wind turbines

Process	Tool	Running wattage (kW)	Time of use (h)	Electricity consumption (kWh)
Wind turbine manufacturing	Jigsaw	0.5	0.1	0.05
	Electric sander	0.5	0.1	0.05
	Electric hand drill	0.5	0.1	0.05
	Rechargeable hand drill	0.5	0.1	0.05
	Drill press	0.5	0.25	0.125
	Angle grinder	0.7	0.5	0.35
	Chop saw	0.7	0.5	0.35
	Electric soldering iron	0.1	2	0.2
	Electric welding machine	3	0.25	0.75
	Total for wind turbine manufacturing (kWh)			1.775

Tower and anchor manufacturing	Electric welding machine	3	0.25	0.75
	Drill press	0.5	0.5	0.25
	Angle grinder	0.7	0.5	0.35
	Chop saw	0.7	0.5	0.35
	Total for tower and anchor manufacturing (kWh)			1.7

Table 9: Breakdown of the electricity consumption for the manufacturing of the 2.4m LMSWT

Input	Quantity for Commercial SWT	Unit
Moving parts		
Copper	11.23155824	kg
Wire drawing	11.23155824	kg
Glass fibre	6.853154179	kg
Epoxy resin	3.807307877	kg
Polyester resin	0.7614615755	kg
Aluminium	3.42657709	kg
Sheet rolling, aluminium	3.42657709	kg
Steel	54.06377186	kg
Section bar rolling, steel	54.06377186	kg
Zinc coating	2	m2
Electricity	74.6232344	kWh
Transport to factory, rail	16	tkm
Transport to factory, lorry	8	tkm
Transport to factory, transoceanic ship	28.8	tkm
Transport to site, transoceanic ship	960	tkm
Transport to site, car	600	pkm
Fixed parts		
Assumed to be the same as for the locally manufactured 2.4 m wind turbine		
O&M		
Lubricating oil	3	kg
Transportation by car (20 km)	800	pkm
Transportation by car (100 km)	4000	pkm
Transportation by car (200 km)	8000	pkm

Table 10: Inventory of the commercial small wind turbine

Table 11 presents the assumptions made for distances and transport modes for the manufacturing of the commercial and the locally manufactured wind turbines.

	LMSWTs	Commercial SWT
Manufacturing location	local workshop	Norman, Oklahoma, US
Materials[4] for moving parts to manufacturing location	rail, 200 km lorry, 100 km passenger car, 200 km	rail, 200 km lorry, 100 km
Magnets to manufacturing location	aircraft, 6000 km	
Materials for fixed parts to site	lorry, 300 km	
Wind turbine to site	passenger car, 100 km	Transoceanic ship, 12000 km[5]

Table 11: Summary of transport modes and distances in the foreground stages

Finally, data for the electricity production of each wind turbine was taken from the following sources:

- For the commercial wind turbine, it was calculated on a technical spreadsheet provided by the manufacturer [49], at 12 m height, for mean wind speed 5 m/s and for a Rayleigh wind distribution.
- For the 2.4 m LMSWT, a study by Latoufis et al. [7] provided measurements for the specific wind turbine at 12 m height, at various wind speeds (5 m/s was selected) and for a Rayleigh wind distribution. In this study, outdoor measurements of the wind turbine's power curve had been conducted according to the standard of the International Electrotechnical Commission 61400-12-1, and its AEP had then been predicted for different mean wind speeds.
- For the 4.2 m LMSWT, data was taken from the estimated monthly energy production at different wind speeds (5 m/s was selected) in Hugh Piggott's Recipe Book [50].

With the above limitations considered, Table 12 shows the lifetime electricity production for each wind turbine and for each delivery model. It can be observed that more participative delivery models yield higher lifetime electricity production, since they allow failures to be fixed faster (less downtime).

Lifetime Electricity Production (kWh)				
Alternatives	**DM1**	**DM2**	**DM3**	**DM-C**
LM 2.4 m	18853.84	18279.35	16973.68	-
LM 4.2 m	50915.84	49364.38	45838.36	-
Commercial	-	-	-	34685

Table 12: Lifetime electricity production for the small wind turbine alternatives

[4] Except magnets, which are assumed to be shipped from China.
[5] Assumed to be shipped from US

7.3. Lifecycle Impact Assessment (LCIA)

When carrying out a Life Cycle Assessment, environmental impact can be assessed with regard to various impact categories. For our specific application, the following four impact categories have been assessed: Global warming, Non-renewable primary fossil energy, Metal depletion and Fossil depletion.

The selection was based on the fact that these impact categories were considered as the most relevant to the small wind lifecycle, the most widely used in similar studies and at the same time sufficiently covered by available LCIA methods. The units for the four impact categories and the methods used to assess them are presented in Table 13.

Impact Category	Unit	Assessment Method
Non-Renewable Primary Energy	MJ_{prim}/kWh	CED V1.09 [54]
Global Warming Potential	g CO_{2eq}/kWh	ReCiPe (Midpoint) (H) V1.11/EU [55]
Metal Depletion	g Fe_{eq}/kWh	ReCiPe (Midpoint) (H) V1.11/EU [55]
Fossil Fuel Depletion	g Oil_{eq}/kWh	ReCiPe (Midpoint) (H) V1.11/EU [55]

Table 13: Selected impact categories, units and assessment methods

The tables in the following sessions present the estimated lifecycle environmental impacts of the seven small wind turbine alternatives, calculated per kWh of generated electricity.

Disaggregation of results has been carried out to identify the specific contributions of the following lifecycle components towards each impact category: ‘Moving parts’, Fixed parts’ and ‘Maintenance’. ‘Moving parts’ comprise the Manufacturing, Installation, Transportation and Disposal of components related to the moving parts of the wind turbine. Similarly, ‘Fixed parts’ comprise the same stages for components related to the fixed parts of the wind turbine. ‘Maintenance’ comprises the maintenance stage of the wind turbines, including transportation for maintenance.

Environmental impacts were calculated for three assumed values of distance from service center: 20, 100 or 200 km. This distance affects the results only as far as Transportation for Maintenance is concerned. In each session, the first table presents impacts calculated for 100 km distance from service center. Then, the second table provides the result of Transportation for Maintenance for all the three assumed distance values.

7.3.1. Non-renewable Primary Energy

Impact Category		Non-renewable primary energy (MJ_{prim}/kWh)						
Life Cycle components		2.4m, DM1	2.4m, DM2	2.4m, DM3	4.2m, DM1	4.2m, DM2	4.2m, DM3	Commercial
Fixed parts	Concrete	0.0487	0.0502	0.0540	0.0315	0.0325	0.0350	0.0353
	Steel	0.1031	0.1064	0.1145	0.0668	0.0689	0.0742	0.0747
	Other	0.0193	0.0199	0.0214	0.0125	0.0129	0.0139	0.0140
	Transportation	0.0705	0.0727	0.0783	0.0457	0.0471	0.0507	0.0511
	Fixed parts	0,2415	0,2491	0,2683	0,1565	0,1614	0,1739	0,1751
Moving Parts	Wood	0.0331	0.0342	0.0368	0.0215	0.0222	0.0239	0.0000
	Copper	0.0048	0.0049	0.0053	0.0031	0.0032	0.0034	0.0097
	Aluminium	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0134
	Magnets	0.0471	0.0486	0.0523	0.0302	0.0311	0.0335	0.0000
	Steel	0.0344	0.0355	0.0382	0.0223	0.0230	0.0248	0.0437
	Stainless steel	0.0159	0.0164	0.0177	0.0103	0.0106	0.0114	0.0000
	Other	0.0205	0.0212	0.0228	0.0133	0.0137	0.0148	0.0367
	Transportation	0.0855	0.0882	0.0950	0.0556	0.0573	0.0618	0.0574
	Moving parts	0,2414	0,2489	0,2681	0,1563	0,1612	0,1736	0,1609
Maintenance	Lubricating oil	0.0123	0.0127	0.0136	0.0045	0.0047	0.0050	0.0067
	Paint	0.0190	0.0196	0.0211	0.0070	0.0072	0.0078	0.0000
	Transportation	0.1533	0.4743	1.3620	0.0568	0.1756	0.5043	0.3333
	Maintenance	0,1845	0,5065	1,3967	0,0683	0,1875	0,5172	0,3399
Total		**0,6674**	**1,0046**	**1,9331**	**0,3811**	**0,5102**	**0,8646**	**0,6758**

Table 14: Non-renewable Primary Energy impacts of different components in the wind turbines' lifecycle. Maintenance transportation impacts are calculated here for 100 km distance

Non-renewable primary energy (MJ_{prim}/kWh) impacts of Maintenance Transportation							
Distance from service center	2.4m, DM1	2.4m, DM2	2.4m, DM3	4.2m, DM1	4.2m, DM2	4.2m, DM3	Commercial
20 km	0,0307	0,0949	0,2724	0,0114	0,0351	0,1009	0,0667
100 km	0,1533	0,4743	1,3620	0,0568	0,1756	0,5043	0,3333
200 km	0,3378	0,9807	2,0777	0,1251	0,3632	1,0215	0,6732

Table 15: Non-renewable Primary Energy impact of Maintenance Transportation for different distance values

7.3.2. Global Warming

Impact Category		Global Warming (gCO2eq/kWh)						
Life Cycle components		2.4m, DM1	2.4m, DM2	2.4m, DM3	4.2m, DM1	4.2m, DM2	4.2m, DM3	Commercial
Fixed parts	Concrete	11,7778	12,1479	13,0824	7,6322	7,8720	8,4775	8,5361
	Steel	7,2032	7,4296	8,0011	4,6678	4,8145	5,1848	5,2207
	Other	1,8946	1,9542	2,1045	1,2277	1,2663	1,3637	1,3732
	Transportation	4,4482	4,5880	4,9409	2,8825	2,9731	3,2018	3,2239
	Fixed parts	25,3238	26,1197	28,1289	16,4102	16,9259	18,2279	18,3539
Moving Parts	Wood	2,1330	2,2000	2,3693	1,3822	1,4257	1,5353	0,0000
	Copper	0,3762	0,3881	0,4179	0,2438	0,2515	0,2708	0,7655
	Aluminium	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	1,2694
	Magnets	3,6703	3,7857	4,0769	2,3564	2,4305	2,6175	0,0000
	Steel	2,5096	2,5885	2,7876	1,6263	1,6774	1,8064	3,3450
	Stainless steel	1,2654	1,3052	1,4056	0,8200	0,8458	0,9109	0,0000
	Other	1,1682	1,2049	1,2976	0,7570	0,7808	0,8409	2,5600
	Transportation	5,8483	6,0321	6,4961	3,8003	3,9198	4,2213	3,9340
	Moving parts	16,9711	17,5045	18,8510	10,9861	11,3314	12,2030	11,8739
Maintenance	Lubricating oil	0,6208	0,6403	0,6895	0,2299	0,2371	0,2553	0,3374
	Paint	0,7590	0,7829	0,8431	0,2811	0,2899	0,3122	0,0000
	Transportation	10,3105	31,9036	91,6205	3,8179	11,8137	33,9265	22,4180
	Maintenance	11,6903	33,3267	93,1531	4,3288	12,3407	34,4941	22,7554
Total		**53,9851**	**76,9509**	**140,1330**	**31,7251**	**40,5980**	**64,9249**	**52,9832**

Table 16: Global Warming impacts of different components in the wind turbines' lifecycle. Maintenance transportation impacts are calculated here for 100 km distance

Global Warming (gCO2eq/kWh) impacts of Maintenance Transportation							
Distance from service center	2.4m, DM1	2.4m, DM2	2.4m, DM3	4.2m, DM1	4.2m, DM2	4.2m, DM3	Commercial
20 km	2,0621	6,3807	18,3241	0,7636	2,3627	6,7853	4,4836
100 km	10,3105	31,9036	91,6205	3,8179	11,8137	33,9265	22,4180
200 km	20,6210	63,8071	137,4307	7,6358	23,6274	67,8531	44,8360

Table 17: Global Warming impact of Maintenance Transportation for different distance values

7.3.3. Metal Depletion

Impact Category		Metal depletion (gFe eq/kWh)						
Life Cycle components		2.4m, DM1	2.4m, DM2	2.4m, DM3	4.2m, DM1	4.2m, DM2	4.2m, DM3	Commercial
Fixed parts	Concrete	0,1102	0,1137	0,1224	0,0714	0,0737	0,0793	0,0799
	Steel	0,2598	0,2680	0,2886	0,1684	0,1737	0,1870	0,1883
	Other	0,0484	0,0499	0,0538	0,0314	0,0324	0,0349	0,0351
	Transportation	0,0595	0,0613	0,0661	0,0385	0,0398	0,0428	0,0431
	Fixed parts	0,4780	0,4930	0,5309	0,3097	0,3195	0,3440	0,3464
Moving Parts	Wood	0,0593	0,0612	0,0659	0,0385	0,0397	0,0427	0,0000
	Copper	5,3173	5,4845	5,9063	3,4457	3,5540	3,8274	10,8196
	Aluminium	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0319
	Magnets	0,2304	0,2377	0,2560	0,1493	0,1540	0,1658	0,0000
	Steel	0,0264	0,0273	0,0294	0,0171	0,0177	0,0190	1,0594
	Stainless steel	1,8548	1,9130	2,0602	1,2019	1,2397	1,3350	0,0000
	Other	0,0026	0,0027	0,0029	0,0017	0,0018	0,0019	0,0171
	Transportation	0,1370	0,1413	0,1521	0,0889	0,0917	0,0988	0,0760
	Moving parts	7,6279	7,8677	8,4729	4,9431	5,0985	5,4906	12,0041
Maintenance	Lubricating oil	0,0067	0,0069	0,0075	0,0025	0,0026	0,0028	0,0037
	Paint	0,0303	0,0312	0,0336	0,0112	0,0116	0,0124	0,0000
	Transportation	0,2272	0,7030	2,0188	0,0841	0,2603	0,7476	0,4940
	Maintenance	0,2642	0,7411	2,0599	0,0978	0,2744	0,7628	0,4976
Total		**8,3700**	**9,1018**	**11,0637**	**5,3507**	**5,6924**	**6,5974**	**12,8481**

Table 18: Metal Depletion impacts of different components in the wind turbines' lifecycle. Maintenance transportation impacts are calculated here for 100 km distance

Metal depletion (gFe eq/kWh) impacts of Maintenance Transportation							
Distance from service center	2.4m, DM1	2.4m, DM2	2.4m, DM3	4.2m, DM1	4.2m, DM2	4.2m, DM3	Commercial
20 km	0,0454	0,1406	0,4038	0,0168	0,0521	0,1495	0,0988
100 km	0,2272	0,7030	2,0188	0,0841	0,2603	0,7476	0,4940
200 km	0,4544	1,4060	3,0282	0,1683	0,5206	1,4951	0,9879

Table 19: Metal Depletion impact of Maintenance Transportation for different distance values

7.3.4. Fossil Depletion

Impact Category		Fossil depletion (gOil eq/kWh)						
Life Cycle components		2.4m, DM1	2.4m, DM2	2.4m, DM3	4.2m, DM1	4.2m, DM2	4.2m, DM3	Commercial
Fixed parts	Concrete	0,0101	0,0105	0,0113	0,0066	0,0068	0,0073	0,0074
	Steel	0,0293	0,0303	0,0326	0,0190	0,0196	0,0211	0,0213
	Other	0,0025	0,0026	0,0028	0,0016	0,0017	0,0018	0,0018
	Transportation	0,0014	0,0015	0,0016	0,0009	0,0009	0,0010	0,0010
	Fixed parts	0,0434	0,0447	0,0482	0,0281	0,0290	0,0312	0,0314
Moving Parts	Wood	0,0013	0,0014	0,0015	0,0009	0,0009	0,0009	0,0000
	Copper	0,0004	0,0004	0,0005	0,0003	0,0003	0,0003	0,0009
	Aluminium	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0018
	Magnets	0,0058	0,0059	0,0064	0,0037	0,0038	0,0041	0,0000
	Steel	0,0088	0,0091	0,0098	0,0057	0,0059	0,0063	0,0103
	Stainless steel	0,0031	0,0032	0,0034	0,0020	0,0020	0,0022	0,0000
	Other	0,0001	0,0001	0,0001	0,0001	0,0001	0,0001	0,0023
	Transportation	0,0020	0,0021	0,0022	0,0013	0,0013	0,0014	0,0012
	Moving parts	0,0215	0,0221	0,0238	0,0139	0,0144	0,0155	0,0165
Maintenance	Lubricating oil	0,0001	0,0001	0,0001	0,0000	0,0000	0,0000	0,0001
	Paint	0,0004	0,0005	0,0005	0,0002	0,0002	0,0002	0,0000
	Transportation	0,0033	0,0101	0,0291	0,0012	0,0038	0,0108	0,0071
	Maintenance	0,0038	0,0107	0,0297	0,0014	0,0040	0,0110	0,0072
Total		**0,0687**	**0,0776**	**0,1018**	**0,0434**	**0,0473**	**0,0577**	**0,0551**

Table 20: Fossil Depletion impacts of different components in the wind turbines' lifecycle. Maintenance transportation impacts are calculated here for 100 km distance

Fossil depletion (gOil eq/kWh) impacts of Maintenance Transportation							
Distance from service center	2.4m, DM1	2.4m, DM2	2.4m, DM3	4.2m, DM1	4.2m, DM2	4.2m, DM3	Commercial
20 km	0,0007	0,0020	0,0058	0,0002	0,0008	0,0022	0,0014
100 km	0,0033	0,0101	0,0291	0,0012	0,0038	0,0108	0,0071
200 km	0,0066	0,0203	0,0437	0,0024	0,0075	0,0216	0,0143

Table 21: Fossil Depletion impact of Maintenance Transportation for different distance values

7.4. Interpretation

To facilitate interpretation, results have been depicted in the following Figures 11-14. In each figure, Maintenance components are aggregated within a yellow, Moving parts within a black and Fixed parts within a red border. Results are presented for the medium distance from service center (100 km). Then, error bars indicate the variation of Maintenance Transportation impacts when altering the distance between the service center and the site from 20 to 200 km.

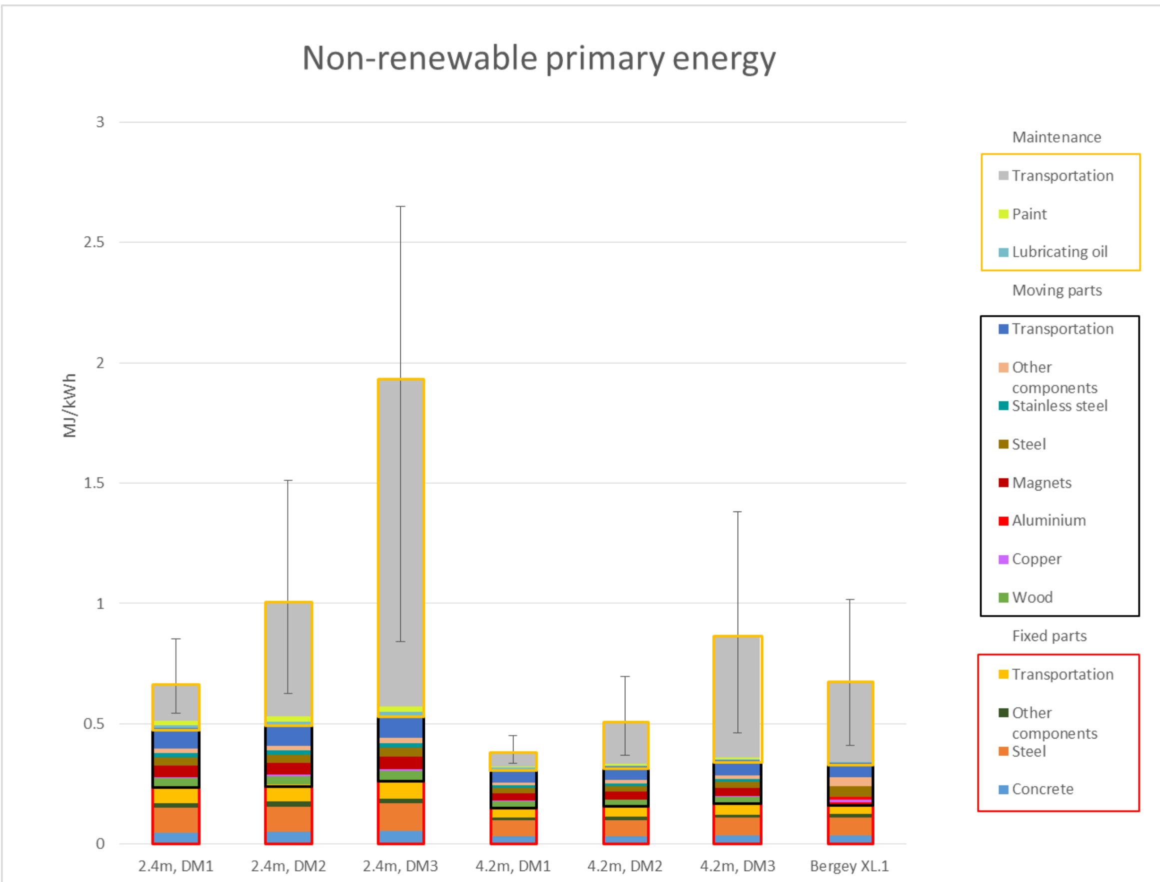


Figure 11: Breakdown of Non-renewable Primary Energy impacts

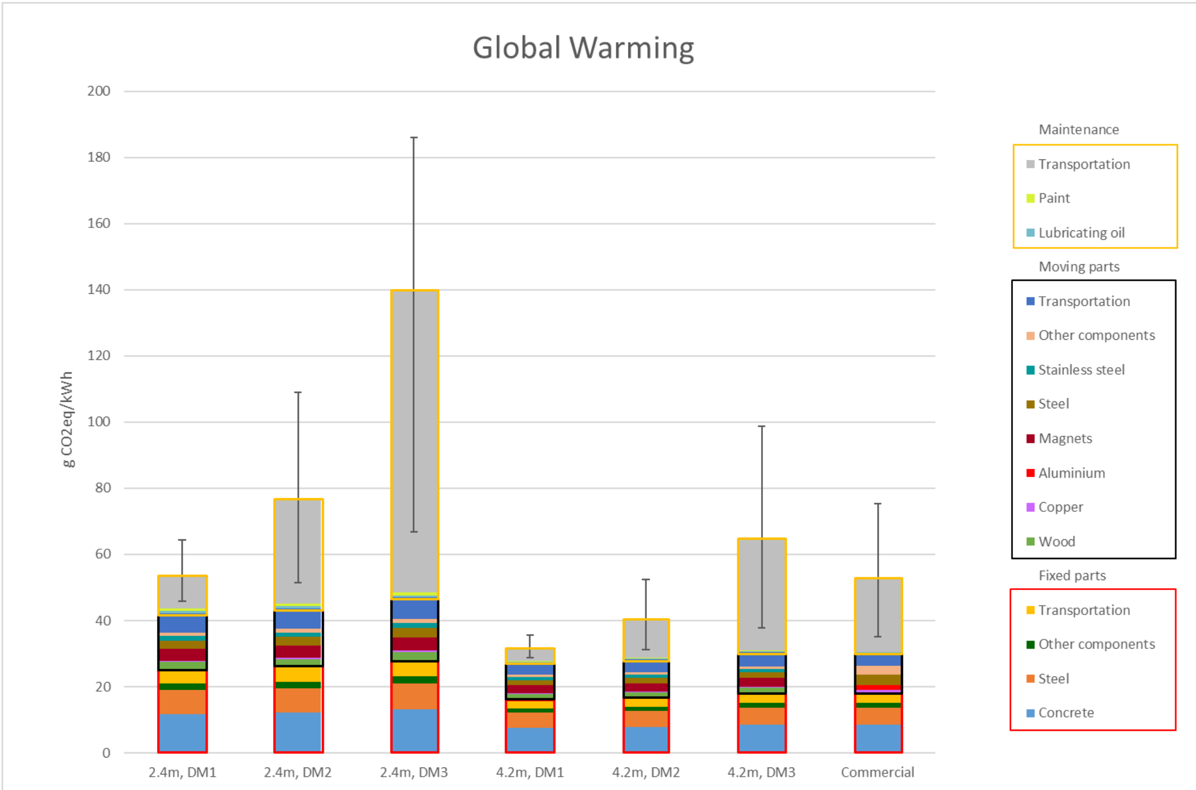


Figure 12: Breakdown of Global Warming impacts

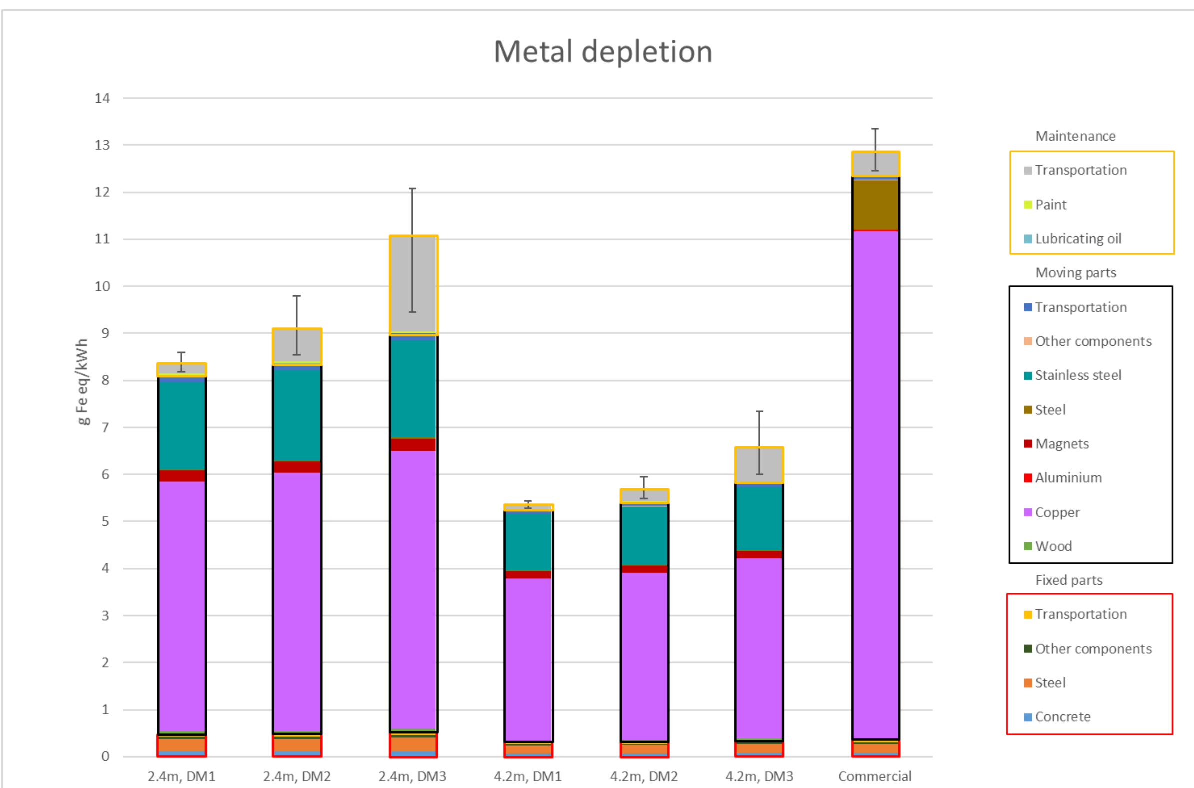


Figure 13: Breakdown of Metal Depletion impacts

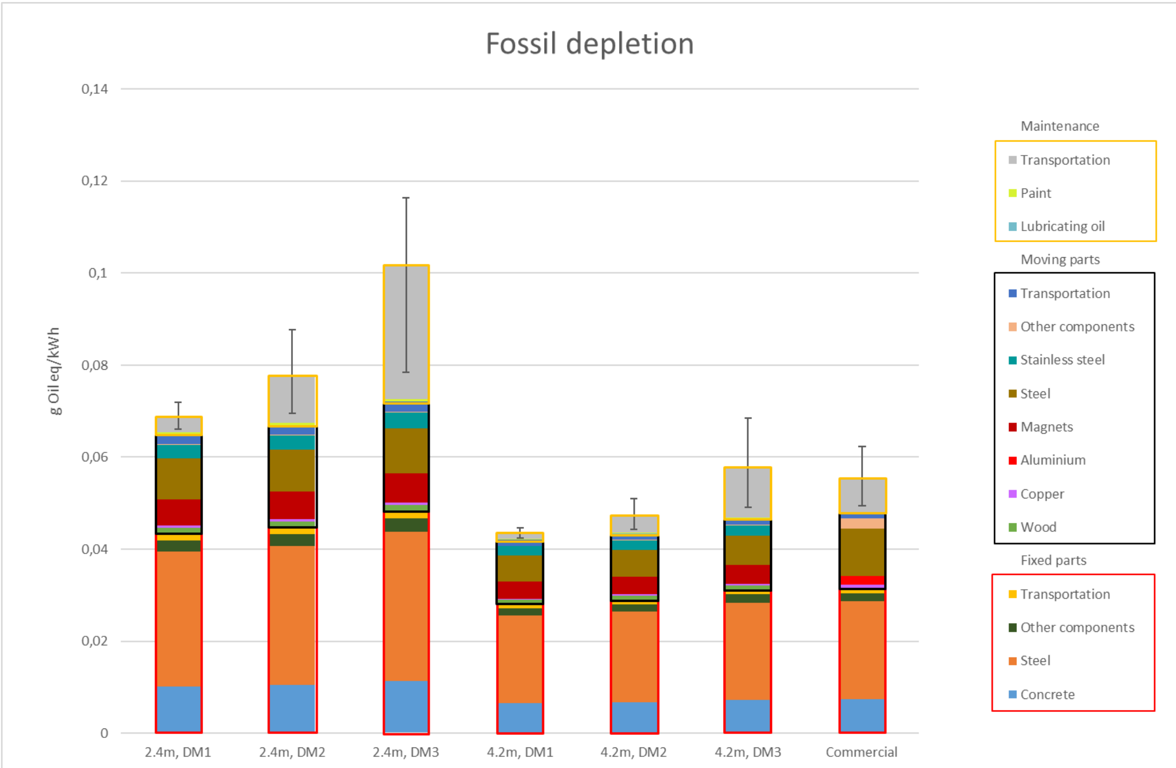


Figure 14: Breakdown of Fossil Fuel Depletion impacts

- **Comparison of the three delivery models for the same wind turbine:**

For all impact categories, it is obvious that for the same wind turbine, the more participative the delivery model is, the less environmental impacts it implies per kWh generated. This is mainly caused by the reduction in maintenance kilometres that participative models achieve and secondly, by the increased electricity generation due to their lower downtime. Especially for Global Warming and Non-renewable Primary Energy, impacts for DM3 are almost three times higher than those for DM1.

Another obvious result is that impacts significantly increase as distance from service center increases, due to the increased distance per maintenance trip. This result is not so important for the participative DM1, since maintenance trips are eliminated in this model, but becomes extremely significant for the non-participative DM3 (refer to the variation of the error bar in DM3 impacts).

- **Comparison of the two LMSWTs for the same delivery model:**

Comparing the 2.4 m with the 4.2 m LMSWT, we observe that the larger wind turbine has significantly lower impacts per kWh, due to its higher electricity generation. So, unlike before, that the variation was observed mainly in the Maintenance component, now the impacts of all three components (Moving parts, Fixed parts and Maintenance) are reduced for the larger LMSWT, as they are divided with a higher electricity generation.

- **Comparison of LMSWTs with the commercial SWT:**

Comparing the two LMSWTs with the commercial SWT we observe different results for each impact category.

 - *Non-renewable primary energy*: The larger 4.2 m LMSWT generally has lower impacts than the commercial SWT, mainly due to its higher electricity production. However, when employed with the non-participative DM3, its impacts increase significantly surpassing those of the commercial SWT. On the contrary, the smaller 2.4 m LMSWT has generally higher impacts than the commercial SWT, due to its lower electricity production, but when it is employed with the fully-participative DM1, its impacts are marginally lower than those of the commercial turbine.
 - *Global Warming*: Results are same as before, with the difference that the commercial SWT has always lower impacts than the smaller 2.4 m LMSWT. Only when the distance from service center is very long (200 km) and the participative DM1 is employed, does the 2.4 m turbine become more advantageous than the commercial.
 - *Metal Depletion*: Here the commercial wind turbine appears to have much higher impacts than all other alternatives, because of its higher copper use. However, the inventory used for the commercial wind turbine [24] assumed a higher use of copper, possibly to substitute the impact of rare earth magnets that were not included in the inventory. It is thus possible that with a more accurate inventory, depletion of metals for the commercial wind turbine would decrease.
 - *Fossil Fuel Depletion*: Results are same as for Non-renewable Primary Energy, with the difference that the commercial SWT has always lower impacts than the smaller 2.4 m LMSWT.

To sum up, it can be said that LMSWTs regardless their size, when employed with fully participative delivery models cause lower impacts than the commercial wind turbine. This is especially true when the distance of the installation site from the service center is very long. On the other hand, when employed with non-participative models, and as distance from service center increases, LMSWTs cause higher impacts than the commercial wind turbine.

Based on these results, it can be recommended that local manufacture should be employed with participative delivery models, especially in remote areas, if it aspires to be considered an environmentally friendly solution compared with commercial alternatives.

In addition, we observe that the remoteness of the site has direct consequence on the environmental impacts of small wind turbines, due to their relatively frequent maintenance requirements. Even commercial small wind turbines have considerable maintenance requirements[6] which cannot be neglected when a long distance has to be covered per maintenance trip.

However, this does not seem to be sufficiently addressed in literature, as in most LCA for SWTs, maintenance impacts are considered negligible. Especially for off-grid installations that take place in rural areas, impacts of transportation for maintenance should be carefully considered.

Finally, based on the above results, it was observed that wind turbines with higher electricity generation, generally have lower environmental impacts per generated kWh, regardless the delivery model and type of manufacture.

[6] Maintenance requirements depend on the robustness of the wind turbine (thus on the manufacturer), but also on the weather conditions of the particular site. Here, a biannual maintenance is considered for the commercial SWT (Bergey XL.1).

8. Calculation of sustainability indicators

Environmental indicators have been calculated, as described in Chapter 7, by performing a cradle-to-grave Life Cycle Assessment for the alternatives.

Regarding all other indicators, a lifecycle approach has also been followed, but with the following two limitations:

- Including only the Manufacturing, Installation, O&M stages and Transportation between them
- Limiting the assessment within the borders of the country where the wind turbines are installed

For example, "Manufacturing of Moving parts" was included in the system boundary for the LMSWTs as it occurs locally, within the country. On the contrary, the same process for the commercial wind turbine is only considered as a "Purchasing moving parts" process, since manufacturing in this case occurs outside the national context we are studying.

These boundaries are further explained graphically in Figures 15 and 16. The system boundary for the non-environmental assessment is depicted within the dark green rectangle.

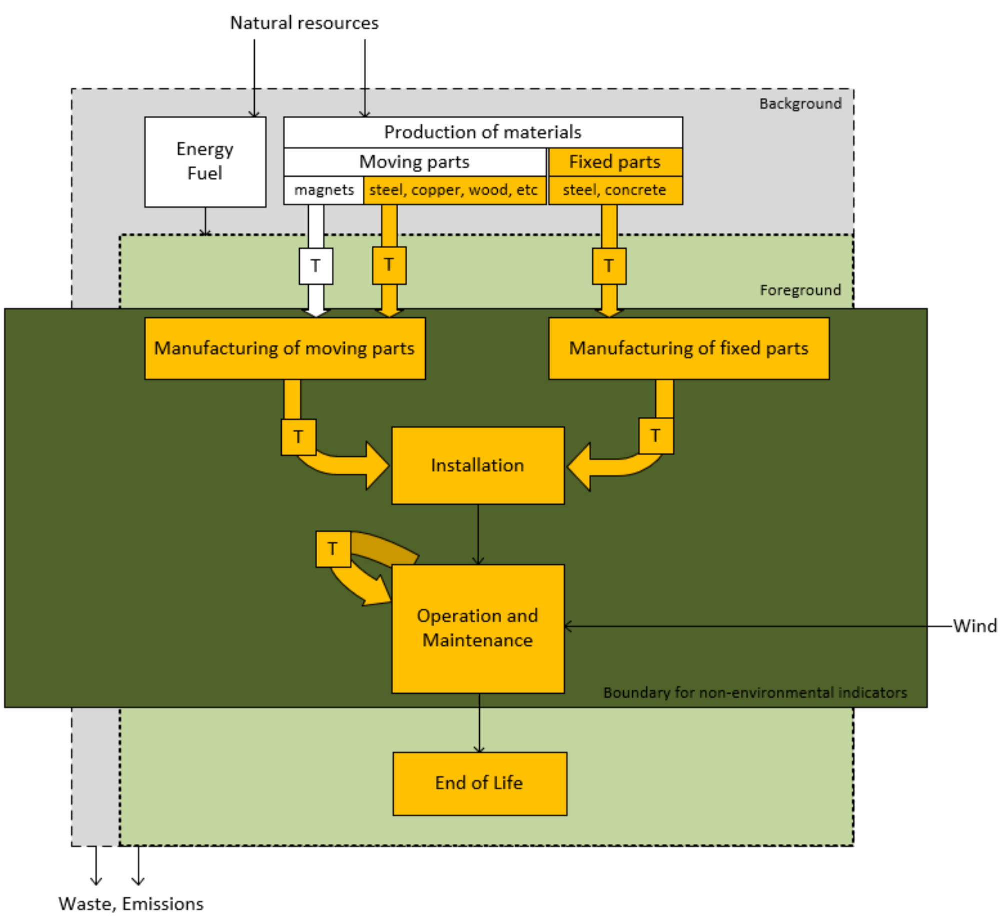


Figure 15: System boundary (depicted in dark green) for assessing non-environmental impacts of LMSWTs

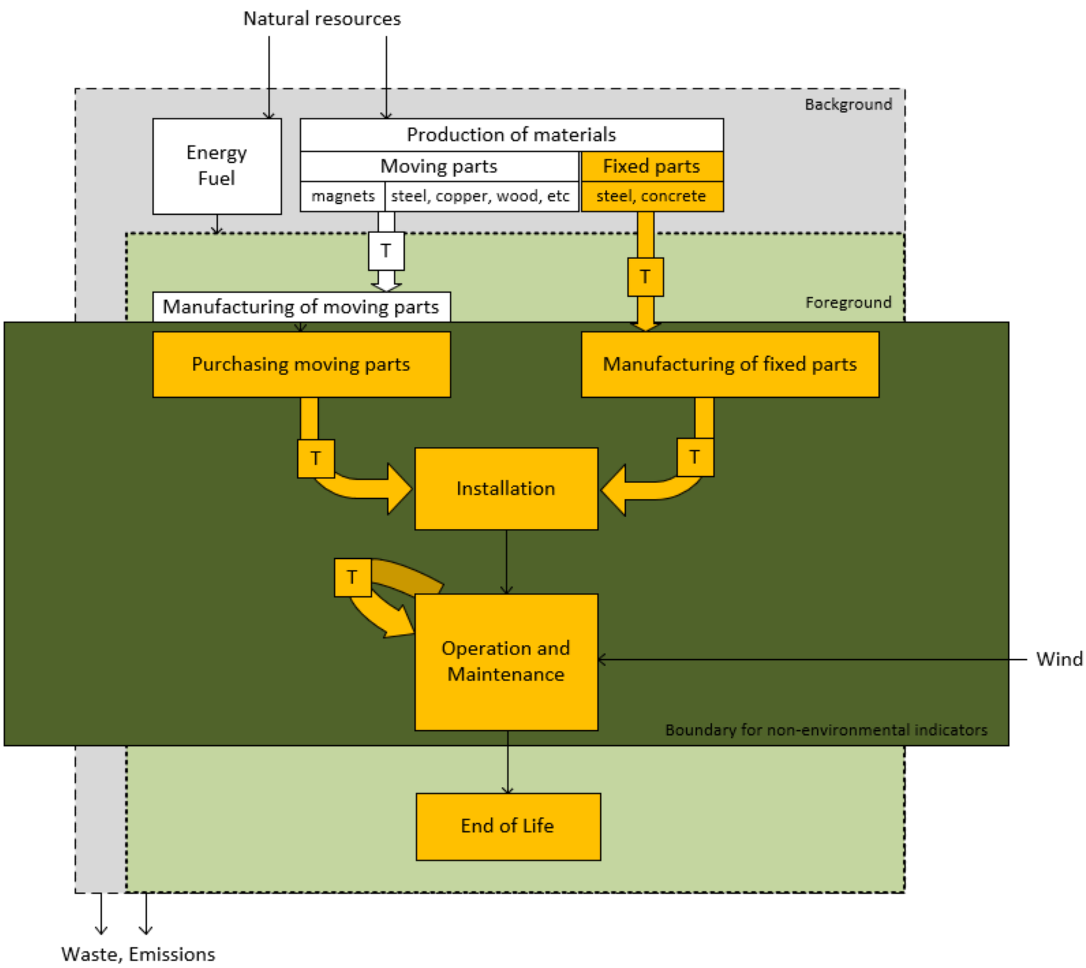


Figure 16: System boundary (depicted in dark green) for assessing non-environmental impacts of commercial SWT

Finally, data for the calculation of the technical, social, economic and institutional indicators were based on case studies of rural small wind turbine experiences [3] and on information offered by practitioners through the Wind Empowerment association [52].

8.1. Environmental indicators

Out of the four impact categories that were assessed during the Life Cycle Impact Assessment, three were selected to be used as environmental indicators: Global Warming, Non-renewable primary energy and Metal depletion. Fossil depletion was not used, as the relative impacts of the alternatives on this category were similar to those of Non-renewable primary energy; thus, it was considered redundant to use both indicators.

Table 22 summarizes the calculations of the selected environmental indicators for the wind turbine alternatives and for different values of the distance parameter.

20 km			
Alternative	Non-renewable primary energy (MJ/kWh)	Global Warming (gCO2eq/kWh)	Metal depletion (gFe eq/kWh)
LM 2.4m, DM1	0.545	45.737	8.188
LM 2.4m, DM2	0.625	51.428	8.539
LM 2.4m, DM3	0.843	66.837	9.449
LM 4.2m, DM1	0.336	28.671	5.283
LM 4.2m, DM2	0.370	31.147	5.484
LM 4.2m, DM3	0.461	37.784	5.999
Commercial	0.409	35.049	12.453
100 km			
Alternative	Non-renewable primary energy (MJ/kWh)	Global Warming (gCO2eq/kWh)	Metal depletion (gFe eq/kWh)
LM 2.4m, DM1	0.667	53.985	8.370
LM 2.4m, DM2	1.005	76.951	9.102
LM 2.4m, DM3	1.933	140.133	11.064
LM 4.2m, DM1	0.381	31.725	5.351
LM 4.2m, DM2	0.510	40.598	5.692
LM 4.2m, DM3	0.865	64.925	6.597
Commercial	0.676	52.983	12.848
200 km			
Alternative	Non-renewable primary energy (MJ/kWh)	Global Warming (gCO2eq/kWh)	Metal depletion (gFe eq/kWh)
LM 2.4m, DM1	0.852	64.296	8.597
LM 2.4m, DM2	1.511	108.854	9.805
LM 2.4m, DM3	2.649	185.943	12.073
LM 4.2m, DM1	0.449	35.543	5.435
LM 4.2m, DM2	0.698	52.412	5.953
LM 4.2m, DM3	1.382	98.851	7.345
Commercial	1.016	75.401	13.342

Table 22: Calculation of environmental indicators

8.2. Technical indicator

- Availability (%)

The Availability factor is a technical indicator typically used for energy systems to indicate the percentage of time the system is available to produce energy. In our study, this translates to the percentage of time the small wind turbine is available to produce electricity, thus excluding the time that the wind turbine is down due to pre-emptive or corrective maintenance.

Availability was calculated through the following formula, taking any value between 0 and 100%.

$$Availability\ (\%) = \frac{(Days\ per\ year) - (Downtime\ days\ per\ year)}{(Days\ per\ year)} * 100\%$$

$$= \frac{(Days\ per\ year) - (Failures\ per\ year * Downtime\ days\ per\ failure)}{(Days\ per\ year)} * 100\%$$

Table 23 presents the calculations for the Availability factor of the alternatives and a graphical representation is available in Figure 17 below. The availability factor is assumed not to be influenced by the distance parameter.

	Downtime (days/failure)	Annual Number of failures	Availability (%)
2.4m, DM1	4	1	98,9
2.4m, DM2	15	1	95,9
2.4m, DM3	30	1,33	89,0
4.2m, DM1	4	1	98,9
4.2m, DM2	15	1	95,9
4.2m, DM3	30	1,33	89,0
Commercial	45	0,5	93,8

Table 23: Calculation of the technical indicator of Availability

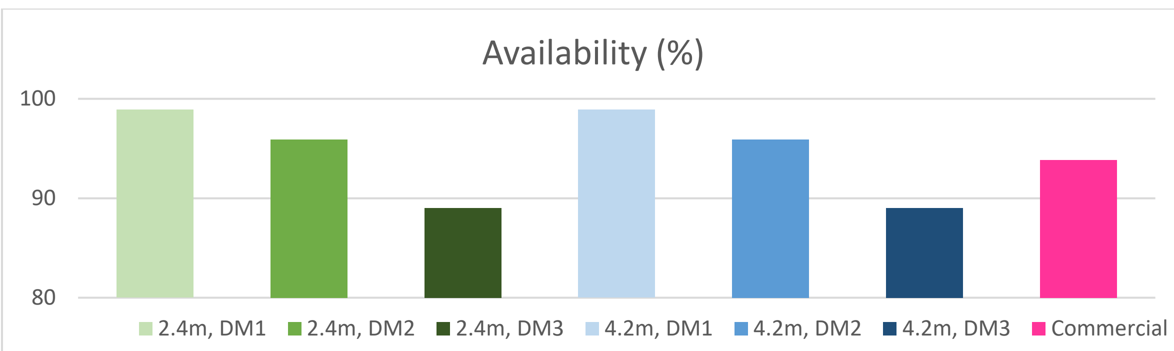


Figure 17: Availability factor of the seven small wind turbine alternatives

We observe that LMSWTs employed with DM1 have the highest availability, and as the models become less participative availability drops. This occurs because in participative models, failures are fixed faster, so the wind turbine is functional for more time during the year. This gives advantage to the LMSWTs employed with DM1 or DM2 against the commercial SWT, even if the latter fails much less frequently.

On the other hand, the commercial wind turbine compared to LMSWTS with DM3 has higher availability. DM3 does not have the advantages of a participative model, so the commercial SWT is now advantageous due to its much fewer failures.

8.3. Economic indicators

The following three economic indicators were considered for the sustainability assessment of the small wind turbine alternatives:

- Initial Investment (€)

For the LMSWTs, initial investment includes all material and labour costs during the Manufacturing, Installation and Training stages of the wind turbines lifecycle. In other words, all the material and labour costs for the system to start operating.

$$I = MMC + MLC + IMC + ILC + TMC + TLC \quad (€)$$

I – Initial Investment (€)

MMC – Manufacturing material costs (€)

MLC – Manufacturing labour costs (€)

IMC – Installation material costs (€)

ILC – Installation labour costs (€)

TMC – Training material costs (€)

TLC – Training labour costs (€)

For the commercial SWT, initial investment is calculated as the sum of the retail price, the delivery cost and the installation cost.

$$I = p + DC + IMC + ILC \quad (€)$$

p – Retail price of wind turbine (€)

DC – Delivery costs (€)

IMC – Installation material costs (€)

ILC – Installation labour costs (€)

Initial investment is measured in €, taking any value equal or greater than zero.

- Annual O&M costs (€/year)

They comprise the annual costs of materials, labour and transportation for performing maintenance.

Annual O&M costs are measured in €/year, taking any value equal or greater than zero.

$$AOMC = AOMMC + AOMLC + AOMTC$$

AOMC – Annual O&M costs (€/year)

AOMMC – Average annual cost of materials for O&M (€)

AOMLC – Average annual cost of labour for O&M (€)

AOMTC – Average annual cost of transportation for O&M (€)

- Levelized Generating Cost (€/kWh)

Levelized Generating Cost (LGC) is calculated as the ratio of total costs of generation and the total electricity generated during the lifetime of the wind turbine, taking into account an appropriate discounting factor. A discount rate of 8% was assumed for the specific application.

It is noted that generation costs, as well as generated electricity are regarded at the generator's output, not taking into account costs and losses of batteries, power electronics and distribution cables. LGC indicates the cost for the generation of each kWh and is different than Levelized Cost of Electricity which indicates the cost for the generation and distribution of each kWh to the consumer.

LGC is measured in €/kWh, taking any value equal or greater than zero.

$$LGC = \frac{I + \sum_0^N \frac{AOMC_t}{(1+r)^t}}{\sum_1^N \frac{E_t}{(1+r)^t}} = \frac{NPC}{\sum_1^N \frac{E_t}{(1+r)^t}} \qquad (€/_{kWh})$$

I – Initial investment (€)

$AOMC_t$ – Annual O&M costs in year t (€)

E_t – Electricity generation in year t (kWh)

r – Discount rate

N – Lifetime of the wind turbine

NPC – Net Present Cost (€)

For all economic indicators, the average daily wage in the context of a developing country was assumed to be 15 $[7]/day. Based on the argument that "local labour tends to be cheaper than labour coming from a nearby city" [3], a different wage was assumed depending on the distance travelled by the technician, with labour offered by community members (condition monitoring and preventive maintenance) considered to be the cheapest (5 $).

Table 24 presents the calculations of the economic indicators for the seven alternatives and for different values of the distance from service center. Results are then depicted graphically in Figures

[7] Costs in literature were found in USD and the conversion rate of 1USD=0.8Euros was used throughout.

18 - 20. For Initial investment, results are depicted only for the 100 km scenarios, as there were no significant differences among the three distance scenarios.

	Manufacturing and installation costs (€)	Training and toolbox costs (€)	Initial Investment (€)	Annual O&M costs (€/year)	NPC (€)	Annual Electricity Production (kWh)	LGC (€/kWh)
20 km							
2.4m, DM1	2275	588	2863	115,33	3850,19	1256,92	0,36
2.4m, DM2	2275	408	2683	122,00	3727,26	1218,62	0,36
2.4m, DM3	2275	0	2275	197,33	3964,07	1131,58	0,41
4.2m, DM1	4118,75	588	4706,75	171,33	6173,27	3394,39	0,21
4.2m, DM2	4118,75	408	4526,75	178,00	6050,34	3290,96	0,21
4.2m, DM3	4118,75	0	4118,75	282,67	6538,23	3055,89	0,25
Commercial	5804,5	0	5804,5	142,00	7198,68	1734,25	0,42
100 km							
2.4m, DM1	2275	628	2903	126,00	3981,49	1256,92	0,37
2.4m, DM2	2275	428	2703	154,00	4021,16	1218,62	0,39
2.4m, DM3	2275	0	2275	304,00	4877,08	1131,58	0,50
4.2m, DM1	4118,75	628	4746,75	184,67	6327,40	3394,39	0,22
4.2m, DM2	4118,75	428	4546,75	218,00	6412,72	3290,96	0,23
4.2m, DM3	4118,75	0	4118,75	421,33	7725,14	3055,89	0,30
Commercial	5804,5	0	5804,5	170,00	7473,59	1734,25	0,43
200 km							
2.4m, DM1	2275	724	2999	145,33	4242,98	1256,92	0,39
2.4m, DM2	2275	476	2751	212,00	4565,61	1218,62	0,44
2.4m, DM3	2275	0	2275	501,33	6566,15	1131,58	0,68
4.2m, DM1	4118,75	724	4842,75	209,33	6634,53	3394,39	0,23
4.2m, DM2	4118,75	476	4594,75	292,00	7094,12	3290,96	0,25
4.2m, DM3	4118,75	0	4118,75	682,67	9962,02	3055,89	0,38
Commercial	5804,5	0	5804,5	220,00	7964,49	1734,25	0,46

Table 24: Calculation of economic indicators

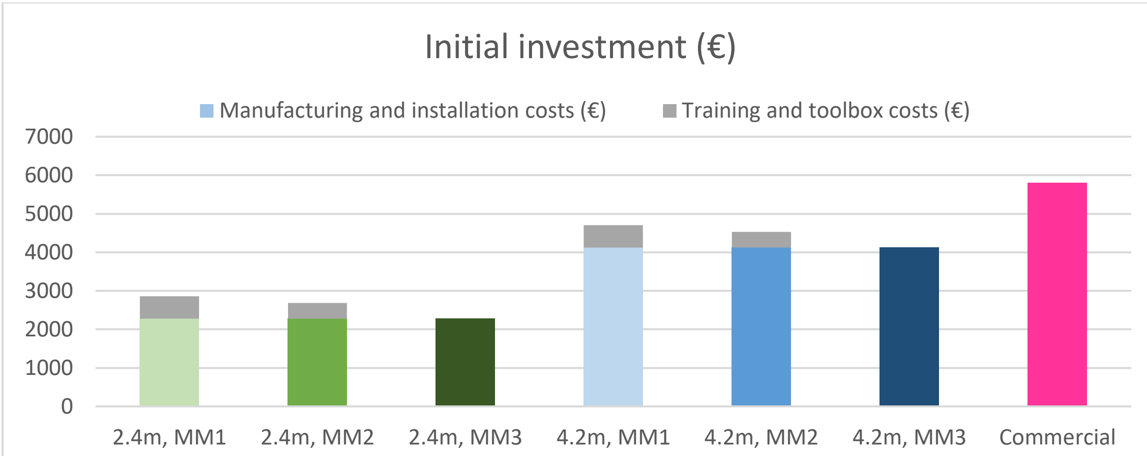


Figure 18: Initial investment for the seven alternatives

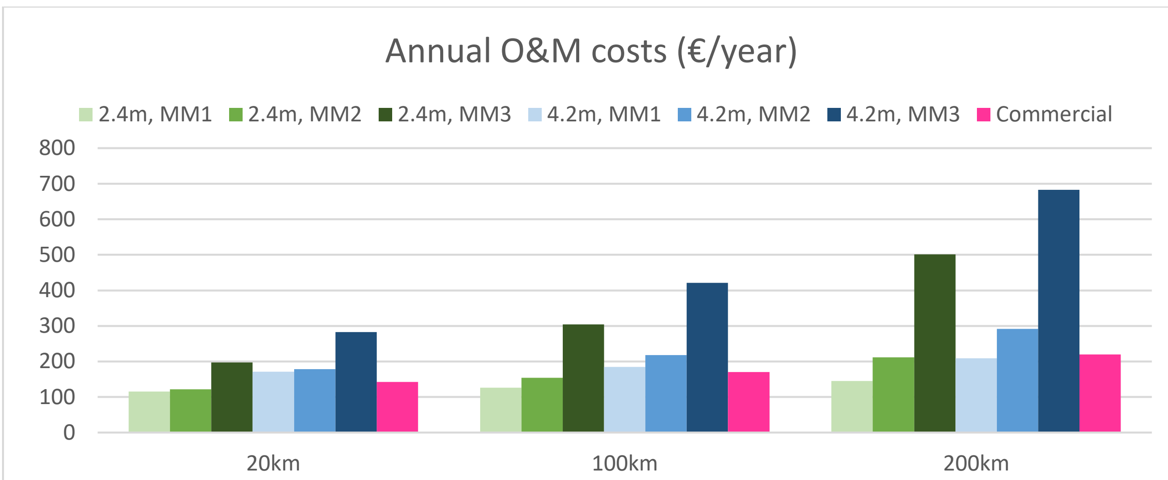


Figure 19: Annual O&M costs for the seven alternatives

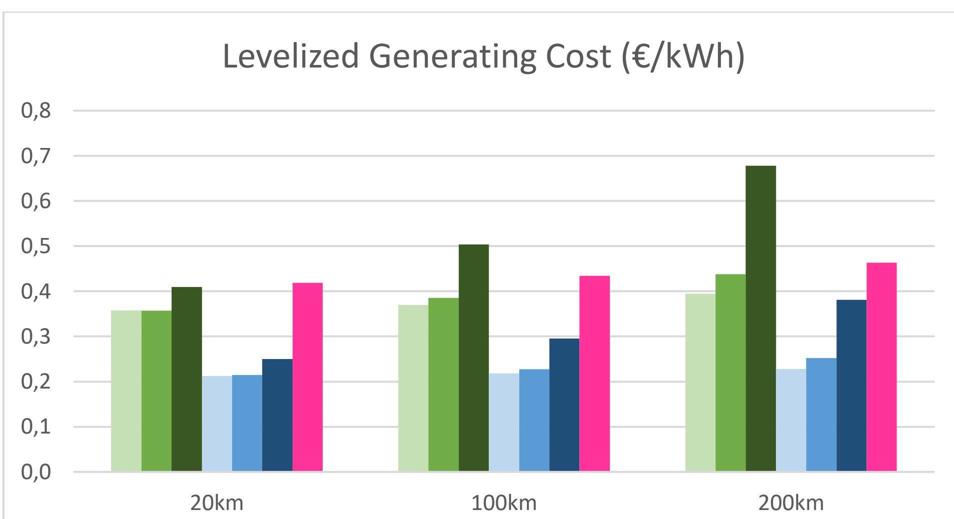


Figure 20: Levelized Generating Cost for the seven alternatives

In Figure 14 we observe that the commercial wind turbine has a much higher initial investment, even higher than the 4.2 m LMSWT which is a wind turbine with considerably higher rated power. As expected, the smaller 2.4 m LMSWT has the lowest initial investment, even when employed with DM1 which incurs an additional cost for training of the users and provision of a toolbox to perform maintenance.

In Figure 15 it is observed that O&M costs are higher for non-participative models and the difference becomes very prominent as the distance from service center becomes longer. It seems that more frequent, longer and more expensive maintenance trips raise the cost by more than 100% when comparing DM1 to DM3 alternatives in the case of 200 km. The commercial wind turbine on the other hand, even though employed with non-participative DM-C, has quite low O&M costs due to its robustness resulting in fewer failures.

Finally, in Figure 16 it can be confirmed that larger wind turbines generally have a lower LGC than smaller ones, when all other parameters are the same. However, a reduction to the LGC is observed for the participative models; a reduction that becomes very prominent for the 200 km case. In this case, the smaller LMSWT employed with DM3 has by far the highest LGC. However, the same wind turbine employed with DM1 or even DM2 has a lower LGC than the commercial wind turbine.

8.4. Social indicators

Two social indicators were chosen in order to indicate the social impacts of each alternative on the country where the wind turbines are assumed to operate.

- National to total expenses rate (%)

This indicator is the percentage of all expenses made at national level over the total expenses throughout the system's lifecycle. This way, it reflects the percentage of wealth that stays within the national economy, an important factor especially for developing countries.

Expenses are considered for both labour and materials during the manufacturing, installation, training and O&M of the small wind turbine systems.

$$National\ to\ total\ expenses = \frac{Expenses\ at\ national\ level}{Total\ expenses} \times 100\%$$

For the LMSWTs, all materials were considered to be purchased at national level, except for the magnets, which were assumed to be ordered from China. For the commercial wind turbine, no material was considered to be purchased at national level.

- Local to national labour rate (%)

This indicator is the percentage of local community labour over total national labour, thus reflecting the provision of employment in remote areas.

Local labour includes all labour during the system's lifecycle, specialized or non-specialized, that is offered by local community members. In our study, this comprises labour for preventive and corrective maintenance of the wind turbines which is offered by the community itself. Local labour is thus increased for the delivery models with increased user empowerment.

National labour includes all labour during the system's lifecycle, specialized or non-specialized, that is offered at national level. This comprises labour for preventive and corrective maintenance and travel days.

$$Local\ to\ national\ labour = \frac{Local\ labour}{Total\ national\ labour} \times 100\%$$

Table 25 presents the calculation of the social indicators and Figures 21 and 22 provide a graphical representation. Only the 100 km scenario is depicted as there were no significant differences observed among the three distance scenarios.

20 km						
	National expenses (€)	Total expenses (€)	National to total expenses rate (%)	Local community labour (persondays)	National labour (persondays)	Local to national labour rate (%)
2.4m, DM1	4203	4593,00	91,51	80	281,25	28,44
2.4m, DM2	4123	4513,00	91,36	60	258,75	23,19
2.4m, DM3	4845	5235	92,55	0	233,75	0
4.2m, DM1	6594,25	7276,75	90,62	120	436,56	27,49
4.2m, DM2	6514,25	7196,75	90,52	90	404,0625	22,27
4.2m, DM3	7676,25	8358,75	91,83	0	364,0625	0
Commercial	1190	8644,5	13,77	0	77,5	0
100 km						
	National expenses (€)	Total expenses (€)	National to total expenses rate (%)	Local community labour (persondays)	National labour (persondays)	Local to national labour rate (%)
2.4m, DM1	4403,00	4793,00	91,86	80,00	285,42	28,03
2.4m, DM2	4623,00	5013,00	92,22	60,00	267,08	22,46
2.4m, DM3	6445,00	6835,00	94,29	0,00	253,75	0,00
4.2m, DM1	6834,25	7516,75	90,92	120,00	440,73	27,23
4.2m, DM2	7134,25	7816,75	91,27	90,00	412,40	21,82
4.2m, DM3	9756,25	10438,75	93,46	0,00	384,06	0,00
Commercial	1750,00	9204,50	19,01	0,00	87,50	0,00
200 km						
	National expenses (€)	Total expenses (€)	National to total expenses rate (%)	Local community labour (persondays)	National labour (persondays)	Local to national labour rate (%)
2.4m, DM1	4789,00	5179,00	92,47	80,00	294,42	27,17
2.4m, DM2	5541,00	5931,00	93,42	60,00	284,08	21,12
2.4m, DM3	9405,00	9795,00	96,02	0,00	293,75	0,00
4.2m, DM1	7300,25	7982,75	91,45	120,00	449,73	26,68
4.2m, DM2	8292,25	8974,75	92,40	90,00	429,40	20,96
4.2m, DM3	13676,25	14358,75	95,25	0,00	424,06	0,00
Commercial	2750,00	10204,50	26,95	0,00	107,50	0,00

Table 25: Calculation of social indicators

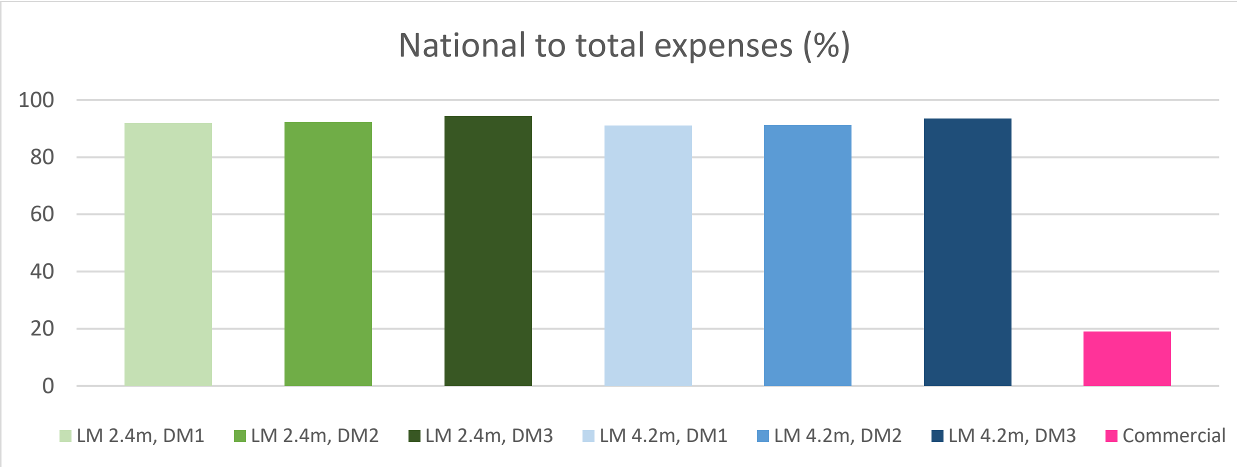


Figure 21: National to total expenses rate for the seven alternatives

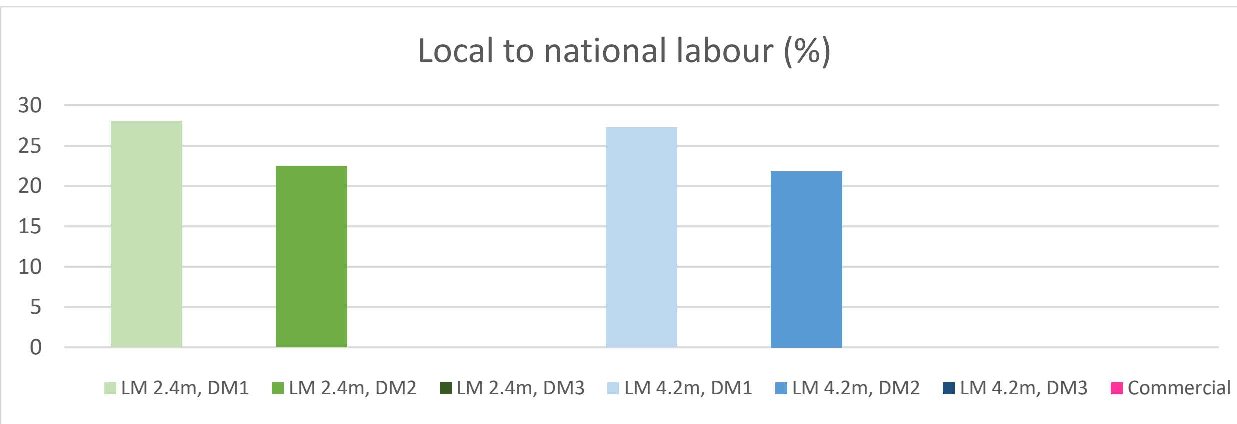


Figure 22: Local to national labour rate for the seven alternatives

Figure 21 clearly shows that for LMSWTs the money spent by the investors/users largely stays within the national economy, while for the commercial SWT most of the money are spent externally (in the manufacturer's country).

Finally, Figure 22 emphasizes the fact that delivery models DM1 and DM2 can create employment locally, supporting the local community rather than bringing expertise from distant urban centers.

8.5. Institutional indicator

- Institutional burden

In order to objectively assess the alternatives in relation to the current situation in the small wind rural electrification field, an additional indicator was introduced that reflects the institutional difficulty for employing the delivery model of each alternative.

Institutional burden comprises generic cost to issue policies, establish infrastructure, supportive network and local capacity, so that each delivery model is functioning in the way it is described.

The delivery models examined for the LMSWTs, especially those which emphasize community empowerment, require some support from institutions (public authorities, universities, policies, etc.) in order to establish the infrastructure, network and local capacity that is required for them to be successful. This does not imply that the commercial delivery model will not need any institutional support in order to be effective in the context of developing countries, i.e. links between foreign manufacturers and local merchants will need to be established and capacity of local technicians will need to be increased. However, in general this is considered to be a more mature model that requires relatively less support.

To indicate the Institutional burden, a qualitative indicator was used, taking integer values from 1-10, where 10 indicates maximum burden. Consequently, if alternative *a* and *b* are assigned with values of 10 and 5 respectively, *a* is considered to have double an institutional burden than *b*.

Table 26 shows the estimated values of the Institutional burden for each of the four examined delivery models, as defined by a multi-disciplinary group of experts.

<table>
<tr><th colspan="3">Institutional burden</th></tr>
<tr><td rowspan="4">Delivery Model</td><td>DM1: Local manufacture, extensive training and stock of spare parts at community</td><td>10</td></tr>
<tr><td>DM2: Local manufacture, good training and stock of spare parts at service center</td><td>8</td></tr>
<tr><td>DM3: Local manufacture, no training, spare parts manufactured on demand</td><td>7</td></tr>
<tr><td>DM-C: Imported wind turbine, no training, spare parts imported on demand</td><td>5</td></tr>
</table>

Table 26: Estimation of the Institutional indicator

9. Multi-criteria Decision Analysis

Decisions related to the aforementioned problem should be definitely supported by an algorithm enabling consideration of performance of alternatives in multiple dimensions, as the ones we examine in the previous sessions. Moreover, the actors involved have different, often conflicting views of the issue at stake.

MCDA methods are particularly used for assessments when there are competing evaluation criteria. Also, the stakeholder position has not been ignored in the multi-criteria literature [56]; specifically this issue has been subject of extended attention of PROMETHEE scholars resulting in formal suggestions [57]. For this reason, and also due to its simplicity and wide use, PROMETHEE was deemed appropriate to implement for the specific application.

9.1. The PROMETHEE method

The PROMETHEE method is one of the most widely known and applied MCDA methods in the category of outranking approaches. As opposed to Value Function methods, Outranking methods do not produce an aggregative value for each alternative, but rather an outranking relation between each pair of alternatives by comparing them in pairs for each criterion [58].

Within the PROMETHEE methodology, six types of generalized criteria (or pseudo-criteria) are provided to represent the preference structure that better fits each criterion. These generalized criteria, accept indifference and/or preference thresholds to define areas of indifference, preference or intermediate preference. A brief description of the method is provided below [59].

Let N be the set of alternatives and M be the set of criteria.

A partial preference index is defined for each criterion j and each pair of alternatives a and b, through the pairwise comparison of a and b in the criterion j:

$$P_j(N \times N) \rightarrow (0,1)$$

For two alternatives a and b we have the following possibilities:

$$P_j(a,b) = 0 \quad \Rightarrow \quad Indifference\ between\ a\ and\ b\ in\ criterion\ j$$

$$P_j(a,b) \sim 0 \quad \Rightarrow \quad Weak\ preference\ of\ a\ over\ b\ in\ criterion\ j$$

$$P_j(a,b) \sim 1 \quad \Rightarrow \quad Strong\ preference\ of\ a\ over\ b\ in\ criterion\ j$$

$$P_j(a,b) = 1 \quad \Rightarrow \quad Strict\ preference\ of\ a\ over\ b\ in\ criterion\ j$$

The partial preference indices are increasing functions of the difference d_j between the performance of the two alternatives in the j^{th} criterion. The difference d_j is defined as:

$$d_j = \begin{cases} p_{aj} - p_{bj} & if \quad p_{aj} \geq p_{bj} \\ 0 & otherwise \end{cases}$$

where p_{aj} and p_{bj} is the performance of alternatives *a* and *b* respectively in criterion *j*. The above relation is valid only when *j* is a maximization criterion. If it is a minimization criterion, the signs of p_{aj} and p_{bj} in the above relation should be reversed.

The generalized form of the preference function is thus:

$$P_j(a,b) = f(d_j)$$

The decision maker can then decide the functional form of *f* among six types of generalized criteria (pseudo-criteria). These types, presented in Table 27 below, are characterized by three parameters: The indifference threshold (*q*), the strict preference threshold (*p*) and the gaussian parameter (*σ*). The values for the three parameters are also decided by the decision maker.

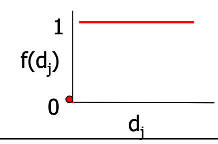
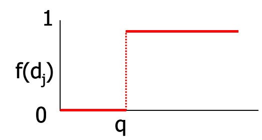
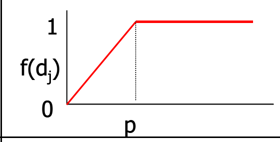
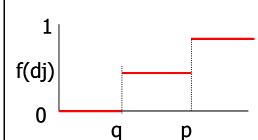
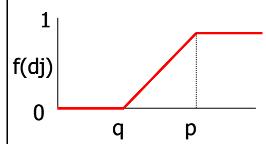
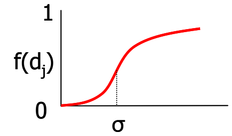
Type of criterion	Mathematical expression	Graphical form
1. Usual criterion	$f(d_j) = \begin{cases} 1, & d_j > 0 \\ 0, & d_j = 0 \end{cases}$	
2. Quasi-criterion	$f(d_j) = \begin{cases} 1, & d_j > q \\ 0, & d_j \leq q \end{cases}$	
3. Criterion with linear preference	$f(d_j) = \begin{cases} 1, & d_j > p \\ \frac{d_j}{p}, & d_j \leq p \end{cases}$	
4. Level criterion	$f(d_j) = \begin{cases} 1, & d_j > p \\ 0.5, & p \geq d_j > q \\ 0, & q \geq d_j \end{cases}$	
5.Criterion with indifference and linear preference	$f(d_j) = \begin{cases} 1, & d_j > p \\ \frac{d_j - q}{p - q}, & p \geq d_j > q \\ 0, & q \geq d_j \end{cases}$	
6. Gaussian criterion	$f(d_j) = 1 - e^{-d_j^2/2\sigma^2}$	

Table 27: Types of generalized criteria in PROMETHEE

The aggregated or multicriteria preference index $\Pi(a,b)$ of alternative a over alternative b is then defined as the sum of the partial preference indices of each criterion multiplied by the respective weight assigned to each criterion:

$$\Pi(a,b) = \frac{\sum_{j-1}^{m} w_j \times P_j(a,b)}{\sum_{j=1}^{m} w_j}$$

where m is the number of criteria. The multicriteria preference index $\Pi(a,b)$ reflects the intensity of preference the DM has for alternative a over alternative b.

This procedure is repeated for all pairs of alternatives, resulting in a $n \times n$ matrix that contains all the multicriteria preference indices $\Pi(i,k)$:

$$\begin{bmatrix} - & \Pi(1,2) & \Pi(1,3) & \ldots & \Pi(1,n) \\ \Pi(2,1) & - & \Pi(2,3) & \ldots & \Pi(2,n) \\ \Pi(3,1) & \Pi(3,2) & - & \ldots & \Pi(3,n) \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ \Pi(n,1) & \Pi(n,2) & \Pi(n,3) & \ldots & - \end{bmatrix}$$

The above matrix is not necessarily symmetrical, as $\Pi(a,b) \neq \Pi(b,a)$ in general. For each row of the matrix, the horizontal sum gives the outranking character of the respective alternative, while the vertical sum of each column gives the outranked character of the respective alternative. In other words, the greater the row sum (or leaving flow) of alternative a, the more preferred it is in comparison with the other alternatives. On the contrary, the greater the column sum (or entering flow) of alternative a, the less preferred it is in comparison with the other alternatives.

$$\text{Leaving flow:} \quad \phi^{+}(a) = \sum_{i=1}^{n} \Pi(a,i)$$

$$\text{Entering flow:} \quad \phi^{-}(a) = \sum_{i=1}^{n} \Pi(i,a)$$

Combining the rankings based on the leaving and entering flows, we obtain the partial preorder of the alternatives (PROMETHEE I), which allows incomparabilities among alternatives.

In order to obtain the complete preorder of the alternatives (PROMETHEE II), the net flow is calculated for each alternative, as the difference between its leaving and its entering flow:

$$\text{Net flow:} \quad \varphi(a) = \varphi^{+}(a) - \varphi^{-}(a)$$

In this case, alternative a outranks alternative b if $\varphi(a) > \varphi(b)$, while a is indifferent to b if $\varphi(a) = \varphi(b)$. Consequently, PROMETHEE II allows for a complete ranking of the alternatives in a decreasing order of preference.

9.2. Integration as criteria in PROMETHEE

PROMETHEE method was used to interpret the results of the sustainability assessment only for the average distance scenario, which assumes 100 km distance of the installation site to the service center.

9.2.1. Specification of two sets of criteria

For the specific application, two main groups of stakeholders have been considered:

- Investors: the community or group which undertakes the costs and benefits of the small wind turbine
- Policymakers: regional or national governing bodies that issue policies to promote rural electrification solutions.

Selecting among the indicators calculated in the previous session, a discrete set of criteria was defined for each stakeholder viewpoint, respecting the coherence family of criteria rule. Subsequently, appropriate types and thresholds were selected for each criterion to match the nature of each criterion and estimate as much as possible the preference function of stakeholders.[8]

The two sets of criteria are presented in Tables 28 and 29.

Investor's viewpoint						
INDICATOR	UNIT	DIRECTION	RANGE OF VALUES	TYPE	THRESHOLDS	CATEGORY
1. Initial investment	€	Min	≥ 0	2	q=50	Economic
2. Annual O&M costs	€/year	Min	≥ 0	3	p=20	Economic
3. Levelized Generating Cost	€/kWh	Min	≥ 0	5	q=0.01, p=0.05	Economic
4. Availability	%	Max	0 - 100%	4	q=0.02, p=0.08	Technical
5. Local to national labour	%	Max	0 - 100%	5	q=1, p=2.5	Social

Table 28: Criteria for Investor's viewpoint

[8] In a real case study, stakeholders should be asked to define the thresholds for the criteria

Policymaker’s viewpoint						
INDICATOR	UNIT	DIRECTION	RANGE OF VALUES	TYPE	THRESHOLDS	CATEGORY
1. Non-renewable primary energy	MJ/kWh	Min	≥ 0	2	q=0.2	Environmental
2. Global warming	gCO2eq/kWh	Min	≥ 0	3	p=5	Environmental
3. Metal depletion	gFeeq/kWh	Min	≥ 0	5	q=0.1, p=0.5	Environmental
4. Levelized Generating Cost	€/kWh	Min	≥ 0	5	q=0.01, p=0.05	Economic
5. National to total expenses	%	Max	0 - 100%	2	q=2	Social
6. Local to national labour	%	Max	0 - 100%	5	q=1, p=3	Social
7. Institutional cost	Qualitative	Min	1 - 10	2	q=1	Institutional

Table 29: Criteria for Policymaker's viewpoint

It is considered that the investor who will undertake the costs and benefits of the SWT has no interest of considering environmental performance unless it is translated in financial flows (subsidies, or penalties for pollution), and will primarily have economic and technical criteria.

Thus, investors’ criteria include the technical indicator of availability and the economic indicators of Initial investment, Annual O&M costs and Levelized Generating Cost. Initial investment in particular is extremely important for low-income investors in developing countries. The social indicator ‘Local to national labour’ was also included, assuming that investors, being at the same time community residents, will care about the impacts on local community employment.

On the other hand, regional or national governing bodies acting as policy makers to support the adoption of RES take into account environmental benefits and socio-economic impacts to regional development in priority, often paying little attention to the financial profitability of technologies. Thus, for the policymakers, criteria include all environmental indicators and social indicators reflecting impacts on the regional and national economy (job creation and value added within the country), as well as one profitability indicator, preferably levelized cost of electricity generated.

The performance of the seven small wind turbine alternatives to the selected criteria are summarized in the performance matrices below (Tables 30 and 31).

Investor viewpoint					
	Initial investment (€)	Annual O&M costs (€/year)	Levelized Generating Cost (€/kWh)	Availability (%)	Local to national labour (%)
LM 2.4m, DM1	2903	126,000	0,370	98,6	28,029
LM 2.4m, DM2	2703	154,000	0,386	97,0	22,465
LM 2.4m, DM3	2275	304,000	0,504	92,7	0,000
LM 4.2m, DM1	4746,75	184,667	0,218	98,6	27,228
LM 4.2m, DM2	4546,75	218,000	0,228	97,0	21,824
LM 4.2m, DM3	4118,75	421,333	0,295	92,7	0,000
Commercial	5804,5	170,000	0,434	95,8	0,000

Table 30: Performance of alternatives to Investor's criteria

Policy maker viewpoint							
	Non-renewable primary energy (MJ/kWh)	Global Warming (gCO2eq/kWh)	Metal depletion (gFe eq/kWh)	Levelized Generating Cost (€/kWh)	National to total expenses (%)	Local to national labour (%)	Institutional burden (Qualitative)
LM 2.4m, DM1	0,667	53,985	8,370	0,370	91,795	28,029	10
LM 2.4m, DM2	1,005	76,951	9,102	0,386	92,189	22,465	8
LM 2.4m, DM3	1,933	140,133	11,064	0,504	94,294	0,000	7
LM 4.2m, DM1	0,381	31,725	5,351	0,218	90,872	27,228	10
LM 4.2m, DM2	0,510	40,598	5,692	0,228	91,246	21,824	8
LM 4.2m, DM3	0,865	64,925	6,597	0,295	93,462	0,000	7
Commercial	0,676	52,983	12,848	0,434	19,012	0,000	5

Table 31: Performance of alternatives to Policymaker's criteria

9.2.2. Weighting of criteria

For this exercise, which does not represent a real case scenario, weights of criteria were not assigned by the relevant stakeholders. Instead a variety of weighting schemes were applied, to represent different stakeholder preference scenarios.

In each weighting scheme, it was assumed that the decision maker is focused more on one of the criteria categories, either social, environmental, economic, technical or institutional. The criteria belonging to the focus category were assigned 40% weight in total, while the remaining 60% was equally divided among the other categories. Finally, a weighting scheme of equal focus in categories was also considered.

Tables 32 - 33 present the weights of the criteria per applied weighting scheme for Investors and Policymakers.

Weighting of Investor's criteria per weighting scheme					
Weighting scheme	Initial investment	Annual O&M costs	Levelized Generating Cost	Availability	Local to national labour
Social focus	10%	10%	10%	30%	**40%**
Economic focus	**13,30%**	**13,30%**	**13,30%**	30%	30%
Technical focus	10%	10%	10%	**40%**	30%
Equal focus	11,10%	11,10%	11,10%	33,30%	33,30%

Table 32: Weights of criteria per weighting scheme – Investor's viewpoint

Weighting of Policymaker's criteria per weighting scheme							
	Non-renewable primary energy	Global Warming	Metal depletion	Levelized Generating Cost	National to total expenses	Local to national labour	Institutional burden
Social focus	7%	7%	7%	20%	**20%**	**20%**	20%
Environmental focus	**13,30%**	**13,30%**	**13,30%**	20%	10%	10%	20%
Economic focus	7%	7%	7%	**40%**	10%	10%	20%
Institutional focus	7%	7%	7%	20%	10%	10%	**40%**
Equal focus	8,30%	8,30%	8,30%	25%	12,50%	12,50%	25%

Table 33: Weights of criteria per weighting scheme – Policymaker's viewpoint

9.3. Ranking with PROMETHEE II and Sensitivity Analysis

The PROMETHEE algorithm was ran from both viewpoints and for the different weighting schemes described above. Then, rankings were calculated by applying PROMETHEE II, where the alternatives are ranked with an absolute order[9]. In order to have better understanding and control of the problem, all calculations have been performed on Excel spreadsheet, without the use of additional software.

As expected, different priorities and points of view result in different classifications of the candidate alternatives. Rankings are presented in Tables 34 and 35 below for the various weighting schemes.

	Ranking of alternatives - INVESTOR			
#	**Social focus**	**Economic focus**	**Technical focus**	**Equal focus**
1st	2.4m, DM1	2.4m, DM1	2.4m, DM1	2.4m, DM1
2nd	4.2m, DM1	4.2m, DM1	4.2m, DM1	4.2m, DM1
3rd	2.4m, DM2	2.4m, DM2	2.4m, DM2	2.4m, DM2
4th	4.2m, DM2	4.2m, DM2	4.2m, DM2	4.2m, DM2
5th	Commercial	Commercial	Commercial	Commercial
6th	2.4m, DM3	2.4m, DM3	2.4m, DM3	2.4m, DM3
7th	4.2m, DM3	4.2m, DM3	4.2m, DM3	4.2m, DM3

Table 34: PROMETHEE II rankings for different weighting schemes - Investor's viewpoint

[9] While PROMETHEE I allows for incomparability between alternatives

	Ranking of alternatives - POLICYMAKER				
#	**Social focus**	**Environmental focus**	**Economic focus**	**Institutional focus**	**Equal focus**
1st	4.2m, DM1	4.2m, DM1	4.2m, DM1	4.2m, DM2	4.2m, DM2
2nd	4.2m, DM2	4.2m, DM2	4.2m, DM2	4.2m, DM3	4.2m, DM1
3rd	4.2m, DM3	4.2m, DM3	4.2m, DM3	4.2m, DM1	4.2m, DM3
4th	2.4m, DM1	2.4m, DM1	2.4m, DM1	Commercial	2.4m, DM2
5th	2.4m, DM2	2.4m, DM2	2.4m, DM2	2.4m, DM2	2.4m, DM1
6th	Commercial	Commercial	Commercial	2.4m, DM3	Commercial
7th	2.4m, DM3	2.4m, DM3	2.4m, DM3	2.4m, DM1	2.4m, DM3

Table 35: PROMETHEE II rankings for different weighting schemes - Policymaker's viewpoint

It was observed that, from the investor's viewpoint, ranking was stable for all weighting schemes. Investors clearly preferred participative delivery models, with the smaller LMSWT preferred over the larger one. The commercial alternative was ranked low, in the 5th position, just before the two LMSWTs with the non-participative DM3, which constitutes the least preferred option.

From the policymaker's viewpoint, it was observed that results were stable when the focus was on either social, environmental or economic categories. In these cases, the larger 4.2 m LMSWT was the first choice and was preferred to the smaller 2.4 m one, regardless the delivery model; for a specific wind turbine, the more participative models were preferred; and the commercial wind turbine was ranked 6th, only before the 2.4 m wind turbine with the non-participative DM3, which was the least preferred alternative.

However, in the last two weighting schemes, ranking was significantly altered and it was observed that this was caused by the increased weight assigned to the institutional criterion. Therefore, a sensitivity analysis was performed for the weight of the institutional criterion, assigning to it values from 20 to 60% with a 10% step. The results, shown in Figure 23, lead to the following observations.

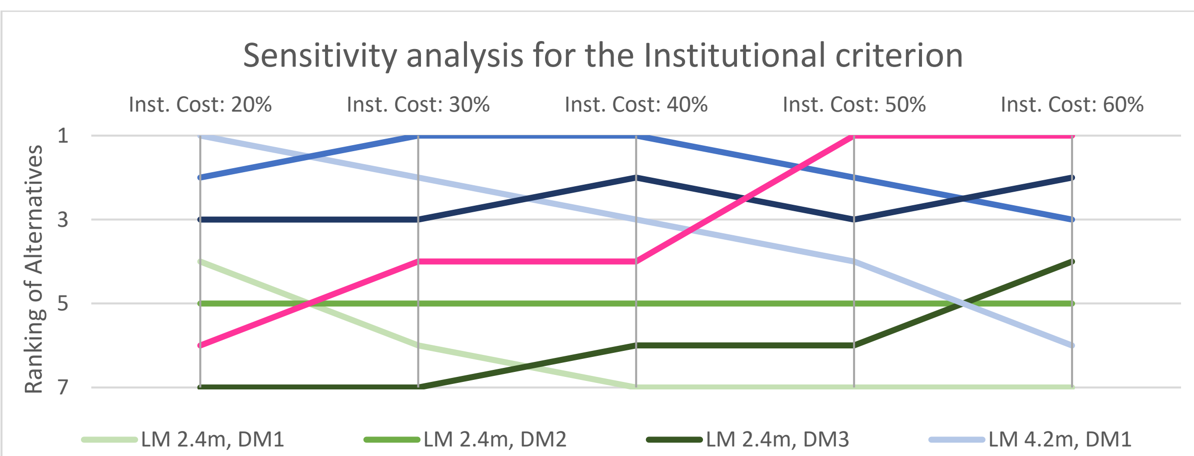


Figure 23: Sensitivity analysis for the weight of the institutional criterion

When the weight for Institutional burden was low (≤0.2), the ranking tends to be as described before. However, as the weight of the institutional criterion increases, the commercial wind turbine gains preference and less participative delivery models are preferred, as they are considered to "cost" less to the Institutions. As long as the weight is lower than 0.5, there is a common trend in the results: the larger 4.2 m LMSWT is always preferred to all others regardless the delivery model. When, however, the weight of Institutional burden is ≥0.5, the commercial wind turbine becomes the first choice.

The effect of the institutional criterion is so significant for policymakers' decisions, that it becomes clear that further analysis and expert elicitation is needed in order to define the weight that policymakers give to this criterion, but also to quantify the institutional cost that each alternative incurs.

10. Conclusions

Two sizes of locally manufactured small wind turbines employed under three different delivery models, have been compared with a commercial small wind turbine for an off-grid, rural application, from a sustainability perspective and from the point of view of investors and policymakers.

The environmental LCA methodology has been extensively applied and global, lifecycle impacts have been assessed, showing that LMSWTs have the potential to save in energy, CO_2 emissions and depletion of metals and fossil fuel when compared with a commercial alternative, but only when they are employed with participative models. Especially in remote sites where technical support can be found at a distance of 100-200 km or more, participative models should be the only solution applied, if LMSWTs are to be used -or arguably any wind turbine is to be used at all.

In addition, Transportation for Maintenance has proved to be an important source of environmental impacts for all alternatives, including the commercial SWT. The longer distance that has to be covered in rural applications and the lower electricity generation of small-scale wind turbines, necessitate that this parameter is not neglected in LCA studies of rural SWTs.

Subsequently, the seven SWT alternatives were also assessed for a set of additional indicators, in technical, economic, social and institutional dimensions. Effort was made to adopt a lifecycle approach for the assessment of these indicators as well, focusing however, on assessing impacts only on the national level of the installation country: from the perspective of sustainability as it would be understood by a national policymaker and a local investor/user.

It was observed that LMSWTs have higher availability than the commercial SWT, but only when employed with participative delivery models (DM1 or DM2). Furthermore, LMSWTs require significantly lower initial investment than the commercial alternative. However, they generally have higher O&M costs, especially if employed with non-participative DMs, and as distance for maintenance increases. As far as Levelized Generating Cost is concerned, the larger 4.2 m wind turbine has clearly the best results; the comparison between the other two SWTs is not so clear and is affected by the delivery model and the distance for maintenance. The influence of the DM is especially prominent in the most remote scenario (200 km). In this context, the smaller LMSWT employed with DM3 has by far the highest LGC, but when employed with DM1 or even DM2 it has a lower LGC than the commercial wind turbine.

The assessment of social indicators showed that around 90% of the LMSWTs' lifecycle cost is spent within the national economy, while for the commercial SWT 80% is externally spent -in the manufacturer's country, as initial purchase cost and cost of spare parts. Additionally, it was clearly shown that employing LMSWTs with participative delivery models can create employment in rural areas, supporting the local community rather than bringing expertise from distant urban centers.

Finally, an institutional indicator was considered to estimate the institutional burden implied for each delivery model to be successful. It was estimated that participative delivery models would require more support to establish the assumed infrastructure, network and local capacity in order to be functional. The commercial wind turbine, employed with a conventional model, was estimated to imply less institutional burden -only half compared to the most participative DM1.

Eventually, MCDA was deemed appropriate in order to obtain a simultaneous evaluation of all indicators. The PROMETHEE method was used to rank the alternatives from the viewpoint of investors and policymakers and perform sensitivity analysis.

It was observed that for both investors and policymakers, local manufacture combined with participative delivery models was ranked first, unless the Institutional burden of employing these models became the most significant criterion for the policymaker. In that case, policymakers opted for less participative delivery models with lower institutional burden, eventually selecting the commercial alternative when the weight of this criterion reached 50%.

This result shows that further investigation –including expert elicitation- is needed into the importance of institutional burden for policymakers, as well as to potentially quantify the performance of alternatives in this criterion. Eventually, this is a decision that has to be taken considering the “small wind turbine ecosystem” [3] that is already in place in each location. In cases where the institutional burden does not prove significant however, policies have to be devised to support the deployment of the specific model -local manufacture and participative delivery model- advocated on environmental, social and techno-economic grounds.

Future work

A limitation of this study is that it is not a real case study; instead, a generic scenario has been studied and several assumptions had to be made concerning the context, the alternatives and the stakeholders.

There are conditions that are valid in some locations but were not addressed in this study’s generic scenario. For example, in several countries, the state may provide subsidies for SWTs but only if they are certified. This would create an advantage for the commercial SWTs which could alter the results in favour of them. However, such conditions can be taken into account when a specific context is concerned.

Therefore, it is clearly understood that in a real case study, the assessment framework has to be redefined according to the existing conditions, and the content, the weights and the thresholds of criteria have to be carefully defined in constant communication with the relevant stakeholders, applying potentially the AHP method to elicit their opinions.

An additional limitation is that the 2.4 m and 4.2 m LMSWTs are not completely equivalent to the commercial SWT in terms of their rated power and annual energy production. Specifically, the former produces less while the latter produces more energy than the commercial at the same wind conditions. Therefore, more accurate results will be obtained if the assessment framework is applied for the 3 m LMSWT, which is a closer match to the specific commercial SWT.

Moreover, concerning the application of MCDA methods, a number of available software may be used to apply the PROMETHEE or another MCDA algorithm, taking advantage of the available features to examine more alternatives and scenarios, perform extensive sensitivity analysis or compare results with different methodologies.

For example, diviz [60] is a free and open-source software where different MCDA methodologies can be applied and compared and where the user is generally given many degrees of freedom to experiment with multi-criteria decision analysis. MCDA packages are also available in R, offering the opportunity to interface data analysis and decision aiding [61]. Visual PROMETHEE & Gaia [62] is the most widely used software to perform the PROMETHEE methodology. Also, MAMCA [63] is a recently published software, offering a framework to assess alternatives for multiple criteria and from multiple stakeholder viewpoints [64].

Furthermore, it would be interesting to adopt more closely the approach of Life Cycle Sustainability Assessment, assessing not only environmental, but also economic and social impacts for all the lifecycle stages of the alternatives, including the acquisition of raw materials and energy and End-of-Life.

Finally, concerning our initial question about how distributed and mass production models compare in terms of sustainability, what this study can tell us is that integrative frameworks, combining multi-criteria and multi-stakeholder approaches with specialized computational tools, are proper decision support methods to deal with such questions, applied each time for a specific application and context. It is thus possible that the approach and framework described in this study can be adjusted and applied for similar applications that are based on an ‘open design and local manufacture’ approach.

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Appendix

Calculation of parameters used for the socio-economic indicators

Distance: 20 km								
Alternatives	O&M cost/trip	O&M costs (trips) ($)	O&M costs-wages ($)	O&M costs-materials ($)	O&M local labour (persondays)	O&M national labour (persondays)	Total lifetime O&M costs (€)	Annual O&M costs (€)
2.4m, DM1	12.5$ (10$wage, 2.5$ travel allowance)	12,5	650	1500	80	92,5	1730	115,33
2.4m, DM2		37,5	750	1500	60	97,5	1830	122,00
2.4m, DM3		100	1600	2000	0	140	2960	197,33
4.2m, DM1		12,5	950	2250	120	137,5	2570	171,33
4.2m, DM2		37,5	1050	2250	90	142,5	2670	178,00
4.2m, DM3		100	2200	3000	0	200	4240	282,67
Commercial		50	500	3000	0	40	2840	142,00
Distance: 100 km								
Alternatives	O&M cost/trip	O&M costs (trips) ($)	O&M costs (wages) ($)	O&M costs (materials) ($)	O&M local labour (persondays)	O&M national labour (persondays)	Total lifetime O&M costs ($)	Annual O&M costs (€)
2.4m, DM1	32.5$ (20$wage, 12.5$ travel allowance)	62,5	800	1500	80	95	1890	126,00
2.4m, DM2		187,5	1200	1500	60	105	2310	154,00
2.4m, DM3		500	3200	2000	0	160	4560	304,00
4.2m, DM1		62,5	1150	2250	120	140	2770	184,67
4.2m, DM2		187,5	1650	2250	90	150	3270	218,00
4.2m, DM3		500	4400	3000	0	220	6320	421,33
Commercial		250	1000	3000	0	50	3400	170,00

Distance: 200 km								
Alternatives	O&M cost/trip	O&M costs (trips) ($)	O&M costs (wages) ($)	O&M costs (materials) ($)	O&M local labour (persondays)	O&M national labour (persondays)	Total lifetime O&M costs ($)	Annual O&M costs (€)
2.4m, DM1		125	1100	1500	80	100	2180	145,33
2.4m, DM2		375	2100	1500	60	120	3180	212,00
2.4m, DM3		1000	6400	2000	0	200	7520	501,33
4.2m, DM1	65$ (40$wage, 25$ travel allowance)	125	1550	2250	120	145	3140	209,33
4.2m, DM2		375	2850	2250	90	165	4380	292,00
4.2m, DM3		1000	8800	3000	0	260	10240	682,67
Commercial		500	2000	3000	0	70	4400	220,00

Distance: 20 km														
Alternatives	MP Manufacturing costs		FP Manufacturing and Installation costs			Purchasing MP		Total	Training costs		Total	Labour		
	Manufacturing costs-materials (€)	Manufacturing costs-labour (€)	Tower - materials (€)	Installation-labour (€)	Installation (foundation materials+transportation) (€)	Delivery costs ($)	Import duty ($)	Total capital costs (€)	Training costs (€)	Toolbox (€)	Total capital costs (incl training) (€)	Wind turbine manufacturing-labour (persondays)	Installation-labour (persondays)	Training labour (persondays)
2.4m, DM1									360	228	2863			15
2.4m, DM2	650	675	300	450	200	-	-	2275	180	228	2683	56.25	37.5	7.5
2.4m, DM3									-	-	2275			-
4.2m, DM1									360	228	4706.75			15
4.2m, DM2	1200	1181.25	600	787.5	350	-	-	4118.75	180	228	4526.75	98.4375	65.625	7.5
4.2m, DM3									-	-	4118.75			-
Commercial	4595		300	450		459.5	-	5804.5	-	-	5804.5	-	37.5	-

Distance: 100 km														
	MP Manufacturing costs		FP Manufacturing and Installation costs			Purchasing MP		Total	Training costs		Total	Labour		
Alternatives	Manufacturing costs-materials (€)	Manufacturing costs-labour (€)	Tower - materials (€)	Installation-labour (€)	Installation (foundation materials+transportation) (€)	Delivery costs ($)	Import duty ($)	Total capital costs (€)	Training costs (€)	Toolbox ($)	Total capital costs (incl training) (€)	Wind turbine manufacturing-labour (persondays)	Installation-labour (persondays)	Training labour (persondays)
2.4m, DM1									400	228	2903			16.67
2.4m, DM2	650	675	300	450	200	-	-	2275	200	228	2703	56.25	37.5	8.33
2.4m, DM3									-	-	2275			-
4.2m, DM1									400	228	4746.75			16.67
4.2m, DM2	1200	1181.25	600	787.5	350	-	-	4118.75	200	228	4546.75	98.4375	65.625	8.33
4.2m, DM3									-	-	4118.75			-
Commercial	4595		300	450		459.5	-	5804.5	-	-	5804.5	-	37.5	-
	Distance: 200 km													
	MP Manufacturing costs		FP Manufacturing and Installation costs			Purchasing MP		Total	Training costs		Total	Labour		
Alternatives	Manufacturing costs-materials (€)	Manufacturing costs-labour (€)	Tower - materials (€)	Installation-labour (€)	Installation (foundation materials+transportation) (€)	Delivery costs ($)	Import duty ($)	Total capital costs (€)	Training costs ($)	Toolbox ($)	Total capital costs (incl training) (€)	Wind turbine manufacturing-labour (persondays)	Installation-labour (persondays)	Training labour (persondays)
2.4m, DM1									496	228	2999			20.67
2.4m, DM2	650	675	300	450	200	-	-	2275	248	228	2751	56.25	37.5	10.33
2.4m, DM3									-	-	2275			-
4.2m, DM1									496	228	4842.75			20.67
4.2m, DM2	1200	1181.25	600	787.5	350	-	-	4118.75	248	228	4594.75	98.4375	65.625	10.33
4.2m, DM3									-	-	4118.75			-
Commercial	4595		300	450		459.5	-	5804.5	-	-	5804.5	-	37.5	-