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Sustainable Rural Electrification: Harnessing a Cosmolocal Wind

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Abstract: In this article, we explore the sustainability potential of an alternative commons-based mode of production called cosmolocalism. Cosmolocal production combines global knowledge production with local physical production. Such a production mode has been applied across the globe for locally manufacturing small wind turbines (SWTs) for rural electrification. We assess the sustainability of such cosmolocal SWTs in a case study of electrifying a rural community in Ethiopia. In this context, the life cycles of five SWT alternatives have been compared, ranging from conventional industrially produced turbines to open-source locally manufactured and maintained ones. Our case study indicates that the local manufacturing and maintenance of SWTs offer significant advantages and may redeem small wind turbines as a sustainable component for rural electrification. Specifically, the fully cosmolocal alternative (A1) performs better than any other alternative in technical, environmental, and social criteria, while it is close to the best-performing alternative with regard to economic objectives. For this solution to be implemented, the institutional burden cannot be neglected, but can rather be considered a sine qua non condition for locally manufactured and maintained SWTs. A set of generic institutional interventions to create favourable conditions for cosmolocal production is proposed, which needs to be elaborated in a context-specific manner.

Keywords: sustainability; life cycle assessment; integrated assessment; small wind turbines; rural electrification; commons-based peer production; sustainable production

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1. Introduction

Transitioning to sustainable energy systems is a major concern at a global level, considering the existential threat of the climate crisis. However, the goal of universal access to sustainable energy will remain elusive without addressing global inequalities [1]. The sustainability, justice, and democracy of energy systems depend on diverse factors that are not purely technical; on the contrary, energy systems should be understood as complex and dynamic systems that comprise technical, economic, social, cultural, environmental, and institutional components [2]. These components influence the operation of energy systems at different scales, leading to the development of various spatial patterns that require the adoption of energy policies on a case-by-case basis [3,4]. Therefore, we need to understand energy systems as socially embedded and, as such, foster their development and innovation at not only technical levels.

Recent decades have seen the gradual liberalisation and decentralisation of energy grids with the proliferation of renewable energy technology. It has been posited that large-scale applications of renewable energy production may cause significant environmental damage on local communities and the environment [5]. Large-scale energy projects are typically installed in rural areas, often disturbing local ecosystems and forcing local residents to resist the degradation of their natural surroundings [6]. Liberalisation of energy also means that individuals can engage in small energy production, but typically within a context of market interactions. This creates a somewhat false sense of empowerment as individuals 'participate at the very last level of a stratified and unequally distributed system which is designed to favour those with the most economic and political power' [2,7], without actually engaging in all levels of energy production.

The issue becomes significantly more challenging in the electrification of remote rural environments. Long distances, sparse population, complex natural terrains, and lack of political will may pose significant challenges for grid expansion in these contexts. While issues of energy democracy and energy justice are particularly relevant in these areas, the exploration of energy solutions designed and appropriate for rural areas is limited [8]. Combining different renewable energy sources, such as solar, hydro, and wind, local demand for electricity can be satisfied with small-scale renewable energy technologies, providing a sustainable solution for the nearly 1 billion people living today without electricity [1] or being dependent on fossil-intensive solutions, such as diesel generators [9,10].

Parallel to the developments in renewable technologies of the past decades, the advent of information and communication technologies has enabled the emergence of a novel mode of production in society. Termed commons-based peer production (CBPP), it was first observed in the unrestricted collaboration of individuals across the globe to coproduce free and open-source software [11] and later in physical manufacturing too. Studies have tracked its manifestation in applications, such as computer hardware and research equipment, farming tools [12], renewable energy systems, prosthetics [13], and even buildings [14]. In some of these instances, such as agriculture and small-scale electrification, it builds on the concept of appropriate technology [15], which aims to produce technologies suitable for local socio-economic conditions. CBPP revitalises and provides an umbrella for the appropriate technology movement, whose activity significantly waned in the early 1990s [16].

Artefacts developed within this mode of production are made available under open licences, essentially making them digital commons. This enables a configuration for CBPP, coined cosmolocalism [17], where knowledge production is free and global while physical production is local, albeit on a small scale, adapted to local needs, and ideally taking place in collaborative open spaces with the capacity for manufacturing, typically called makerspaces [18]. This would enable the 'scaling wide' of production activities through a networking of multiple local spatialities, rather than the scaling up as is common in conventional practices.

Overall, proponents of cosmolocalism highlight the sustainability and affordability potential of such a production mode, as it presumably reduces reliance on obfuscated global supply chains built on economies of scale, and enables on-demand, localised production, which utilises a shared physical and digital infrastructure [13,19]. Applied to energy production, it could potentially enable local communities to tap into designs for technology available in these digital commons, as well as create designs that are suitable for their local market availability for materials, and environmental conditions and capacities.

Here, we adopt the case of small wind turbines (SWTs) as an exemplar of a renewable energy technology that can be compatible with the cosmolocal paradigm. SWTs have been used for generations by farmers in rural areas for productive uses, such as water pumping and grain milling, and more recently for aquaponics applications, food processing, and refrigeration of agricultural products. With the falling price of solar panels though, commercial SWTs are gradually considered less of a cost-competitive solution. Even in off-grid regions with consistently high wind resources, the maintenance requirements of SWTs hinder their wide adaptation [20,21]. Manufacturers are typically located thousands of kilometres away from installation sites, making maintenance a very time-consuming and costly process. Additionally, in several cases, manufacturing companies have shut down, leaving customers without technical support and spare parts [22].

However, what is often disregarded is the fact that SWTs can be manufactured using only basic tools, techniques, and materials, and can thus be produced and maintained locally [21]. Although SWTs may not be appropriate for all rural areas, it has been suggested that manufacturing SWTs locally creates 'a much greater potential than the limited circumstances in which [they are] currently employed' [23] (p. 10). Using basic workshop facilities and open designs shared as a digital commons [13,23], nonexperts can manufacture, install, and maintain small wind turbines. Around the world, practitioners produce such 'locally manufactured small wind turbines' (LMSWTs) in sizes ranging from 1.2 to 7 m rotor diameters [24]. Especially in rural off-grid areas, LMSWTs can be a socially embedded factor that boosts the autonomy of local economies through the open sharing of knowledge [14].

Hugh Piggott is a pioneer small wind expert who has developed a wind turbine design made of locally sourced materials using simple tools and techniques. His seminal manual, *A Wind Turbine Recipe Book*, [25] available in more than 10 languages, and the organisation of educational workshops for building SWTs, have facilitated the dissemination of this technology across the globe. Inspired by Piggott's work, a growing community of organisations, universities, NGOs, enterprises, and individuals has been established to support the local production and maintenance of SWTs. More than 50 organisations are connected today through the Wind Empowerment association, a global platform that fosters communication, education, and networking in the field of rural electrification with SWTs. Such organisations, which can also be found in other sectors, such as agriculture, share an open-source ethos and uphold it as the binding element for forming global connections with like-minded individuals and groups.

Rather than being optimised for high-rated power, these LMSWTs are designed for functioning even at low-average wind speeds, making them potentially appropriate in contexts where typical SWTs available in the market would not make sense [20]. Their manufacturing and maintenance typically follow a bottom–up approach to build decentralised technical capacity, often engaging local schools and NGOs [26]. This approach lays the foundation for successfully addressing the high maintenance requirements of SWTs, which is often cited as the main barrier to their sustainable diffusion in rural areas [20,21,26]. Another common barrier, which is the high capital cost of commercial SWTs [27], can be overcome with LMSWTs, as they have significantly lower capital cost, thanks to their open-source design, simple materials, and potential to be manufactured locally.

Considering their potential to be produced and maintained locally, LMSWTs could arguably be more sustainable than conventional SWT alternatives [21]. However, empirical assessments of their sustainability are still limited [13,28] and fragmented. LMSWTs have been compared with commercial alternatives in terms of their financial viability [29]; their life cycle environmental impacts have been explored [30]; and their scalability and adaptability potential to fit different societal landscapes [13,24], as well as their potential to boost the local economy [23,31], have been discussed. However, an integrated assessment of their environmental, social, and economic impacts, in comparison with commercial alternatives—currently missing from the literature—could inform both practitioners and policymakers who are interested in integrating small wind turbines in rural electrification schemes. Furthermore, while previous studies have explored the contours of developing energy production technology under a cosmolocal configuration [13,32], sustainability assessments of this production mode are limited. Emerging in seed forms within the dominant system, it is difficult to gauge its potential for sustainability in a systematic way, simply because the infrastructures associated with it have yet to be developed.

In this study we attempt to evaluate the cosmolocal dynamic in the small niches it manifests and extrapolate its structural dissemination in society, while at the same time informing these nascent structures to achieve the most sustainable forms possible. For this purpose, we compare the sustainability potential of small wind turbines developed under the cosmolocal versus commercial market configurations through a case for the electrification of a rural community in Ethiopia. We employ a framework to simultaneously assess sustainability indicators for five SWT alternatives, ranging from cosmolocal LMSWTs to commercial ones. At the first level, we aim to explore how different ways of producing and maintaining SWTs affect their sustainability. The underlying goal is to examine whether this small-scale application of cosmolocalism does foster more sustainable electrification practices and discuss its wider implications afterwards.

The paper is structured as follows: Section 2 describes the methodology used in this study, including the sustainability assessment framework and relevant data sources. Section 3 presents the case study, specifying the context and compared alternatives, the sustainability indicators used, and the results of the analysis. Section 4 discusses the key findings of the study and its implications on the sustainability potential of cosmolocalism, and the last section offers our concluding remarks.

2. Methodological Framework

To examine how local manufacturing and maintenance influence the sustainability of an SWT in a remote off-grid area, the studied context was set by a case study of rural community electrification in Ethiopia. The multidimensional sustainability issue of renewable energy systems was addressed by adopting the concept of 'delivery models', which is used in the energy access and development literature to describe possible ways for energy projects to overcome barriers towards sustainability and scale-up [33]. We investigated both locally manufactured and commercial SWTs that follow different delivery models regarding their manufacturing, operation, and maintenance. Differences derive from contextual specificities, including legal and institutional frameworks to which the delivery models should conform to satisfy diversified needs and expectations.

2.1. Assessment Scheme

The sustainability assessment framework employed in this study integrates the environmental life cycle assessment (LCA) methodology with the assessment of socio-economic, financial, technical, and institutional indicators. Performing an environmental LCA for LMSWTs has been proposed by scholars in the hopes of pinpointing sustainable alternatives to the conventional model of mass production [13,30,34,35]. Additionally, a combination of diverse criteria is vital for assessing rural electrification systems in off-grid areas since, for instance, it has been posited that purely economic assessments would possibly result in further environmental degradation and social inequities in already-disadvantaged areas [36,37]. To this end, our analysis criteria integrate various sustainability dimensions and the life cycle perspective into an integrated life cycle assessment framework.

The sustainability indicators for the assessment were defined through a review of the literature on sustainability assessment of electricity generation systems and semistructured interviews with a multidisciplinary group of rural electrification experts and practitioners within the Wind Empowerment network. As such, a set of sustainability indicators was selected, considering that they should be: (a) relevant to the goal and scope of the assessment and the studied context, (b) coherent with sustainability assessment frameworks in the literature, (c) sufficient to highlight diverse aspects and differences among the alternatives, (d) able to cover at least three dimensions of sustainability (environmental, social, economic), and (e) able to be calculated with reliable data and methods. Building on previous LCA applications on electricity generation systems [38–40], we applied the methodology of attributional LCA to assess environmental indicators and a life cycle approach for nonenvironmental indicators.

2.2. Data Sources

For the calculation of the socio-economic, financial, technical, and institutional indicators, data were obtained from reports generated in the context of the studied project in

Ethiopia [41], case studies of SWT experiences available in the literature [35], and empirical information gathered by practitioners through the Wind Empowerment association.

For the purposes of the environmental LCA, inventory data for the materials, energy, and fuel consumed during the life cycle of an LMSWT were acquired directly from SWT practitioners of the Wind Empowerment network. However, inventory data for the commercial SWT could not be acquired from the manufacturer. In fact, even the bill of materials alone could not be provided. The lack of access to primary data from the company led us to seek secondary data in the literature. To this end, inventory data of a commercial 5 kW horizontal axis wind turbine [42] were used and scaled down to 1 kW.

Restricted access to manufacturing data for industrial products is arguably a wider trend, due to both the unwillingness of private firms to offer such information and the labyrinthine global supply chains. While the latter can potentially be true for artefacts produced with commons-oriented practices, whatever information can be provided is by definition accessible, especially in the case of highly localised production (meaning using local materials and manufacturing infrastructure). Such data restrictions for commercial products often hinder a robust evaluation of their life cycle impacts and the transparent comparison of different artefacts.

3. Case Study Analysis

3.1. Specification of Context

In the context of the PRIME (Pastoralist Areas Resilience Improvement through Market Expansion) project, four organisations, V3 Power from the UK, Nea Guinea and RurERG from Greece, and ILWP-Tanzania from Tanzania, in collaboration with the Wind Empowerment association and Mercy Corps Ethiopia, implemented a rural electrification project in Handew, a village situated 15 km away from the capital of the Somali region of Ethiopia, Jijiga.

During this project, a 3 m rotor diameter wind turbine was manufactured locally and installed along with 300 W of solar panels to electrify a local shop in Handew. The electric load of the shop comprised a small fridge, lights, and mobile phone charging and was estimated to be at 1.2 kWh daily. The measured wind speed in the area had an average of 3.12 m/s at 12 m, while a Rayleigh wind distribution was considered as a reference according to the IEC standards [43]. A view of the rural settlement where the wind turbine was installed is shown in Figure 1.

Figure 1. The rural settlement in Handew. Reprint with permission, rurerg.net (accessed on 24 May 2022).

The small wind turbine was manufactured during a 7-day training course at the Jijiga Polytechnic College (Figure 2). A total of 22 participants attended, including students, graduates, and teachers of the college. Hugh Piggott's *Recipe Book* [25] was used as a reference for its manufacturing process. During the course, participants were divided into three working groups, each focusing on a different part of the construction: metalwork, woodwork, and generator. At the end of each day, summary sessions were held for the working groups to share what they had learnt. Photos from the training course are shared in Figure 2.

Figure 2. Small wind turbine construction course at the Jijiga Polytechnic College. Reprint with permission, rurerg.net (accessed on 24 May 2022).

Upon completion of the course, the wind turbine, along with the solar panels and the electrical system, was installed with the help of the participants to electrify the shop of the rural settlement in Handew (Figure 3). Thanks to the provision of training to local students and technicians in Jijiga, maintenance of the wind turbine occurs locally, minimising transportation and downtime.

Figure 3. The 3 m wind turbine installed next to the shop in Handew. Reprint with permission, rurerg.net (accessed on 24 May 2022).

This type of SWTs is aligned with cosmolocal principles, considering the utilisation of open knowledge and collaborative manufacturing and maintenance of a shared infrastructure. This activity has been considered the base alternative in our comparative assessment, which was compared with other SWT alternatives, such as that of importing a commercial SWT as presented next.

3.2. Specification of Alternatives

The 3 m rotor diameter LMSWT manufactured during the course in Jijiga was compared with a mass-produced commercial SWT from Bergey Windpower. The main technical specifications (Table A1) and photos (Figure A1) of the two compared wind turbines can be found in the Appendix A. The selected wind turbines entail different delivery models in terms of their production and maintenance processes. These delivery models range from conventionally manufactured commercial ones to the commons-driven cosmolocal ones discussed earlier. Such delivery models have been recorded in surveys conducted within the Wind Empowerment association [44]. Drawing from these empirical data, we explore how the different models of deploying an SWT may impact its sustainability.

The examined delivery models are summarised below:

- Delivery Model Local 1 (DM-L1) includes the local manufacturing and installation of the wind turbine led by an SWT business within Ethiopia and the provision of training to local students and engineers in Jijiga so that they can provide maintenance services locally.
- Delivery Model Local 2 (DM-L2) includes the local manufacturing and installation of the wind turbine led by an SWT business within Ethiopia. However, no training is provided to the locals in this case, so maintenance is provided by an SWT business in a nearby city.
- Delivery Model Conventional (DM-C) includes importing an industrially produced commercial SWT, for which the installation and maintenance are provided by an SWT business within Ethiopia, and spare parts are imported on demand. No training is provided in this case.

Another parameter that we included in the analysis was the distance of the in-country SWT business from the installation site. For this purpose, two urban centres in Ethiopia were considered as possible locations where the SWT business is operating: (i) Dire Dawa (DD), located 140 km away, and (ii) Addis Ababa (AA), located 600 km away from the installation site.

Thus, considering the three aforementioned delivery models in addition to the two possible locations of the SWT business, the following alternatives were formed:

- Alternative A1 (DM-L1): Local manufacturing and maintenance in Jijiga (base alternative).
- Alternative A2 (DM-L2, DD): Local manufacturing and maintenance support provided from Dire Dawa.
- Alternative A3 (DM-L2, AA): Local manufacturing and maintenance support provided from Addis Ababa.
- Alternative B1 (DM-C, DD): Imported wind turbine and spare parts, maintenance support provided from Dire Dawa.
- Alternative B2 (DM-C, AA): Imported wind turbine and spare parts, maintenance support provided from Addis Ababa.

In that sense, alternatives A1, A2, and A3 refer to cosmolocal manufacturing processes but differ in the way that maintenance is provided. At the other end of the spectrum, alternatives B1 and B2 describe conventional processes, where the manufacturing and maintenance of technologies are 'closed', leaving scarce or no room for users' engagement.

Besides the base alternative (A1) that was implemented in Handew, all others are hypothetical for the specific context. As such, assumptions were made regarding their life cycle based on data from other case studies where such alternatives are implemented, but adjusted to the specificities of the case. The basic parameters regarding the lifetime operation of the five alternatives, such as maintenance frequency and electricity generation, are presented in Appendix A (Table A2).

3.3. Selection of Sustainability Indicators

In Table 1, we present the multicriteria hierarchical structure followed in this article, which includes the sustainability dimensions, indicators, and relevant units of measurements.

Table 1. The set of sustainability indicators employed for the assessment of the SWT alternatives.

Sustainability Dimension	Indicator	Unit
Environmental	1. Global warming potential	gCO_{2eq}/kWh
	2. Nonrenewable primary energy	MJ/kWh
	3. Metal depletion	gFe_{eq}/kWh
Technical	4. Availability factor	-
Financial	5. Initial investment	€
	6. Annual O&M costs	€/year
	7. Levelised generating cost	€/kWh
Socio-economic	8. Local to national labour rate	-
	9. National to total expenses rate	-
Institutional	10. Institutional burden	Qualitative

Delving into the environmental sustainability indicators used in our analysis, LCA was performed for three impact categories (i.e., global warming, metal depletion, nonrenewable primary fossil energy) using the RECIPE and cumulative energy demand methods.

The technical aspect of sustainability was calculated through the availability indicator, which equals the percentage of time the SWT is available to produce electricity, thus excluding the time that it is inactive due to maintenance (pre-emptive or corrective).

The financial aspect comprises three main elements: (a) the initial investment, including all material and labour costs during manufacturing, training, and installation in the case of LMSWTs, and similarly, for the commercial SWTs, initial investment comprises the retail price, the delivery cost, and the installation cost; (b) the annual operation and maintenance (O&M) costs, which include materials, labour, and transportation costs for performing maintenance; and (c) the levelised generating cost (LGC), calculated as the ratio of the total generation costs to the total generated electricity throughout the wind turbine's lifetime, considering an appropriate discount rate.

Concerning the socio-economic indicators, the national-to-total expense rate is the ratio of the expenses made at the national level over the total expenses throughout the wind turbine's life cycle. In other words, it reflects the percentage of wealth that stays within the national economy, an important indicator particularly for developing countries. Further, the local-to-national labour rate is the ratio of local labour to total national labour, which reflects the provision of employment in remote areas. This ratio is, for instance, increased in the case of the first delivery model due to the participation of the locals in maintenance.

Finally, the institutional burden, as will be further discussed in Section 4, is used as a qualitative indicator to describe the generic cost of interventions required for the delivery models to function as described. Such interventions include issuing policies, offering incentives, establishing infrastructure, supportive network, and local capacity. It is assessed on a scale of 1 to 5, where 1 indicates minimum and 5 maximum burden.

3.4. Calculation of Sustainability Indicators

An attributional LCA was carried out to calculate environmental impacts from cradle to grave, according to the ISO standards [45,46] and using the SimaPro software. Both the moving (blade rotor, generator, mounting frame, and yaw system) and the fixed parts (tower and foundation) of the wind turbines were included in the assessment.

As depicted in Figure 4, the considered life cycle stages were manufacturing, installation, operation and maintenance, end of life, and transportation between these stages, as well as the upstream processes of material, fuel, and energy acquisition. A substantial difference between locally manufactured and commercial small wind turbines is the location where the life cycle stages occur. Many of the life cycle stages of LMSWTs take place within the country of installation. This is further depicted in Appendix A (Figure A2).

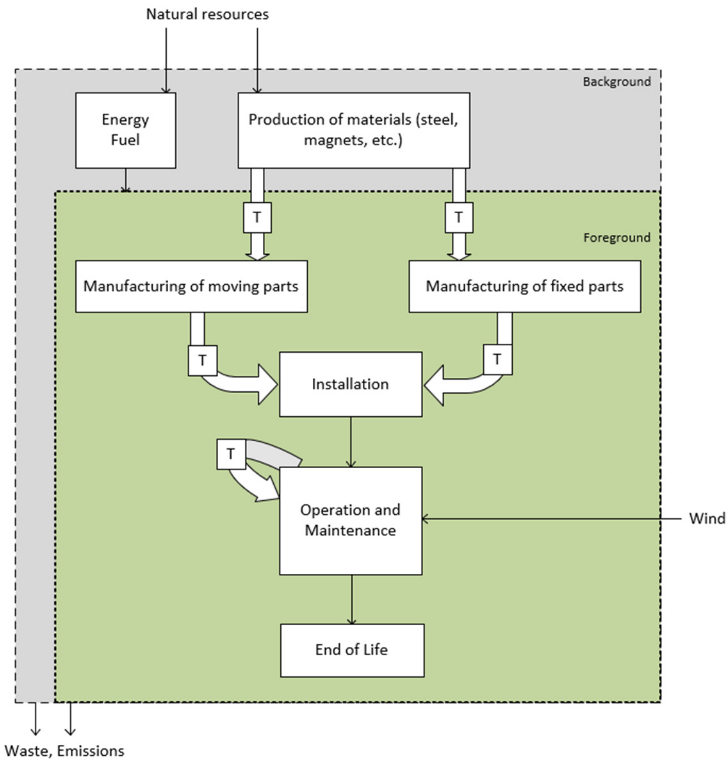

Figure 4. Flowchart of a small wind turbine's life cycle stages: Foreground processes are depicted in green colour, and background processes in grey colour. T represents transportations. Reprint with permission [47].

Regarding nonenvironmental indicators, a life cycle approach was applied but with the following limitations: (i) the end-of-life and upstream processes were not considered, and (ii) the assessment was limited within the country where the wind turbines are installed. For instance, for the LMSWTs, manufacturing of moving parts was considered within the system boundary as it takes place within the country, whereas the same process for the commercial SWT is considered as the process of purchasing moving parts, given that manufacturing occurs outside the national boundaries in this case.

Regarding the institutional criterion particularly, alternatives were rated according to the assumed institutional burden of the delivery model employed. Alternatives B1 and B2 employed with the conventional delivery model imply the lowest institutional burden since the conditions to realise this model presumably exist in most countries. The conventional delivery model would have also implied some institutional burden if we had assumed that effort was made to reduce delays associated with importing and performing maintenance for commercial wind turbines. Instead, we have accepted these delays as the 'business-as-usual' scenario, and have accounted for them in our calculations, so no additional burden was assumed for this delivery model.

The delivery models DM-L1 and DM-L2 both entail manufacturing the wind turbines locally within the country of installation. Fostering the development of a small wind industry based on local manufacture requires stable institutional support, as evidence from successful initiatives suggests [23]. More specifically, institutional support may be needed to create market opportunities for local manufacturers, to provide the physical infrastructure required for the LMSWTs to work properly, to develop standards and guidelines related to the operation and maintenance of LMSWTs [48], to conduct research and development [23], and to ensure adequate ancillary services, such as supply chain, maintenance network, and local capacity [49]. Considering the institutional changes needed for LMSWTs to be effectively implemented in local contexts, DM-L1 and DM-L2 were assigned high values of institutional burden. DM-L2 was assigned the value of 4. DM-L1 was assigned the maximum value (5) since more radical interventions are required for these models to be applied, as will be further discussed in the next section.

With these considerations in mind and based on the definitions detailed in Section 3.3, the specified sustainability criteria have been calculated for the five SWT alternatives, and the results are depicted in Table 2. All input data and used equations for the calculation of the sustainability criteria may be found in the Supplementary File S1.

Table 2. Performance of the SWT alternatives in the sustainability criteria: for each criterion, best performance values appear in green colour, and worst performance values in red colour.

		Technical	Financial			Environmental			Socio-Economic		Institutional
		Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6	Criterion 7	Criterion 8	Criterion 9	Criterion 10
Indicators		Availability	Initial Investment (€)	Annual O&M Costs (€/year)	Levelised Generating Cost (€/kWh)	Non-renewable Primary Energy (MJ/kWh)	Global Warming (gCO_{2eq}/k	Metal Depletion (gFe_{eq}/kWh)	Local-to-National Labour Rate	National-to-Total Expenses Rate	Institutional Burden
Alternatives	A1	0.992	3207	148	0.75	1.680	136.424	41.178	0.289	0.937	5
	A2	0.959	2632	197	0.76	3.766	278.762	56.671	0.000	0.941	4
	A3	0.918	2828	392	1.16	11.735	820.713	113.351	0.000	0.963	4
	B1	0.959	5801	131	1.59	2.955	232.862	63.495	0.000	0.270	1
	B2	0.938	5997	229	1.89	8.133	585.047	100.377	0.000	0.415	1
Direction		*max*	*min*	*min*	*min*	*Min*	*min*	*min*	*max*	*max*	*min*

Regarding environmental criteria, the 'fully' cosmolocal alternative with local maintenance (A1) has by far the best performance. However, in the cases of external support for maintenance (from either Dire Dawa or Addis Ababa), the commercial alternatives B1 and B2 score better than the cosmolocal ones A2 and A3. This can be explained by the fact that LMSWTs need more frequent maintenance; therefore, proximity of maintenance services is crucial for their sustainability. Regarding financial criteria, all the cosmolocal alternatives (A1, A2, A3) need a significantly lower initial investment than the commercial ones (B1, B2), while the commercial alternatives have lower annual O&M costs. When both these criteria are considered, as in the levelised generating cost, the cosmolocal alternatives A1 and A2 score the best, and even A3 has a lower LGC than the commercial alternatives.

Regarding socio-economic criteria, all the cosmolocal alternatives have a very high percentage of their total expenses spent within the country of installation, unlike the commercial ones. The cosmolocal alternative A1 has also the best score at the 'local-to-national labour rate' criterion, as it is the only alternative that entails local labour. Regarding the 'availability' criterion, A1 has the best performance, followed by A2 and B1 (the SWTs serviced from Dire Dawa). The cosmolocal alternative A3 (serviced from Addis Ababa, 600 km away from the installation site) has the worst performance in this criterion, indicating again the unsustainability of LMSWTs when a local/regional supportive network is not established. Finally, regarding the institutional burden, as already mentioned, all the cosmolocal alternatives require increased support compared with the commercial alternatives.

In summary, A1, the fully cosmolocal scenario, performs better than any other alternative in technical, environmental, and social criteria, while it is close to the best-performing alternative with regard to economic objectives. For this solution to be implemented, the institutional burden, namely, the offering cost of issuing policies, offering incentives, and establishing infrastructure, a supportive network, and local capacity cannot be neglected, but can rather be considered a sine qua non condition for the locally manufactured and maintained alternative. In the next section, we discuss the implications of our findings and reflect on the potential for wider implementation of the cosmolocal configuration for production.

4. Discussion and Policy Implications

Our analysis indicates that the cosmolocal alternative (and the one that was actually implemented) tops all categories of indicators, including the environmental ones, despite them, potentially, not being a priority. It is reasonable to assume so, given the financial hurdles that local communities face in developing countries, unless environmental performance is translated into cash flows (i.e., subsidies or penalties for pollution). Further, it is clear that relevant costs rise when maintenance technicians are located far away from the installation sites (600 km in this case).

Maintainability also arose as a crucial factor for the sustainability of SWTs, especially the locally manufactured ones. Our results confirm the evidence in the literature, where SWTs are often recorded inactive due to the lack of local resources required for maintenance or the inability of suppliers to provide spare parts [23,50]. Developing the capacity for local action tackles this issue significantly, while potentially enhancing the regional and national economy through job creation and value added within the country. For example, combining LMSWTs with solar technology to generate energy for productive uses, such as processing of agricultural products, can mobilise cooperatives to offer organisational and technical expertise, as well as optimising electricity use among production units and household consumers [51].

Obviously, the case is highly context specific; however, we attempt to draw generalisations that would be applicable in other contexts. While the technical and financial indicators are fairly clear-cut, the socially derived ones were defined considering the local socio-political context in Ethiopia based on discussions with the project team and secondary resources. The institutional burden indicator, specifically, is purposefully broad to account for multiple country/location-specific hurdles and institutional inertia. In other words, it refers to the structural considerations that would be required for the wider adoption of the commons-oriented cosmolocalism. Currently still in seed form, but continuously expanding, the various initiatives across the globe under its umbrella function in the fringe of the current market-oriented industrial mode of production. For lack of actual infrastructure to support the relevant activity, it requires certain assumptions to tentatively test its sustainability.

Within this context, our Ethiopian case constitutes an ideal congregation of the necessary social groups and interests to successfully implement the model. Recreating the capacity elsewhere requires additional and significant efforts, hence the rating of 5 in our analysis as opposed to 1 assigned in the conventional model, which, presumably, would not require any noteworthy structural change. Needless to say, the institutional interventions required to create favourable conditions specifically for locally manufactured and maintained SWTs should be studied in a context-specific manner. However, for the purposes of this paper, we can foresee the following for further applications of the cosmolocal framework:

- Create communal manufacturing facilities, in the same vein as makerspaces, fab labs, hackerspaces, and other types of small-scale fabrication that have been proliferating the past few years [18,52].
- Establish an institutionalised network of local technicians capable of providing training and maintenance services locally.
- Devise the legislative protocols and legal provisions to recognise and institutionalise this type of activity, as it does not fit within the private or public sector frameworks.
- Create the necessary incentives, monetary or otherwise, for more businesses and individuals working in the design and manufacturing of technologies to adopt an open-source business model, as current business practices demand aggressive antagonistic behaviours for financial viability.

Viewed under a sustainability transition literature lens, our case study here may draw direct parallels to the widely utilised multilevel perspective framework [53], which describes how innovative activities outside established regimes may gain momentum and grow. Regimes comprise the established technologies, practices, rules, institutions, and social groups that stabilise the incumbent systems. The locally manufactured small wind turbines, which we study here, form a radical niche within the existing energy regime. Cosmolocalism can be viewed as a mode of production that cuts across multiple socio-technical regimes in society. It offers the blueprint for transitions based on the principles we described above. Building on this blueprint, Giotitsas et al. [2] explored how the entire energy regime could be reconceptualised around the concept of energy as a commons.

The institutional recommendations provided above imply a concerted governance action that would shape an overall favourable environment initiated at the regime level with regard to the LMSWTs as niches. The interaction between the regime and related niches is crucial for encouraging or hampering the deployment of emerging technologies and the development of relevant business models towards the energy transition [54]. The case of LMSWTs analysed here in a rural context exemplifies how the transition to cosmolocal modes of production could actualise.

Regarding the type of state partnership envisioned for such a transition through cosmolocalism, commons scholars [19,55] have been developing the framework of coexistence between civil society and the state. This framework is conceptualised as an evolution of the welfare state built on the basic tenets and practices of commons-based peer production. Overall, the welfare state attempts to complement capitalist production by redistributing wealth in order to tackle externalities, such as environmental degradation and income inequality [19]. The commons framework proposes shifting the focus from redistribution to predistribution, building on the productive dynamics of the commons, while the process of commoning internalises externalities by incorporating productivity within social and ecological limits [19]. It is within this type of state partnership that we see the cosmolocal configuration thriving towards sustainable production in a rural context and beyond.

5. Conclusions

In this article, we provided an evidence-informed understanding of the sustainability dynamics of a commons-based model for energy production. LMSWTs were analysed as an emerging mode of producing energy that could strengthen the sustainability of decentralised energy systems, bridging demand and supply and enabling the governance of energy systems at a local scale. Five small wind turbines were assessed that range from commercial ones to open-source locally manufactured and maintained ones. The analysis included environmental, technical, socio-economic, financial, and institutional indicators. Different scenarios were explored with regard to the maintenance of wind turbines, which includes various distances that need to be covered so that maintenance is provided.

The fully cosmolocal alternative came up as the best-performing solution in environmental, financial, socio-economic, and technical criteria—thus, arguably the most sustainable. However, when maintenance is not locally provided, the proximity of the service centre is crucial, especially for LMSWTs. Overall, our study indicated that the local manufacturing and maintenance of SWTs offer significant advantages and may redeem small wind turbines as a sustainable component for rural electrification—provided that the policies to support it are in place. Such policies should be planned not only at a national scale but also at a local and regional level [56], matching the context-specific nature of SWTs and empowering local actors to participate in the energy transition.

The outcomes of this study can be used as a reference for the generic performance of LMSWTs in rural areas compared with conventional alternatives. Given that decisions on how to produce and maintain technologies are highly context dependent, more in-depth, transdisciplinary, and place-based assessments that engage local actors [57] should also be conducted on a case-by-case basis. Still, for the goals of this study, the case illustrates a significant promise for the sustainability potential of the emerging cosmolocal configuration.

The way applications of the cosmolocal configuration could be bridged with contextual specificities, including existing regimes, infrastructures, and practices, remains an open question. A study of successful cases of LMSWTs in different contexts or other artefacts entirely could shed light on relevant opportunities, barriers, and appropriate strategies to deal with them. A broader understanding of sustainability, which includes cultural, ethical, and political aspects, could also bring to the fore additional impacts of commons-based technologies and delivery models that might have been missed in this study.

It is worth emphasising that the advantages observed in the preferred SWT alternative were achieved not through technological innovation but rather by a different way of organising the production and delivery of technology in local settings. This research highlights the sublimity of delivery models that tap into global knowledge commons and build local capacity to enable manufacturing and maintenance of technologies. To this end, cosmolocal principles and processes could point an alternative way forward towards the pertinent question of sustainable production in society. Still, for such commons-based practices to be sustainable, great hurdles need to be surpassed and radical changes should be made. However, considering the looming concerns over the climate crisis and the ongoing supply chain disruptions, it is now the time, more than ever, for such ambitious change.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en15134659/s1, Spreadsheet S1: Input data and calculations.

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Appendix A

Table A1. Specifications of the compared wind turbines.

Compared Wind Turbines		
Wind turbine	**LM 3 m**	**Bergey XL.1**
Wind turbine topology	3-blade, horizontal axis wind turbine (HAWT)	
Generator topology	Axial flux permanent magnet	Radial flux permanent magnet
Rotor diameter (m)	3	2.5
Rated power (W)	900 (at 11 m/s)	1000 (at 11 m/s)
Annual yield at 3.12 m/s, 12 m (kWh)	630	470
Lifetime of moving parts (years)	20	20
Lifetime of fixed parts (years)	30	30

Table A2. Basic parameters for the five SWT alternatives.

	Alternatives	Frequency of Maintenance Activities [1] (Times/Lifetime)	Lifetime Distance Covered for Maintenance [2] (km)	MTTR [3] (days)	Operating Time per Year [4] (days)	Lifetime Electricity Generation [5] (kWh)
A1	LM, DM-L1	20	600	3	362	12,496.4
A2	LM, DM-L2, DD	20	5600	15	350	12,082.2
A3	LM, DM-L2, AA	20	24,000	30	335	11,564.4
B1	Commercial, DM-C, DD	10	2800	30	350	9013.7
B2	Commercial, DM-C, AA	10	12,000	45	342.5	8820.5

[1] LMSWTs typically require more frequent maintenance than commercial ones. Based on expert opinions and previous literature [36], we assumed that maintenance for the LMSWT is conducted once per year, while for the commercial SWT, once per 2 years. [2] Calculated for each SWT alternative based on the associated frequency of maintenance, distance of technicians to the installation site, and lifetime of the wind turbines. [3] Mean time to return, which is the average time needed for a repair. It measures resilience. MTTR values have been assigned to each alternative after expert elicitation to reflect reasonable repair times associated with each delivery model. [4] Calculated based on MTTR and frequency of maintenance. [5] Calculated for each SWT alternative based on the annual yield of the wind turbine, the operating time per year, and the lifetime of the wind turbine.

(**a**) (**b**)

Figure A1. The compared wind turbines: (**a**) a 3 m rotor diameter locally manufactured small wind turbine (source: rurerg.net, accessed on 24 May 2022); (**b**) a Bergey XL.1 (source: bergey.com, accessed on 3 July 2020).

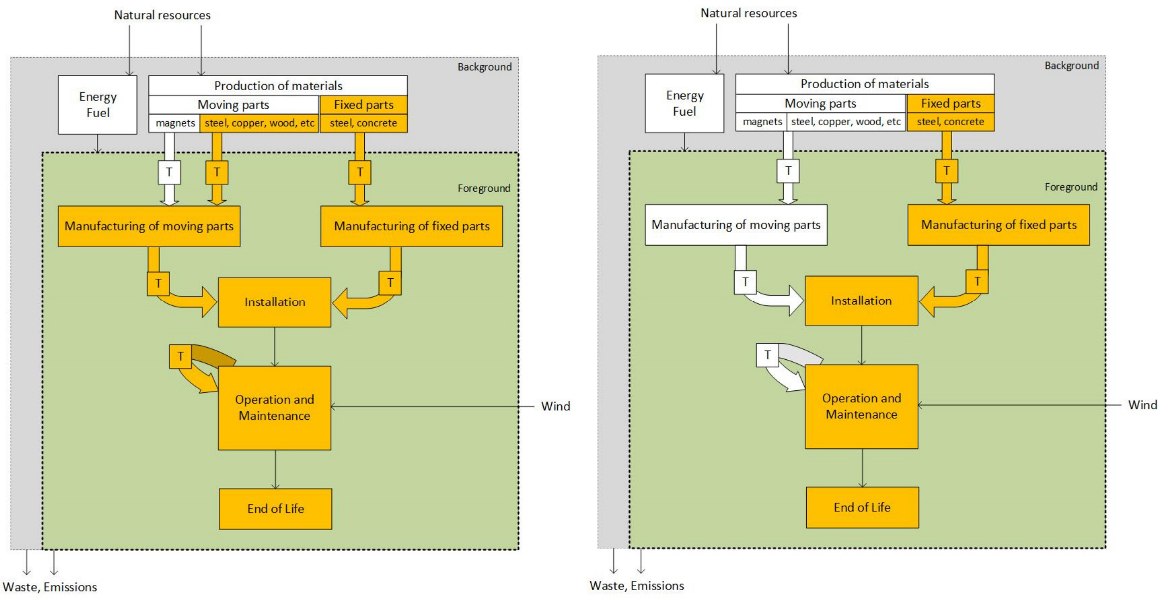

Figure A2. Wind turbine life cycle stages taking place 'locally': the stages that occur within the country of installation are depicted in yellow, for the locally manufactured (**left**) and the commercial wind turbine (**right**) [47].

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