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Decentralized renewable energy technology alternatives to bridge manufacturing sector energy supply-demand gap in East Africa: A systematic review of potentials, challenges, and opportunities

Meselu Tegenie Mellaku [a,b,*], Yibeltal Tebikew Wassie [b,c], Pernille Seljom [d,e], Muyiwa S. Adaramola [a]

[a] Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences (NMBU), P.O. Box 5003, NO-1432, Ås, Norway
[b] Wondo Genet College of Forestry and Natural Resources, Hawassa University, P.O. Box 128, Shashemene, Ethiopia
[c] Chalmers University of Technology, Department of Space, Earth, and Environment; Division of Energy Technology, SE- 412 96, Gothenburg, Sweden
[d] Department of Energy Systems, Institute of Energy Technology (IFE), PO Box 40, Kjeller, NO-2027, Norway
[e] Department of Technology Systems, University of Oslo (UiO), Norway

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ABSTRACT

The economy of East Africa (EA) is striving for a structural transformation with a strong focus on expanding the manufacturing sector. However, challenges related to modern and reliable energy supply have hindered the sector's growth performance across the region. This systematic review explores the potential, opportunities, and challenges to integrating decentralized renewable energy solutions to bridge the energy supply-demand gap in the EA's manufacturing sector. It also provides up-to-date insights into the extent of integration of decentralized renewable energy technologies in the EA manufacturing sector. Relevant data and information for the review were retrieved from 46 references, including databases and web-based sources. The findings highlight that the EA region possesses abundant untapped solar, wind, and bioenergy resources that can close the sector's energy supply-demand gap. The review also reveals that renewable energy solutions are becoming increasingly techno-economically competitive with conventional energy sources for hybrid and stand-alone applications in the manufacturing sector. However, several challenges impede the integration of decentralized renewable energy technologies in the sector, including a lack of enabling regulatory frameworks, limited financing options, limited access to renewable technologies, and a lack of skilled labor. Nonetheless, international initiatives aimed at supporting developing countries in combating climate change can help overcome the region's financial and technological constraints by facilitating technology transfer, capacity building, and offering affordable financing options. Furthermore, the ambition of East African nations to expand their manufacturing sectors presents a stimulating opportunity to accelerate the integration of decentralized renewable energy technologies into the sector.

1. Introduction

Countries in East Africa (EA) are experiencing higher economic growth compared to the African average [1]. However, the manufacturing sector's contribution to Gross Domestic Product (GDP) and employment is still low, even by African standards [2,3]. Meanwhile, the economic growth of these EA countries is challenged by infrastructure deficit, including energy [4]. The food and beverage sector is the dominant manufacturing sub-sector in EA (Fig. 1), accounting for over 50 % of the manufacturing in most of the countries in the region.

Recently, national growth plans and strategies aimed at expediting structural economic transformation in countries of the EA have placed a greater emphasis on the manufacturing sector. For example, Kenya, Uganda, and Ethiopia have set ambitious targets to boost the economic contribution of the manufacturing sector. Kenya targets to enhance the manufacturing sector's contribution to GDP to 20 % by 2030 from 7 % by 2023, creating ample employment opportunities [6]. Uganda aims to raise the manufacturing sector's contribution to GDP from about 15 % in

* Corresponding author. Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences (NMBU), P.O. Box 5003, NO-1432, Ås, Norway.

E-mail address: meselu.tegenie.mellaku@nmbu.no (M.T. Mellaku).

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Acronyms

AI	Artificial Intelligence
AREI	African Renewable Energy Initiative
BG	Biogas
CF	Capacity Factor
CHP	Combined Heat and Power
CSP	Concentrated Solar Power
DRETs	Decentralized Renewable Energy Technologies
EA	East Africa
Eff	Efficiency
FC	Fuel Cell
GDP	Gross Domestic Product
HAWT	Horizontal Axis Wind Turbine
HTF	Heavy Fuel Oil
IC	Installed Capacity
IEA	International Renewable Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPP	Independent Power Producers
IRENA	International Renewable Energy Agency
ISCC	Integrated Solar Combined Cycle
LCOE	Levelized Cost of Electricity
LFO	Light Fuel Oil
MW	Mega Watt
NDC	Nationally Determined Contributions
ORC	Organic Rankine Cycle
PPA	Power Production Agreements
PPPs	Public-Private Partnerships
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PV	Photovoltaic
R&D	Research and Development
R&T	Research and Technology
RE	Renewable Energy
RET	Renewable Energy Technology
RETs	Renewable Energy Technologies
SDG	Sustainable Development Goals
SDG-7	Sustainable Development Goal 7
SDG-8	Sustainable Development Goal 8
SDG-13	Sustainable Development Goal 13
SHIP	Solar Heat in Industrial Processes
SSA	Sub-Saharan Africa
SWOT	Strengths Weaknesses Opportunities and Threats
TVET	Technical and Vocational Education and Training
USA	United States of America
USD	United States Dollar
VAT	Value Added Tax

2018/2019 to 26 % in 2029/30 and enhance its share of national employment contribution from around 10 % to 15 % during the same period [7]. Ethiopia aims to increase the manufacturing sector's contribution to GDP and employment by approximately ten percentage points each between 2019/20 and 2029/30 [8].

However, the growth of the emerging manufacturing sector in EA countries is challenged by inadequate infrastructure, including the energy infrastructure, which has a negative multiplier effect. Electricity access is low in the EA [9,10]. Power outages, high electricity and fuel costs in Rwanda, low electrification and costly energy alternatives in Uganda, volatile power supply, and low electrification in Tanzania are some of the energy infrastructure challenges facing the manufacturing sector [11]. Power interruption and power shortage are two of the top challenges limiting the sector's performance in Ethiopia [12]. Generally, weak economic infrastructure, including the absence of adequate energy supply and high cost of supplementary energy generation technologies to mitigate the energy supply-demand gap, are the major barriers that constrain the development of the manufacturing sector in the region [2]. The energy deficit not only limits the growth of the manufacturing sector in the region but also hinders the entire social and economic development [10]. Additionally, the growing consumption of fossil fuels in the emerging industry sector is contributing to rising carbon emissions [13]. Besides, recent studies suggest the potential of renewable energy technologies (RETs) for unlocking energy infrastructure constraints in EA. For example, Wesseh and Lin agree with Gordon on the potential of RETs to power industries in EA [14,15]. Gordon outlines the role of wind and solar energy in addressing the region's energy challenges. Wesseh and Lin also highlight the future potential of replacing non-renewable energy with renewable energy. A review of solar thermal utilization for industrial heating and cooling in Global and Ethiopia reveals the potential benefits of integrating solar thermal into the manufacturing sector [16]. Furthermore, discussing the availability of untapped renewable energy resources in the EA region, McMillan outlined the comparative advantage of expanding low-cost green manufacturing in

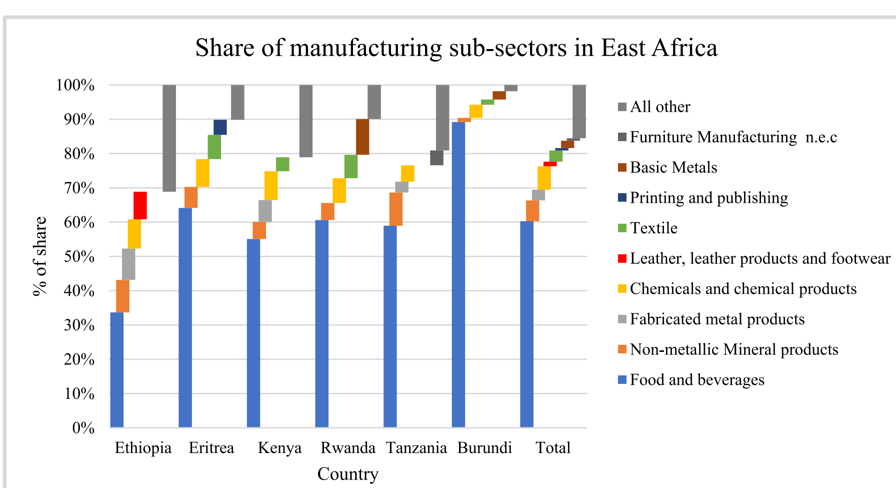

Fig. 1. Manufacturing sub-sector distribution in EA [5].

the EA region using renewables [17]. The study also indicated that EA's low-cost green manufacturing stimulates domestic and foreign investment in manufacturing in compliance with international climate commitments. Studies such as [18,19] also found that adopting RETs increases export performance. Hence, the potential for expanding green manufacturing in EA, as well as the role of green manufacturing in increasing export intensity, promotes the realization of the ambitious structural economic transformation targets in EA. In addition, the low-cost clean energy production from renewables can potentially enhance the productivity of the region's manufacturing sector [17]. Furthermore, the increased use of DRETs promotes efforts to achieve sustainable development goals of universal energy access (SDG7) and increasing decent formal and informal job opportunities (SDG8) [20]. Therefore, the role of RETs in reducing fossil-fuel consumption in the expanding manufacturing sector in EA countries strengthens their efforts to achieve national climate targets, meet the Sustainable Development Goals(SDGs), and comply with international climate agreements, such as the Paris Agreement, to which they are signatories.

However, comprehensive information on the potentials and challenges of decentralized renewable energy integration in the manufacturing sector to mitigate the energy supply-demand gap in EA is lacking. Hence, this review presents updated and synthesized information to broaden knowledge and inform policy and practice. The paper explores the potential, challenges, and opportunities of integrating DRETs into the manufacturing sector in EA. It also assesses the status of integrating decentralized solar, wind, and bioenergy technologies into the sector. The following questions are addressed in this review:

i. What is the integration status of decentralized renewable energy technologies into East Africa's manufacturing sector energy system?
ii. What is the potential of renewable energy resources and technologies to bridge the energy supply-demand gap in the East African manufacturing sector?
iii. What are the opportunities and challenges for harnessing and integrating decentralized renewable energy technologies in East Africa's manufacturing sector?

This review is unique in that it addresses the knowledge gap regarding the status of DRET integration in the EA manufacturing sector as well as the potentials, opportunities, and challenges surrounding it. It serves as a foundation for further research on the role of DRETs in bridging the energy supply-demand gap in the manufacturing sector, advancing green manufacturing, and facilitating structural economic transformation in the region.

2. Methodology

Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), a widely recognized methodological framework for conducting systematic reviews and meta-analyses, guided this review. PRISMA is a four-phase, seven-domain, and 27-item checklist guideline for a systematic review and Meta-Analysis framework [21]. The four phases of the PRISMA guideline, identification, screening, eligibility, and inclusion, encompass seven domains. The 27-item checklists embedded in the four phases and seven domains provide a structured format for reporting the review methods and findings. The guideline ensures the reproducibility of the review study. Hence, the PRISMA guideline was used for this review.

In the review process, keywords were first identified that were expected to yield relevant literature that fit the review's purpose. The search words include a combination of "Solar Energy Technology", "Biomass Energy Technology", "Bioenergy Technology", "Biomass Energy Conversion Technology", "Wind Energy Technology", "Renewable Energy Technology", "Manufacturing", "Manufacturing Industry/ Sector", "Developing Countries", "Sub-Saharan Africa, "East Africa" and related words. Searches of articles published in English between 2010 and 2024 in the Scopus database, using a combination of these keywords with Boolean operators "AND" and "OR", resulted in a limited number of articles. Hence, a snowball literature search strategy was employed to identify additional relevant literature. References of articles were examined to get additional literature, including databases, websites, and reports. The snowballing technique was further extended by exploring the citations of the newly identified articles, reports, documents, books, and book sections, creating a chain of references that enabled access to additional records, including peer-reviewed articles, websites, databases, and reports. This iterative approach not only broadened the scope of the review but also enhanced the inclusion of relevant records that might not have been identified through the initial search strategy, enhancing the comprehensiveness and depth of the review. Furthermore, SCiSpace, an AI-powered research tool [22], was used to identify additional literature with the same time frame and combination of keywords used in the Scopus database search. The self-describing PRISMA procedure used in retrieving and screening records in this review is shown in Fig. 3. In addition, a summary of the types of records included in the review, along with the publication years, is given in Table 1. The study area map is shown in Fig. 2.

3. Results and discussion

3.1. State of decentralized renewable energy technology integration into the manufacturing sector of East Africa

This subsection of the study discusses the state of decentralized solar, wind, and bioenergy technology integrated into EA's manufacturing sector. Decentralized energy production, also known as distributed energy system [24] is the option of generation and storage of energy at or proximate to the consumer site utilizing distributed energy resources [25]. This energy production option includes both grid-integrated and isolated(stand-alone) energy production options [24]. Solar, bioenergy, and wind energy technologies are among the leading RETs suitable for decentralized applications [24].

According to the IEA's [26] statistics for 2021, a significant share of manufacturing sector energy consumption in EA comes from biofuel and waste (51 %), followed by oil (23 %), coal (12 %), electricity (11 %), and natural gas (3 %) (Fig. 4). However, the manufacturing sector's energy consumption profile does not show solar and wind. This indicates that the sector's use of decentralized solar and wind energy technology is limited. Furthermore, bioenergy consumption in the manufacturing industries varies between the EA countries. The highest manufacturing sector bioenergy consumption is in Uganda (83 %)(Fig. 4).

However, according to the SHIP Plants Database and Global Energy Monitor records, in some countries of the EA, solar thermal and bioenergy decentralized energy technologies are integrated into the manufacturing sector (Table 2). Bioenergy, cogeneration using solid agricultural wastes such as bagasse, is used in sugar industries in Kenya, Ethiopia, Sudan, and Uganda. Although solar energy technologies are

Table 1
Number of records included in the review by type and publication year.

Publication Year	Count	Record Type	Count of Item Type
2011	1	Book/book section	3
2015	1	Dataset	5
2016	1	Report and documents	14
2018	1	Journal article	22
2019	3	Webpage	2
2020	5	**Total**	**46**
2021	12		
2022	8		
2023	7		
2024	7		
Total	**46**		

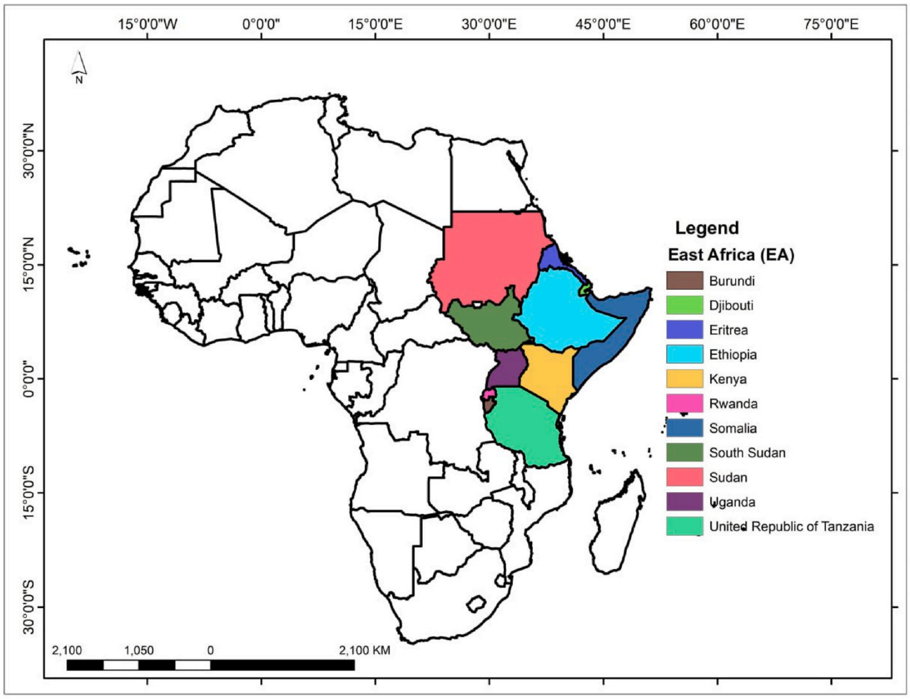

Fig. 2. Study area map.

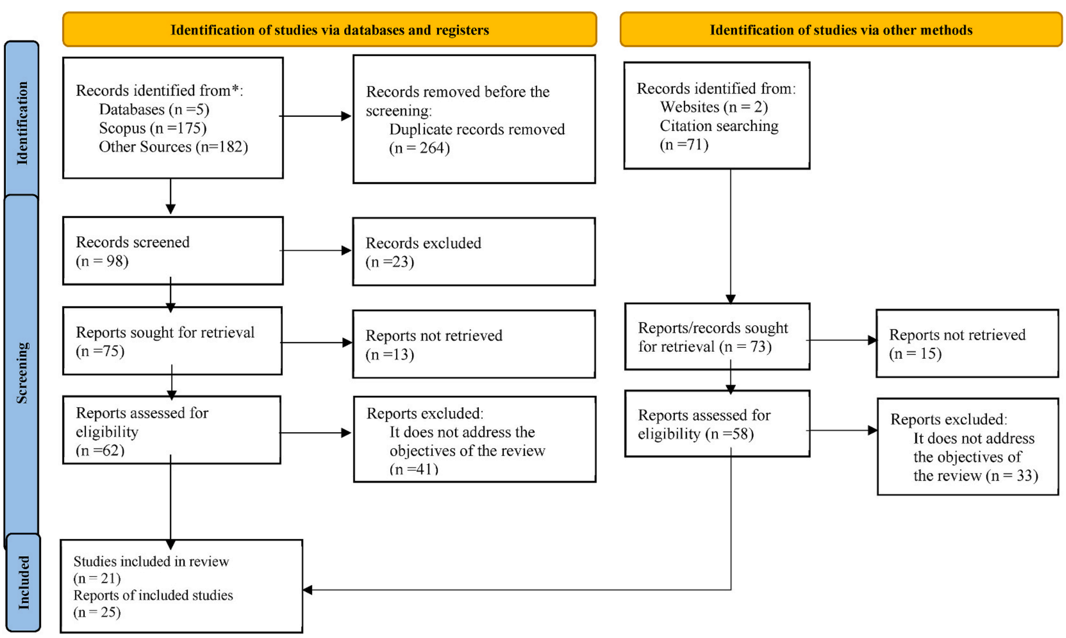

Fig. 3. PRISMA flow diagram for searching and extracting data [23].

becoming alternative sources of electricity and industrial process heat in the manufacturing sector globally [28], the integration of solar technologies into the sector in EA remains limited. For example, in Ethiopia, the use of solar technology is limited to telecommunications, water pumping, public lighting, agriculture, water heating, and grain drying applications [29]. Among countries in EA, solar thermal collectors are used only in the Kenyan manufacturing sector (Table 2). Solar home systems dominate solar PV use in EA [30]. During this review, no wind energy technology was found integrated into EA's manufacturing sector. However, EA uses wind, solar PV, thermal, and bioenergy technologies for centralized power generation.

Although DRET integration into the EA's manufacturing sector is in its infancy, the potential benefits of DRETs to the manufacturing sector are discussed in the literature. For example [33], indicated that integrating DRETs into the manufacturing sector would promote green manufacturing practices and sustainability.

[34] uncovers the potential use of biomass gasifiers to substitute high fossil fuels in the manufacturing sector in Uganda. Similarly [35], found that distributed small-scale bioenergy production is suitable for enhancing economic, social, and environmental performance in Uganda [36]. uncovered the potential of biomass briquettes as a substitute for fossil fuels in the Kenyan industry sector. The literature supports these

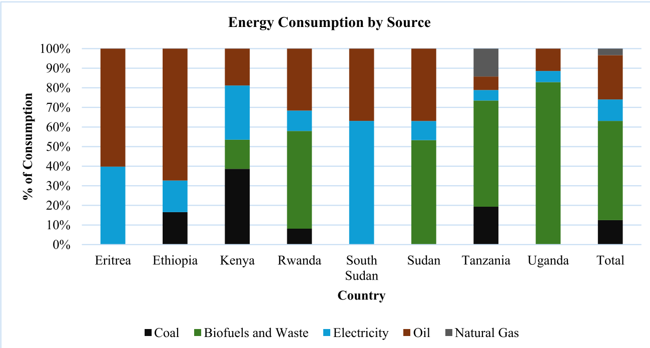

Fig. 4. Manufacturing sector Energy consumption of East Africa by source [27].

Table 2
Renewable energy technologies integrated into the manufacturing sector of EA.

Manufacturing Subsector	Integrated Renewable Technology	# of projects	Capacity (MW)	Reference
Kenya			1007	[31]
Manufacture of leather and related products	Solar thermal: Evacuated tube	01	406	
Agriculture, forestry, and fishing	Solar thermal: Flat plate	01	336	
Mining and quarrying	Solar thermal: Parabolic trough	01	231	
Sugar manufacturing	Bioenergy: Agricultural waste(solids)	01	34	[32]
Ethiopia			278	
Sugar manufacturing	Bioenergy: Agricultural waste(solids)	06	278	
Sudan			138	
Sugar Manufacturing	Bioenergy: Agricultural waste(solids)	03	138	
Uganda			30	
Sugar Manufacturing	Bioenergy: Agricultural waste(solids)	01	30	

study results. For example, the IRENA global study report outlines the potential of bioenergy to balance the energy supply system and replace fossil fuel feedstocks in manufacturing [37]. [38]uncover the role of integrating bioenergy technologies into the manufacturing sector to improve energy security with reduced energy costs and low carbon intensity of manufactured products. Furthermore, studies on the biogas industry strengthen the potential use of bioenergy (e.g., biogas) for electricity and heat applications [39]. uncovered the potential use of biogas in gas turbines (GTs), boilers, and combined heat and power (CHP) applications for countries with considerable biomass energy potential, such as those in EA. This study also emphasized the role of bioenergy technology in creating a sustainable circular economy, a state-of-the-art development path.

Furthermore, for industries in remote areas where grid infrastructure is inaccessible, integrating wind power systems into the industries is identified as a feasible option [40]. [41,42] agree on the potential of wind turbines to supply reliable power in remote areas of Ethiopia, particularly when combined with other renewable resources, such as solar. Similarly [43], reveals the potential use of wind turbines in many parts of Kenya. A global study on the application of wind turbines and photovoltaics supports findings of the studies in EA, highlighting the potential of hybrid systems, combining wind and solar energy with other energy production and storage technologies, to power industries in remote areas [40]. Hence, the integration of DRETs into the EA manufacturing sector provides multiple benefits. These benefits include replacing fossil fuels with renewable energy, promoting green manufacturing, enhancing energy security, and enabling expansion of the manufacturing sector to areas where grid access is limited or costly. A SWOT analysis study on the benefits of hydropower also finds the role of renewables to reduce imported oil dependency and improve access to energy in remote areas [44]. Furthermore, expanding DRET integration into the EA manufacturing sector could enhance its contribution to GDP and employment generation by addressing the existing sector's energy supply-demand gap.

The integration of RET into the manufacturing sector of EA is not only essential for closing the energy supply-demand gap but also promotes efforts to achieve SDGs [45], such as SDG-7 (Affordable and Clean Energy) and SDG-13 (Climate Action). A scenario modeling study on the African energy future supports that renewable energy development, accompanied by energy efficiency measures, is the priority for enhancing sustainable development in the face of climate change and population growth [46]. However, sustainable biomass harvesting concerns [37], waste disposal, and recycling of RETs [47] need careful attention.

3.2. Renewable energy potentials in East Africa for decentralized applications

This section explores two aspects of decentralized renewable energy alternatives: the region's renewable energy resource potential and the technology potential. The increasing need for manufacturing sector expansion in EA, the region's limited access to centralized power grids, and existing power failure challenges for grid-dependent manufacturing firms underscore the need for reliable and sustainable energy supply alternatives (Section 1). Decentralized renewable energy in EA may offer promising alternatives to mitigate the region's persistent energy supply challenges.

3.2.1. Renewable energy resource potential in East Africa

Although development efforts such as expansion and capacity utilization in the manufacturing sector are constrained by limited access to reliable energy, EA possesses substantial renewable energy potential. Large-scale hydro, small-scale hydro, utility-scale solar PV, biomass, and Wind are the primary renewable energy resources in EA (Table 3). The mean capacity factor, the ratio of actual output from a power plant to its maximum rated output, in EA for solar PV (24 %) is even higher than the global average (18 %) [48]. Ethiopia, Uganda, and Tanzania have higher solar PV capacity factors than the EA average. Biomass productivity, the net primary production amount of carbon fixed by plants and accumulated as biomass per year, measured in tc/ha/yr (tons carbon/-hectare/year), is also higher than the global average 3-4tc/ha/yr in EA. The yearly biomass productivity is 8.5tc/ha/yr in Burundi, Rwanda, and Uganda, 6.5tc/ha/yr in Tanzania, and 4.5tc/ha/yr in Ethiopia [48]. Only Djibouti, Somalia, and Sudan have biomass productivity less than the global average [48]. A summary of the potential of renewable energy resources in EA is given in Table 3.

According to the estimate in Table 3, the EA countries' renewable energy potential exceeds the 2023 estimate of the total grid and off-grid installed capacity from renewable and non-renewable sources by more than threefold. This demonstrates the potential of renewable energy resources to enhance energy access and energy security in the region, thereby contributing to the intended structural economic transformation, including the target of expanding the manufacturing sector.

Studies done in EA, such as [36,51], uncover the potential of biomass energy resources for modern energy production in Ethiopia and Kenya, respectively. Solar and wind are found to have the potential to cover a significant share of the electricity demand in Sudan [52]. A study on biofuel potential in EA uncovered that the region could grow

Table 3
Potential of renewable energy resources in East Africa [49,50].

Country	Hydro (MW)		Solar PV (MW)	Biomass (MW)	Wind (MW)	Total Potential (in MW)	2023 Installed Capacity (MW)	% 2023 Installed Capacity (IC) Compared to RE potential
	Large scale	Small-scale						
Burundi	331		299	308		938	253	370 %
Djibouti			1270	3	844	2117	406	521 %
Ethiopia	46831	11	16491	3981	5929	73243	11288	649 %
Kenya	1573	11	3005	1931	4970	11490	6836	168 %
Rwanda	266		330	211		807	599	135 %
Sudan	5022	10	2160	2066	5778	15036	7612	198 %
Tanzania	5242	24	8744	2138	6005	22153	4009	264 %
Uganda	4067		1711		1228	7006	2650	483 %
South Sudan	2172					2172	450	553 %
Total	**65504**	**56**	**34010**	**10638**	**24754**	**134962**	**34886**	**387 %**

drought-resistant biofuel crops to mitigate energy supply gaps when climate-dependent resources fail to supply power [53]. Although Uganda is suffering from low electricity access, the utilization of renewable energy is below a quarter of its potential [54]. Similarly, solar PV is found to be an essential resource to mitigate energy supply gaps in Kenya [55].

However, it is essential to note that the power output from wind and solar energy is weather-dependent [56] compared to bioenergy sources, such as biogas. Energy storage devices and flexible power supply sources are essential to mitigate the challenges posed by the intermittency of wind and solar power outputs [56,57]. Among flexible energy supply sources, bioenergy is a renewable option for mitigating the challenges posed by the increased integration of wind and solar energy [57]. In EA, bioenergy can serve as a flexible backup energy source for wind and solar-based energy supply systems, helping to balance energy supply by providing power when intermittent renewable sources are unavailable. Studies, for example, [58], underscore the potential role of biogas in balancing energy production gaps from intermittent renewable energy sources such as wind and solar. The availability of solar, wind, and bioenergy resources in EA, along with the balancing role of bioenergy to wind and solar energy systems, demonstrates the potential of these renewables to mitigate the energy supply-demand gap in the region. Furthermore, owing to the renewable energy potential of EA, the geopolitical benefits of increased renewable energy use outweigh the risks [59].

3.2.2. Renewable energy technology potential for decentralized applications in the manufacturing sector of East Africa

This sub-section paper explores the potential of wind, solar, and bioenergy technology for decentralized integration into the EA manufacturing sector. The potential of RETs for decentralized applications in the EA's manufacturing sector is discussed based on the progress of the techno-economic parameters of these technologies globally. The levelized cost of electricity (LCOE), capacity factor (CF), and energy conversion efficiency (Eff.) are the key techno-economic parameters used to describe the techno-economic feasibility of these technologies. LCOE is an economic parameter that decision-makers use to compare alternative energy technologies and identify the least-cost alternative. It encompasses all costs associated with the technology's installation, operation, and maintenance over its lifetime, normalized per unit of electricity produced. However, LCOE fails to account for renewables' intermittency and non-dispatchability, such as solar and wind energy [60]. Eff is the ratio of useful energy output to total energy input. It measures how effectively a technology converts energy from one form to another [61]. Cf is the ratio of the actual energy output of a renewable energy plant over a specific period to its maximum possible output if it operates at full capacity in the specified period [62]. Indicative temperature measures the specific temperature range at which a thermal technology operates, reflecting the level of heat it can generate or utilize for various applications.

Globally, the technical and economic feasibility of RETs is increasing due to increased technological innovation, policy support for increased funding for research and development (R&D) activities, economies of scale, and increasing competitiveness of technology supply and installation [63]. The following subsections discuss progress in the techno-economic feasibility of solar, bioenergy, and wind power, demonstrating their potential for decentralized use.

3.2.2.1. Potential of solar energy technologies. Solar Photovoltaic (PV) and solar thermal are the two major classes of solar technologies used to harness sunlight to produce heat and power/electricity [64]. Solar PVs produce electricity by converting sunlight into electricity using a conversion process called the photovoltaic effect [65]. Solar thermal technology harnesses sunlight to generate heat, which can be utilized for various applications such as water heating, space heating, process heating, and electricity generation [66]. Solar thermal technologies use solar collectors or mirrors of various types to concentrate and absorb solar radiation to heat a fluid such as water, molten salt, industrial oil, or compressed gas. This provides heat for heating and industrial purposes or generates steam that rotates a turbine to produce electricity [67]. Detailed descriptions of solar energy technologies that are currently commercialized and in the R&D phase can be accessed from studies such as [68].

The techno-economic feasibility of solar technologies is under continuous development due to ongoing R&D activities globally. Between 2010 and 2022, the capacity factor of CSP and solar PV technologies has increased by 19 % and 23 %, respectively (Table 7). During the same period, the LCOE of CSP and solar PV technologies declined by 69 % and 89 %, respectively. The LCOE of CSP technologies is 0.118 2022 USD/kWh [48], and the LCOE of PV is about 0.049 per kWh in 2022 USD (Table 7). The installation cost of solar technologies is generally declining, with 58 % and 83 % for CSP and solar PV technologies, respectively, between 2010 and 2022 (Table 7). Furthermore, there is a continuing effort to enhance the lifespan of solar technologies. For example [69], indicated that the service life of solar modules can be extended to 40 years. The life span of solar thermal technologies ranges between 20 and 35 years [70]. The mean life span of both solar thermal and solar PV technologies is about 25 years (Table 7). The indicative temperature of solar thermal collectors installed globally(Table 4) also demonstrates the feasibility of these technologies for industrial process heat applications in many manufacturing sectors [71]. A summary of key techno-economic parameters of solar energy technologies is given in Tables 4 and 7. Furthermore, the techno-economic performance of solar energy technologies may be higher than the global average since solar radiation is relatively higher than the global average solar radiation in EA [48], as the number of sunny hours per day and sunny days per year are higher in EA.

Furthermore, annual jobs created for installing and operating RETs

Table 4
Characteristics of solar thermal power plants integrated into the manufacturing sector globally [71].

Technology	Life Span		Installation Cost USD2020 per kW			LCOE_ USD2020 per kW			Receiver inlet Temperature (^{0}c)		Receiver outlet Temperature (^{0}c)	
	Min	Max	Mean	Min	Max	Mean	Min	Max	Min	Max	Min	Max
Beam-Down Tower Dish	20	20	5395,3	5395.3	5395.3				290	290	570	570
Hybrid CSP-PV	35	35										
Hybrid. Linear Fresnel[a]											250	250
Hybrid. Parabolic Trough [b]	25	25	8623.9	7248	9599.4	0.43	0.3	0.57	252	293	312	393
Linear Fresnel	20	25	5168.3	2929.9	7033	0.16	0.1	0.3	140	290	270	550
Parabolic Trough	10	30	7590.7	2914.1	11756.3	0.26	0.1	0.72	93	318	176	570
Power Tower	20	25	6986.7	2634.9	17909.3	0.194	0.08	0.64	290	310	540	565

[a] Linear Fresnel with Integrated Solar Combined Cycle (ISCC).
[b] Parabolic Trough integrated with Natural gas boiler or ISCC or Biomass or.

Table 5
Annual construction and operation jobs created [70].

Country/Technology	Construction jobs per year		Operation Jobs per year	
	Min	Max	Min	Max
China	1200	1500	50	100
Beam-Down Tower	1500	1500	52	52
Linear Fresnel	1300	1300		
Parabolic Trough	1300	1300	100	100
Power Tower	1200	1500	50	100
France	10	10	3	3
Linear Fresnel	10	10	3	3
Spain	300	950	1	85
Hybrid, Parabolic Trough			30	30
Linear Fresnel			1	25
Parabolic Trough	300	950	31	85
Power Tower	800	800	45	45
Thailand	120	120	10	10
Parabolic Trough	120	120	10	10
United States	50	1896	5	90
Dish	50	50	5	5
Hybrid, Parabolic Trough				
Parabolic Trough	350	1500	30	85
Power Tower	130	1896	12	90

are also other aspects of renewable energies considered during decision-making. Given that renewable energy technology(RET) is competitive with other substitute conventional technologies in terms of technical and economic parameters, the employment potential of the technology is of prime importance for regions with high unemployment, such as the EA. Based on the data accessed from an open-source database of concentrating solar power plants in the world [70], the maximum number of annual jobs created during construction ranges between 10-person jobs for constructing a hybrid parabolic trough in Egypt, a Linear Fresnel in France, and 1896 annual person jobs for constructing a power tower in the USA. About 1500 annual jobs were also created for constructing a beam-down tower and power tower in China, and 1500 annual jobs for parabolic troughs in the USA. The annual jobs created for the operation of solar thermal technologies vary from a single-person annual job to operate Linear Fresnel in Spain to 100 annual-person jobs to operate parabolic troughs and power towers in China (Table 5).

Therefore, the increasing techno-economic feasibility of solar energy technologies globally, combined with the availability of solar radiation in EA countries, demonstrates their potential in supplying heat and electricity in EA. Furthermore, the employment potential of installing, maintaining, and operating solar energy technologies promotes the realization of employment targets outlined in their national growth plans.

3.2.2.2. Potential of bioenergy technologies. Biomass energy is the largest and sole carbon-based renewable resource plant produced through photosynthesis [72]. In other words, it is a form of renewable energy called bioenergy derived from recently living biological material (biomass) [73]. Furthermore, biomass is a resource available in almost all countries worldwide that can be considered a CO_2-neutral energy feedstock if harvested sustainably [74]. Modern bioenergy, excluding traditional domestic use of biomass, accounts for 46 % of the total renewable energy consumption globally [75] and can potentially substitute all forms of fossil fuels, solid, liquid, and gaseous [76].

Bioenergy technologies are employed to produce biofuels, heat, and power. A recent study classifies biomass-to-energy conversion processes into five classes: biochemical, physicochemical, chemical, thermo-chemical, and physical methods [77]. Each comprises several biomasses-to-energy conversion sub-processes that result in at least one type of biofuel/bioenergy form. Anca-Couce et al. add hydrothermal processing as an emerging biomass-to-energy conversion technology to this list [74]. Details of descriptions of biomass-to-energy conversion processes can be accessed in many literature, including [78].

Like solar technologies, bioenergy technologies are becoming techno-economic feasible and competitive with alternative energy technologies due to increased R&D activities in the sector. Since 2010, on average, the weighted installation cost of bioenergy has been declining (Fig. 5). The weighted LCOE of bioenergy per kWh has declined by 25 % between 2010 and 2022 [48]. The average LCOE of

Table 6
Techno-economic characteristics of renewable energy technologies [48].

Renewable Technology Type	Levelized Cost of Electricity (LCOE)		Installed cost		Capacity factor (%)		Lifetime years	Reference
	2022 USD/ kWh	% change 2010–2022	(2022USD/ kW)	% change 2010–2022	2022	% change 2010–2022		
Solar PV	0.049	−89 %	876	−83 %	17 %	+23 %	25	[48]
Onshore wind	0.033	−69 %	1274	−42 %	37	+35 %	25	
CSP	0.118	−69 %	4274	−58 %	36	+19 %	25	
Geothermal	0.056	+6 %	3478	+20 %	85	−2 %	25	
Bioenergy	0.061	−25 %	2162	−26 %	72	+1 %%	20	
Hydropower	0.061	+47 %	2881	105 %	46	+4 %		

Table 7
Summary of challenges of deployment of renewable energy technologies in East Africa.

Technology Name	Application area and region	Challenge	Reference
Bioenergy /Biomass	Energy and material feedstock use, global	Lack of financing options, lack of regulatory frameworks facilitating innovation and adoption of bioenergy technology, cultural and awareness barriers in addition to the cheap oil price, high cost of bioenergy technology, and concerns of sustainable supply of biomass	[37]
	Energy generation in EA (Ethiopia)	Lack of comprehensive national biomass policy and regulation, weak institutional coordination, inadequate transfer of technology and localization, and land availability and land use rights,	[112])
Solar	Industrial process heat application, global	Intermittent nature of solar energy, Shorter payback period expectations, high capital and installation costs, low fossil fuel prices, perceived risk, reluctance to change, and downtime	[113] [114]
	Energy generation in EA (Tanzania)	Absence of government commitment wrong perception of the potential of solar technologies, absence of adequate incentives for private investors, and political interference in utility and regulatory decisions	[115]
	Energy generation in EA (Ethiopia)	Absence of adequate technical skills for installation and maintenance. Absence of training institutions and lack of infrastructure, lack of suitable financing options, absence of stimulating coherent policies, lack of awareness, and poor supply chain network,	[107]
	Energy generation EA(Tanzania)	Absence of government commitment, wrong perception of the potential of solar technologies for large-scale energy production, absence of adequate incentives for private investors, and political interference on utility and regulatory decisions	[115]
Wind	Energy generation in EA (Ethiopia)	Lack of investment capital, lack of technical skill, limited awareness of the potential of wind power, Lack of supporting infrastructure, limited research, and capacity development,	[107]
	Energy Generation Africa	Preference to other alternative energy resources like hydro and limited commitment to emission reduction, Lack of financing options for windfarm development, lack of coherent enforceable government rules and regulations	[116]
	Global	High investment and maintenance costs, limited policy support to unlock market competitiveness challenges, high intermittency, land use competition, limited technical capacity to design and manufacture wind turbine blades, inadequate trained manpower and training.	[78]
	EA (Uganda)	Absence of wind resource data, high investment cost, weak infrastructure, inadequate policies, limited research and development	[117]

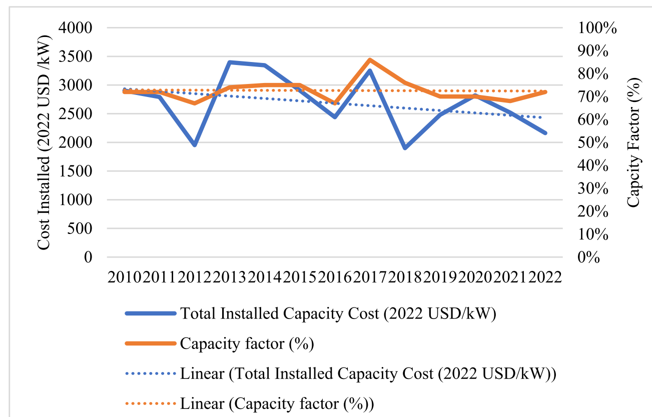

Fig. 5. Installed bioenergy capacity cost (in 2022 USD) and capacity factor (%) dynamics 2010–2022 [48].

bioenergy is 0.061 USD per kWh (in 2022 USD), and the installation cost is USD 2162 per kW with an Eff of 72 % with an average lifetime of 20 years (Table 7). The weighted capacity factor of so far installed bioenergy technologies globally ranges between 67 % and 86 % [48]. Furthermore, the techno-economic performance of bioenergy technologies may be higher than the global average, as biomass productivity is relatively higher than the global average biomass productivity of most countries in EA [48].

Furthermore, the capacity factor of bioenergy technologies is higher than that of fossil fuel, solar, and wind energy technologies [79]. In the meantime, biomass to energy conversion process outputs, power/-electricity, heat, and biofuels (solid, liquid, and gas fuels) are almost useable in all sectors, including the manufacturing sector [73]. This further indicates the unique role of bioenergy technologies in substituting fossil fuels across various sectors. Additionally, if biomass is harvested sustainably, it significantly reduces greenhouse gas emissions [74].

Biomass-to-energy conversion processes include preprocessing, feedstock collection, transportation, drying, storage, and upgrading. This characteristic of bioenergy technologies presents a unique opportunity to involve multiple stakeholders and create sustainable jobs throughout the supply chain, from biomass feedstock to the final energy production. For example, the increased use of wood for bioenergy might benefit local forest growers [73]. As a result, the increasing improvement in the techno-economic feasibility of bioenergy technologies, the availability of bioenergy resources in EA, and the suitability of the technology to substitute all forms of fossil fuels demonstrate the feasibility of the technology as a decentralized energy source for the manufacturing sector in EA. Furthermore, the potential of bioenergy technologies to reduce carbon emissions, job creation, and other economic gains associated with a sustainable supply of bioenergy resources pronounces the potential of the technology to be used as a decentralized energy source for the manufacturing sector in EA.

3.2.2.3. Potential of wind power technologies. Between 2010 and 2022, onshore wind turbines were the leading RET for capacity factor improvement, followed by solar PV. The LCOE of wind is the lowest among all RETs. The installation of onshore wind per kW is the second lowest cost, following solar PV (Table 6). Onshore wind power's LCOE and installation costs have significantly declined since 2010 (Table 6). Furthermore, a study in China revealed that the economic gain from the decentralized use of wind turbines in the manufacturing sector is significant [80]. Hence, onshore wind power is among the promising RETs globally that can be integrated into the EA manufacturing sector in suitable locations. However, the techno-economic performance of onshore wind energy technologies may deviate from the global average, since wind resource potential in EA also deviates from the global average.

Generally, the LCOE of solar PV, solar thermal, bioenergy, and wind energy technologies is either below or comparable with the electricity tariff of many countries in EA, such as Kenya, Rwanda, and Burundi [81], Tanzania, Uganda, and Rwanda [82]. The price of industrial electricity consumption in EA ranges between 0.03 USD cents per kWh and 0.163 USD cents per kWh [82]. The lowest electricity tariff for industrial consumption per kWh is in South Sudan, and the highest is in Kenya. According to the Ethiopian Electric Utility, Ethiopia's electricity tariff for industrial consumption is below one-third of Kenya's electricity tariff per kWh in the same sector [83]. This makes Ethiopia one of the countries in the EA with the lowest electricity tariffs for industries. The increased techno-economic competitiveness of RETs with conventional energy technologies demonstrates their potential for decentralized applications. The role of bioenergy technologies in serving as a flexible backup energy source for solar and wind energy technologies provides a substantial opportunity for using these technologies in combination in resource-potential countries like the EA. Furthermore, the increased use of these technologies promotes the effort to achieve sustainable development goals of universal energy access (SDG7) and increasing decent formal and informal job opportunities (SDG8) [20] in addition to the other economic gains.

3.3. Opportunities for renewable energy technology integration into the manufacturing sector of East Africa

Building on EA's renewable energy resource potential, increased techno-economic enhancement, and the increasing market deployment of RETs to integrate into the region's manufacturing sector, this subsection explores the opportunities for decentralized use of these technologies in EA's manufacturing sector.

Although DRET integration into the manufacturing sector of EA is not without challenges, new opportunities can enhance the capacity to harness the untapped renewable resources available in the region. These opportunities extend from internal national green industrialization demands to the availability of international/global technological and financial support schemes, including the effort to increase the penetration and development of RET globally.

Countries in EA are initiating new economic growth policies and strategies to eradicate extreme poverty and realize sustainable development. For example, in its new ten-year plan, Ethiopia aims to transform the agriculture-led economy into an industry by increasing the manufacturing sector's contribution to GDP following a green growth path [8]. Kenya aims to promote competitiveness, leveling the playing field for manufacturers for sustained job creation and investment growth in the sector [84]. In its five-year development plan, Tanzania planned to increase the manufacturing sector's contribution to GDP from around 6 % in 2019/20 to 10 % by 2025/26 [85]. A study on the manufacturing industry and economic development in EA pronounces the importance of structural economic transformation to industry, favoring the manufacturing sector as a historically demonstrated economic growth path [86]. The ambition of countries of EA for structural economic transformation into the energy-intensive sector, the manufacturing sector, can only be possible by integrating untapped renewable energy resources in the region. Hence, the increased demand for energy for the ambitious expansion plan of the green manufacturing sector is an internally induced opportunity to promote the integration of DRETs into the manufacturing sector. Mekhilef and his co-authors show the advantage of decentralized renewable energy utilization for industries in remote areas where the grid connection is inadequate, there is a possibility of large-scale RET integration, and the price of oil is high [28]. The EA is an example of a region with limited grid access, dependent on imported fossil fuels, and targeting the expansion of large industrial parks as a means of industrialization. Hence, integrating decentralized RETs is a promising solution to meet the energy demands of the expanding manufacturing sector in the region.

In addition to the increased energy demands, technological advancements, economic competitiveness, and the growing market deployment of renewable technologies are key opportunities that drive the increased integration of decentralized RETs. Between 2010 and 2021, the capacity factor of solar PV, onshore wind, and CSP increased by 25 %, 35 %, and 19 %, respectively [48]. Between 2010 and 2019, solar and wind technology costs decreased by 85 % and 55 %, respectively [87]. In the same period, market deployment of RETs has also increased. For example, solar technology supply increased more than 10-fold between 2010 and 2019 [87]. The IPCC report also indicated that technical advancements and cost reductions in RET costs are achieved through a mix of policy instruments, such as increases in public research and technology (R&T) funding and subsidies.

Literature also describes the complementary characteristics of RETs that can be integrated into the manufacturing sector's energy system. Hybrid renewable energy systems are becoming technically efficient and economically viable for energy production. For example, an optimization study that compared three off-grid hybrid renewable energy systems, PV/WT/BG/FC, PV/BG/FC, and PV/WT/FC, for electricity and freshwater problems in India revealed that the energy systems with more energy technologies (PV/WT/BG/FC) are technically more efficient and least cost than the other alternatives [88]. The study also uncovered that the integration of biogas (BG) into a photovoltaic (PV) and wind turbine (WT) hybrid system offered substantial cost reductions by reducing the dependency of the system on fuel cells (FC). A review study on hybrid PV-Wind turbine systems also revealed the complementary characteristics of PV and wind turbines. The wind can potentially complement the absence of solar production at night and its reduction in winter, making the hybrid PV-Wind turbine system technically more reliable than standalone systems [89]. This study also indicated that a hybrid PV-WT system is economically advantageous in reducing investment and maintenance costs. Iran, India, and China, the top three countries with the largest hybrid PV-WT installations globally, reveal the complementary role of these technologies. Mazzeo et al. also argued that the grid could play the role of the battery if the hybrid PV-WT is connected to the grid, which might be a possible option to supply energy to the manufacturing sector in countries of EA [89]. When the PV-WT hybrid system has a deficit to supply the baseload, the grid can supply the deficit power. If the hybrid PV-WT produces more energy than is required, the surplus power can be supplied to the grid [89]. Hence, the increased technical efficiency and economic feasibility of RETs, combined with increased technology learning and investment in R&D globally, are opening promising opportunities for the manufacturing sector in EA to use decentralized RETs. A case study highlighting the positive contribution of the hybrid use of PV with the co-generation system to power a computer manufacturing company in Thailand towards the progress of carbon neutrality [90] also demonstrates the potential use of RETs with other conventional technologies to close the supply-demand energy gap of the manufacturing sector in EA.

The other key global-driven opportunity to promote decentralized renewable energy integration into the manufacturing sector in EA is the availability of global cooperation frameworks, which have opened up opportunities for financial access and technology transfer. The Paris Global Climate Agreement, adopted in 2015 and signed by nearly every country in the world, is one that includes a scheme promoting the transfer of technology and financial flows from developed to developing regions, such as the EA. Particularly, the Nationally Determined Contributions (NDCs) initiative mainly targets financial, technology development, and technology transfer support to nationally initiated climate resilient and low greenhouse gas emission development strategies to least developed countries and small island developing states [91]. The agreement encourages countries to continually enhance their efforts and submit updated NDCs every five years to achieve increasingly ambitious targets. Hence, this framework enables the countries of EA to access financial and technological support to promote DRET integration into the manufacturing sector.

In the meantime, although there is no empirical evidence of the impact of the Paris Agreement on promoting decentralized renewable energy integration into the manufacturing sector in EA, a study of 22 countries covering developed and developing countries (e.g., India, Malaysia, and South Africa) indicates that renewable energy production and deployment increased by about 38 % after the Paris Agreement [92]. A similar study on the role of globalization in promoting environmental quality in India also reinforces the assertion that international frameworks play a crucial role in facilitating the deployment and adoption of renewable technologies [93]. In compliance with the Paris Agreement, most countries in the EA have also submitted at least the first NDC reports, which outline energy targets, expecting support and cooperation from the agreement. Ethiopia aimed to substitute petroleum with sustainable biomass and electricity in the industrial sector [94], while Somalia focused on producing non-forest biomass fuel briquettes and enhancing energy investments through diversified energy technologies to address energy poverty problems [95]. Kenya is targeting to build a climate-proof energy infrastructure, focusing on renewables and eco-labeling industries [96]. Rwanda promoted biomass and solar-based energy production, including biogas, waste-to-energy, and various solar applications such as water heaters and off-grid systems, to bolster energy security [97]. Tanzania outlined the diversification of energy sources from renewable energy resources, including wind, solar, bioenergy, and waste-to-energy, to expand access to clean and affordable energy [98]. Uganda focuses on energy production from renewables such as solar, wind, biomass (bagasse), and waste-to-energy [99]. The priorities identified in the NDC documents agree that diversifying renewable energy bases of energy production commonly meets the region's development targets while reducing emissions. However, decentralized renewable energy integration into the manufacturing sector lacks clear attention in the NDCs, despite its role in supporting the manufacturing sector's expansion and decarbonization targets.

3.4. Challenges to renewable energy technology integration into the manufacturing sector of East Africa

DRET integration into the manufacturing sector of EA offers opportunities to close the energy supply-demand gap, enhance energy independence, reduce carbon emissions, and support economic development (Section 3.3). However, it is stranded by many challenges. Although some challenges may be unique, the manufacturing sector shares the barriers associated with renewable energy utilization that are common to other sectors. The literature on the challenges of integrating RET into EA's manufacturing sector is scant. As a result, this study examines the challenges of integrating renewable energy into the manufacturing sector of EA, drawing on literature that discusses the challenges of utilizing RETs in a wide range of industries, including the manufacturing sector both in EA and outside of EA.

The key challenges that limit the use of RETs in EA are technical, financial, regulatory, social, and political limitations. Furthermore, the intermittency of solar and wind and the sustainability concerns of bioenergy pose significant challenges. While some of these challenges are common, others are specific to EA, underscoring the significance of customized solutions.

Among the key globally shared challenges surrounding the utilization of RETs, high initial costs, regulatory failures, and political barriers are the most common [37,100]. Intermittency, variability, and uncertainty in energy generation from solar and wind resources are the other globally shared resource-specific challenges of integrating solar and wind energy into the manufacturing energy system [101]. Similarly, the utilization of bioenergy technology as a reliable energy source for the manufacturing sector is challenged by issues associated with sustainable harvesting [37]. The low attention given to the role of bioenergy from sustainable biomass in promoting energy independence and energy security, when compared to wind and solar [102], is the other barrier impeding the adoption of bioenergy technology in the global energy market. In addition, the financial risk of substituting conventional technologies with bioenergy technologies such as biogas [39] challenges the integration of bioenergy technologies into the manufacturing sector globally. Besides, wind power development bears environmental and biodiversity challenges such as wildlife disturbance, noise pollution, visual effects, and negative impact on the land ecosystem [103]. The finding of case studies on the barriers to solar technology integration in the manufacturing sector also confirms that political, regulatory, technical, and financial barriers are determinantal for increased RETs integration into the manufacturing sector energy system. For example, a study on the barriers to solar energy technology integration into the steel manufacturing sector in India indicated that the absence of adequate incentives and skill gaps in designing, installation, operation, and maintenance are among the determinantal factors that limit the integration of RETs into the sector [47]. A similar study in Mexico also indicated that high initial cost, the comparative advantage of using alternative fuels (e.g., Natural gas), lack of training and knowledge for designing, installing, operating, and maintaining RETs, poor infrastructure, intermittency nature of RETs, and political uncertainty are the key berries [104]. These studies highlighted that establishing multi-stakeholder platforms with key stakeholders, including representatives from the public and financial sectors, the manufacturing sector, and renewable energy manufacturers, might help tackle these barriers, strengthening cooperation and reducing unintended conflicting actions. Particularly [104], indicated that tax benefits intended to reduce tax burdens and government funding to cover the substantial initial investment costs (up to 50 %) in RET are used in Mexico to promote the integration of RET into the energy system of industries, including the manufacturing sector. Bank credits, loan facilities, and government financing options are highlighted as key mechanisms to offset the high initial costs of renewable technology integration into the manufacturing sector energy system [47].

The recommendation of hybrid RETs to address the energy supply reliability challenges of using single RET also faces operational and technical challenges in meeting flexible energy demands. Coordination and control issues [105], and optimal sizing [106], which account for the selection of energy technologies, optimization of power flow, and dynamic control techniques to meet the system load demand, are some of the key challenges in addition to the investment cost of installing multiple RETs. A review study on the integration challenges for hybrid energy generation uncovered that optimization algorithms could be used to generate optimal energy required from hybrid energy systems, resolving operational challenges of the hybrid energy system such as maximizing power generation and usage from each source, dynamic power output adjustment based on energy availability, demand, and smooth energy source changeover ensuring proper integration of the energy technologies [105]. These hybrid RET integration challenges into existing establishments in congested urban areas may be enormous; however, for EA countries where the expansion of the manufacturing sector is based on new establishments, optimal sizing barriers to integrating hybrid energy technologies can be minimized by selecting appropriate manufacturing sites and integrating complementary manufacturing sectors.

In addition to the shared global challenges to integrating RETs into the manufacturing sector, the use of RETs in EA is challenged by many region-specific factors. For example, in Ethiopia, the challenges include limited Independent Power Producers (IPPs) participation, non-cost-reflective tariffs, financing gaps, grid expansion delays, and various technical, economic, and informational barriers [75,107]. Kenya RET integration effort faces inefficient administrative and regulatory frameworks, delays in signing PPA, high financing costs, land acquisition issues, and delays in grid connection [75]. High investment costs, limited human capital and training, a poor regulatory system, and a lack of institutional coordination are among the main factors limiting the progress of renewable energy integration in Uganda [108]. Similarly, weak institutional, regulatory, and legal frameworks, limited financial and technical capacity, and competition from low-cost alternative energy sources such as natural gas are the challenges to the integration of RETs in Tanzania [109]. Furthermore, a study in Ethiopia uncovered a low capability to develop and manufacture RETs locally [110], the other key challenge to promote RETs in EA. These challenges of RET deployment in EA are also shared with other countries in Sub-Saharan Africa (SSA) [111].

The summary of key challenges of using RETs in EA are summarized in Table 7.

To sum up, the challenges discussed and summarized here limit the use of renewable energy in EA in two ways. The first challenge stems from limiting existing opportunities for technology adoption by creating a protracted, corrupt, and bureaucratic local governance system that fails to establish a favorable governance framework and business environment. The absence of adequate policy and regulations, including poor institutional coordination, policy incentives to promote RET integration, and weak land use rights in EA, restricts the existing opportunities. For example, in Tanzania, the absence of government commitment, wrong perception of the potential of solar, absence of attractive incentives for the private sector, and political interference on utility and regulatory decisions are limiting the deployment of solar energy technologies in the country [115]. The absence of coherent policies, regulatory frameworks, poor institutional coordination, land use competition of bioenergy crops with food crops, and weak land use rights limit Ethiopia's adoption and manufacture of RETs [112]. The absence of suitable local financing options, low infrastructure, and limited skilled manpower to install and maintain RETs also limit the use of RETs in EA. The lack of training institutions to supply skilled manpower and the lack of infrastructure to install and maintain solar and wind energy technologies are limiting the use of solar energy technologies in Ethiopia [107]. These local challenges impeded, in one way or another, the integration of RETs into EA's manufacturing sector. Furthermore, the absence of a conducive business environment limits EA's efforts to transfer RET. For example, political instability and social unrest, the two barriers to establishing a conducive business environment, generally affect the adoption rate of RET by limiting private investment flows. An example is a study in Tunisia showing the association of government instability with decreased renewable energy adoption [118]. The political stability index of countries in EA is negative except for Rwanda [119]. Therefore, political instability is one of the key regional barriers to the increased deployment of RETs, including the integration of these technologies into the manufacturing sector. Furthermore, recent studies have also uncovered that the role of institutional quality (political stability, governance effectiveness, and control of corruption) in promoting renewable energy consumption is higher in developing countries than in developed countries [92].

The second challenge surfaces from the inadequate commitment of governments globally to prioritize and invest in RET research and innovation, compounded by the absence of suitable global financing mechanisms. This dual shortfall hampers developing and deploying competitive RETs with conventional energy technologies. For instance, the lack of political commitment to comply with international agreements, such as the Paris Agreement, has challenged efforts to foster innovations in clean technologies. The lag of technological progress in low-emission technologies, including renewables, in the USA, a global leader in RET innovation and deployment, following the withdrawal from the Paris Agreement, is an example [120]. Similarly, the withdrawal of the USA from the Paris Agreement in 2017 created an annual financial gap of USD 2 billion to set up the Green Climate Fund (GCF) [121]. The GCF is a global climate financing mechanism established in 2010 under the United Nations Framework Convention on Climate Change (UNFCC) to support developing countries like the EA region in combating climate change, including promoting clean energy technologies [122]. Such global challenges limit the integration of RETs in the EA manufacturing sector by limiting the availability of suitable RETs in the market and narrowing financial and technical support opportunities.

Therefore, overcoming the indicated regional and global challenges is a crucial step in advancing the integration of RET into EA's energy sector generally and the manufacturing sector specifically.

4. Conclusion

This review examined the potential and challenges of integrating renewable energy into the manufacturing sector in the EA, with a focus on solar, bioenergy, and wind energy technologies. The findings reveal that the integration of RET into the EA manufacturing sector is limited. Among the EA countries, only Kenya has made notable progress by integrating solar energy technology into the leather and related products manufacturing. Furthermore, while the global deployment of renewable energy continues to grow, EA's reliance on renewables other than hydropower remains low. This is despite that grid covers only 36 % of the region. The current estimate of off-grid and on-grid renewable energy other than hydropower contributes about 20 % of the total electricity. Fossil fuels contribute 30 % of the electricity generation mix. The remaining 50 % of the region's electricity is generated from hydropower. Yet, the review finds that countries in the EA have untapped renewable energy resources that exceed three times their current installed capacity.

A lack of adequate energy infrastructure and the intermittency of renewable energy sources remain as key challenges to the manufacturing sector's performance and development efforts in the EA. However, ongoing global R&D efforts have significantly improved techno-economic feasibility of RETs, making them a promising solution for addressing energy challenges in the EA manufacturing sector. Given the region's abundant renewable resources, particularly solar, wind, and bioenergy, the increasing market deployment and integration of RETs into the manufacturing sector globally signal the potential of these technologies for overcoming energy supply limitations in the manufacturing sector. Additionally, hybrid power systems that integrate wind and solar energy with bioenergy and energy storage technologies can effectively mitigate intermittency issues. Particularly in regions with potential for bioenergy resources, such as EA, integrating wind and solar energy technologies with flexible bio-fueled power and energy storage systems presents a viable option to mitigate the energy supply challenge posed by the intermittency of wind and solar. Energy storage systems could serve as a backup for DRET energy systems.

Despite these potentials, integrating DRETs into East Africa's manufacturing sector faces several challenges, including the absence of institutions dedicated to RET integration, weak institutional coordination, inadequate financing for RET deployment, limited skilled labor, and a lack of awareness about the benefits of distributed renewable energy generation for the manufacturing sector. Nevertheless, key opportunities also exist, including the untapped renewable energy potential, improved technological and economic feasibility, and increased global market deployment of RETs. Additionally, successful integration of DRETs requires addressing barriers related to technology standardization, poor integration design, installation, inadequate maintenance, and inefficient operation. This calls for effective policies, strategies, regulatory frameworks, and incentives, including investments in skilled labor and workforce development. Research highlights the importance of strong institutions and political stability in facilitating renewable energy deployment, fostering cooperation with global climate initiatives such as the Paris Agreement, and creating a conducive business environment [92]. Therefore, ensuring political stability should be a priority for countries of EA to realize the intended economic transformation through increased development of renewables in manufacturing.

Policy frameworks and strategies should foster effective collaboration among government agencies, private sector stakeholders, research and training institutions, NGOs, and the manufacturing sector to establish clear regulations on technology standardization, financing, and waste management. Financial mechanisms, such as subsidies, tax reductions, feed-in tariffs, soft loans, and public-private partnerships (PPPs), are essential to lowering the initial investment costs of RETs. Additionally, enhancing grid infrastructure to allow decentralized renewable energy generation, introducing renewable energy utilization mandates for the manufacturing sector, facilitating technology transfer, setting up technology transfer agreements and local RET manufacturing support systems, and establishing mandated RET research, development, and capacity-building institutions are all critical for the successful integration of renewables into EA's manufacturing sector. Lessons from India—a leading example of renewable energy adoption in the manufacturing sector among developing countries—demonstrate the effectiveness of such strategies [123].

Developing a skilled workforce is critical for RET deployment. This requires strengthening training institutions, such as universities and Technical and Vocational Education and Training (TVET) centers, forging partnerships with global technology providers, and fostering collaboration between industry and academia. Engaging key stakeholders—including RET manufacturers, training institutions, government bodies, and the private sector—is vital for building the necessary human capital to drive renewable energy integration [124].

Furthermore, the strong demand for manufacturing expansion in EA reinforces the need for RET capacity building initiatives and sustainable energy solutions. to meet the energy supply-demand gap in the sector.

The key findings of this review study and the research questions addressed are summarized in Table 8.

4.1. Future research Directions

This review offers a comprehensive analysis of decentralized renewable energy integration in EA's manufacturing sector, serving as a valuable resource for researchers, policymakers, and stakeholders in the sector. Future research should focus on overcoming key barriers to RET adoption and leveraging existing local and global opportunities. Specific areas for further study include:

Addressing policy and sustainable financing issues: investigating regulatory framework gaps, incentive mechanisms, and financing options to facilitate RET integration. **Empirical and pilot studies**: Conduct field and SWOT analysis studies to identify local technical and policy challenges and develop site-specific solutions for integrating renewable energy. **Simulation and economic analysis**: Evaluating the economic, financial, and environmental benefits of integrating RET systems-both with and without storage across different manufacturing sub-sectors. **Energy supply reliability studies**: Assessing the flexibility and reliability of various RET combinations in meeting the dynamic energy demands of manufacturing sub-sectors. **Resource assessments and policy synergies**: Identifying gaps and synergies in renewable energy and industrialization policies, strategies, and regulatory frameworks to promote renewable energy integration and energy transition in the manufacturing sector. **Sector-specific analysis**: Investigating opportunities and barriers for RET integration in specific manufacturing sub-sectors to develop tailored solutions. Such research will provide critical insights for policymakers, investors, and industry leaders to implement targeted strategies that accelerate RET integration in the manufacturing sector, fostering economic growth and sustainability in the region.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Table 8
Summary of findings and research questions.

Research questions	Findings
1) What is the integration status of decentralized renewable energy integration into EA manufacturing sector?	- Renewable energy integration in EA's manufacturing sector remains at its early stage despite increasing global momentum.
2) What is the potential of renewable energy resources and technologies to bridge the energy supply-demand gap in the East African manufacturing sector?	- EA countries are endowed with vast untapped renewable energy resources (solar, bioenergy, and wind) that can close the energy supply-demand gap in the manufacturing sector. - RETs, including solar, bioenergy, and wind power, are increasingly becoming techno-economically feasible for hybrid and standalone applications in the manufacturing sector.
3) What are the opportunities and challenges for harnessing and integrating decentralized renewable energy technologies in East Africa's manufacturing sector?	Key opportunities include: - The availability of abundant untapped renewable energy resources in the region, - Increasing techno-economic feasibility and market deployment of RETs globally, - Growing national demand of the countries of EA for manufacturing-driven economic transformation, and - The availability of international financial and technological support schemes (e.g., the Paris Agreement) to promote the outlined national green economic development targets of the countries of EA. Major challenges include: - Lack of adequate and supportive regulatory frameworks, - Poor institutional coordination and governance systems - Limited deployment of RET in the region, - High investment cost and limited financing options, - Shortage of skilled human capital and Information, and - Lack of awareness about the multiple potential benefits of RET integration in the manufacturing sector (energy security, green manufacturing, job creation, to mention a few)

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Data availability

No data was used for the research described in the article.

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