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Technical note

Energy transitions in Kenya's tea sector: A wind energy assessment

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ABSTRACT

Kenya's tea sector provides livelihoods for more than 500,000 farmers but energy access in the region remains limited. Clean, affordable distributed energy systems could transform the tea-growing regions by lowering tea production costs and increasing farmer profits. On-site generation could power tea factories and enhance grid stability by reducing electricity draw from the grid. Wind power's potential in Kenya's tea regions is unknown. A pre-feasibility study using the Solar and Wind Energy Resource Assessment (SWERA) data set revealed that 29% of Kenya's tea factory sites have wind resources that could be suitable for development. There were more "moderate"-rated tea factory sites west of the Rift Valley, but tea factories east of the Rift Valley had greater wind resources. Economic analysis using RETScreen found that wind power in the eastern region had a positive net present value (NPV) under a wide range of assumptions. In the base case, a 750 kW wind turbine with a capital cost of US\$1.5 million (US\$1984/kW) at the most suitable tea factory had an NPV of US\$515,779. The life cycle cost of energy at this location was estimated at \$0.156/kWh. SWERA data are conservative and may underestimate the wind resource at some locations. End use demand in the tea sector is driving the transition to distributed, renewable energy in Kenya's tea-growing regions. Whether this development can catalyze a positive feedback loop with spillover benefits to energy-poor rural communities remains to be seen.

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1. Introduction

Kenyans, particularly rural residents, are energy-poor. Nationally 16% of Kenyans had access to grid-based electricity in 2009. Kenya's per capita electricity use in 2010 was 156 kW-hours (kWh) per year compared to 4802 kWh in South Africa [1]. Although electricity access is not one of the eight Millennium Development Goals (MDGs), energy services "are essential to both social and economic development and that much wider and greater access to energy services is critical in achieving all of the MDGs" [2]. Kenya's Vision 2030, a plan to make Kenya a middle-income country by 2030, includes goals of institutional reforms in the energy sector and encouraging additional electricity generation [3]. Expanding energy access, especially electricity access in rural areas, is essential to sustainable development in Kenya.

Kenya is the world's third largest producer of tea and the tea industry provides livelihoods for hundreds of thousands of rural Kenyans. Kenya's tea factories rely on grid electricity to power the production line and biomass for thermal power to dry the tea.

Electricity alone accounts for 17% of tea production costs [4]. Tea factories are subject to frequent electricity outages in part because of their rural locations (Fig. 1). Many tea factories have diesel backup generators but these are expensive to operate [5]. Kenya is currently developing newly discovered oil reserves. Oil, however, is traded on global markets and Kenya's production is unlikely to affect the world market price of petroleum and derived products. That is, domestic oil production will not substantially lower domestic diesel or petrol prices. The rising costs of grid electricity and diesel backup led the Kenya Tea Development Agency (KTDA, a farmer-owned cooperative), the Tea Research Foundation of Kenya, and others to seek alternative sources of electricity.

The twin energy challenges in Kenya's tea-growing regions, alleviating energy poverty and increasing grid reliability, could be addressed by enhancing the electricity infrastructure in rural areas. KTDA has established a power subsidiary to support energy development at its tea farms and factories [6]. Energy production at tea farms and factories could have several benefits.

- Cost effective generation may lower the tea production costs and increase profits for KTDA's farmer-owners.
- Generating power for internal consumption can help stabilize the electricity grid in remote areas by reducing the draw from the grid.

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Fig. 1. Tea is grown in two regions east and west of Kenya's Rift Valley.

- In some cases, selling excess generation onto the grid can raise revenue for the tea factory while also supplying electricity to the grid and enhancing its stability.
- Substituting a low-carbon energy source for the diesel generators can reduce local air pollution and carbon emissions.
- Improvements in rural grids can increase energy access and spur new business models such as battery charging services.

The challenge is to identify low-cost local energy resources to support on-site electricity generation and catalyze development. Tea factories, depending on their locations, may have opportunities to develop small hydropower, solar, biomass, and/or wind energy resources. This paper offers a starting point for assessing the economic feasibility of wind power to contribute to a renewable energy transition in Kenya's tea-growing regions.

The objective of this analysis is to determine the economic feasibility of wind power to support energy transitions in the Kenya tea industry. The paper comprises testing of two pairs of hypotheses.

- Hypothesis 1: wind resource assessment
 - H1₀: less than 20% of tea factory sites will have moderate (Class 3) or higher wind resources, as indicated by the Solar and Wind Energy Resource Assessment (SWERA) for Kenya.
 - H1_A: At least 20% of Kenya's tea factory sites will have moderate (Class 3) or higher wind resources.
- Hypothesis 2: Economic assessment
 - H2₀: Hypothetical wind energy projects in Class 3 (or better) wind resource areas will be not economically efficient, as

indicated by a negative net present value (NPV) at the pre-feasibility stage.

- H2_A: Hypothetical wind energy projects in Class 3 (or better) wind resource areas will be economically efficient, as indicated by a positive NPV at the pre-feasibility stage.

The analysis integrates wind resource and ancillary data through geo-spatial and economic frameworks to assess the wind energy generation potential of tea factories. The peer-reviewed literature on the feasibility of African wind energy is rather thin. This pre-feasibility analysis is a novel contribution to the literature in that it is the first journal-published pre-feasibility assessment of mid-scale wind in East Africa. It also highlights the innovative work in the energy-agricultural nexus emerging from Kenya's vibrant tea sector. The results of the pre-feasibility study will help guide decisions about locally appropriate energy development in Kenya's tea sector. Tea factories with suitable wind resources and promising economic analyses can be targeted for site-specific investigations. Other rurally based agricultural industries in East Africa can use this as a model for transitioning to sustainable, distributed energy systems in their own regions.

The present analysis is a pre-feasibility study and is limited in scope. The assumptions are realistic and conservative. No attempt was made to find the optimum turbine size or model or estimate the actual economic returns for a particular project. This analysis also focuses solely on wind energy and does not compare wind energy to other on-site generation options. Those decisions are left for future, site-specific feasibility analyses.

Table 1
Wind resources classes as defined by the SWERA project.

Class number	Class description	Wind speed (m/s)	Wind power density (W/m ²)
1	Poor	0–4.5	0–90
2	Marginal	4.5–5.5	90–165
3	Moderate	5.5–6.5	165–275
4	Good	6.5–7.5	275–425
5	Very good	7.5–8.5	425–615
6	Excellent	>8.5	>615

2. Materials and methods

2.1. SWERA resource assessment

The wind resource assessment was based on the data from the SWERA Project. The SWERA Project produced a nationwide data set for Kenya (and other countries) on a 5×5 km grid. The SWERA wind data for Kenya are based on mesoscale models and five years of data from 10 meteorological stations nationwide. The wind speeds and power densities are reported for 50 m above ground level and it accounts for topography, surface roughness, and obstacles. SWERA's numerical values are validated with measured data [7].

The SWERA documentation classifies wind resources into six resource classes (Table 1). These classes are different from those used by the US National Renewable Energy Laboratory (NREL). The SWERA classes were used to interpret the results in this

analysis. These coarse scale (25 km²) data are useful for pre-feasibility assessments of large areas such as Kenya's tea-growing regions.

Kenya's tea farms and factories are found across 13 counties in two main regions east and west of Kenya's Rift Valley (Figs. 2 and 3). The 83 tea factory locations in the data set were provided by the Consultative Group on International Agricultural Research (CGIAR) from their *Future Climate Scenarios for Kenya's Tea Growing Areas* project [8]. The wind speeds and wind power densities were extracted to the tea factory points from the SWERA data using ArcGIS 10.

2.2. Economic assessment

The tea factory sites with the greatest wind resources were selected for additional economic analysis in RETScreen [9]. RETScreen is an Excel-based modeling tool for pre-feasibility and feasibility studies of renewable energy and energy efficiency projects. This project used a wind turbine and central grid with internal load as the basic parameters. The city of Meru was selected for the climate data location in the eastern region and Kericho was selected for the west. Each site was analyzed independently but the turbine model, cost, and financial parameters were identical in each analysis. They only varied by the local climate data and SWERA wind speeds.

A Goldwind S48 750 kW turbine was selected as the turbine model for several reasons. First, this model is available on the secondary market (even new turbines) which reduces capital costs.

Fig. 2. Thirty-nine tea farms are located east of the Rift Valley.

Fig. 3. Forty-four tea farms are located west of the Rift Valley.

Second, the model is smaller than large capacity turbines and thus easier to transport. Third, its output in favorable areas is on the order of consumption for an average Kenyan tea factory. Fourth, its size qualifies it for the Government of Kenya's feed-in-tariff (>500 kW) [10]. Many other turbine choices, both new and reconditioned, are available and may be more or less suitable for a particular project. The optimal turbine, or suite of turbines, for a particular project is a task more suited for a true feasibility study rather than a high level pre-feasibility study.

Tea factories are subject to frequent power outages and so rely on a combination of grid electricity and diesel backup generation. Electricity costs in Kenya are volatile and the average monthly rate in 2012 for 33 kV commercial grid power was \$0.16/kWh (13.9 Kenya shillings/kWh) [11]. Diesel backup electricity is considerably more expensive at \$0.36/kWh [12]. On average, grid electricity is available 93% of the time and the remainder powered by diesel generators [5]. The weighted average electricity price is \$0.173/kWh. Kenya tea factories spend between \$300,000 and \$650,000 annually on electricity [4]. The midpoint between these two figures, \$475,000, was used to establish the baseline energy consumption for the cost model. At \$0.173/kWh, a typical tea factory consumes approximately 2,745,000 kWh per year.

The proposed Corner Baridi project [13], along with other pre-feasibility assessments, served as a guide for selecting the specific inputs into the RETScreen model. The turbine cost was obtained from a supplier. Most other costs were derived from the 50 MW Corner Baridi study by calculating a cost per kW, scaling that cost to the 750 kW turbine, and adding 50% to account for the economies

of scale in the Corner Baridi project. This method captures the local capital and labor prices in Kenya but sacrifices some accuracy due to differences in project scale. These estimates were then cross-checked with other published estimates for similarly sized projects in other parts of the world to ensure that they were reasonable. This method provides a reasonably realistic picture of the capital and operating costs but it does not provide sufficient detail for a project-specific analysis.

In this model, no electricity is exported to the grid. All of the electricity generated by the turbine proportionally displaces the grid and diesel-generated electricity consumed by the tea factory. The factory is assumed to supplement the turbine's electricity with a combination of grid and diesel generation as necessary. The model does not preferentially displace the higher cost diesel generation. Investments in energy efficiency are often the most cost effective options for lowering energy costs. This pre-feasibility assessment, however, did not consider energy efficiency. It strictly focused on wind power production.

Where appropriate, the model was populated with more conservative values. For example, the debt interest rate was set at 10% based on the Corner Baridi project. It is likely, however, that KTDA would be able to obtain a more favorable rate of 6% (L. Maina, KTDA, personal communication). The model also assumes that there are no economic incentives (carbon credits, production tax credits, grants, etc.) other than the 10-year tax holiday specified in the Kenya National Energy Policy [14]. In addition, a sensitivity analysis was conducted to test the effects of several key model parameters on the project's NPV. Pre-feasibility studies have a high level of

uncertainty. Varying the key parameters by $\pm 20\%$ can illustrate the wide range of possible outcomes.

RETScreen was used to calculate indicators of financial viability such as NPV, IRR, and payback period. NPV is the sum of the discounted costs and benefits over the life of the project and is the only financial indicator that is consistent with profit maximization. Thus NPV (equation below) is the key indicator for this assessment.

$$NPV = \sum_{n=0}^N (B_n - C_n)(1+r)^{-n}$$

where n is the number of years in the project; B_n and C_n are the benefits and costs in Year n , respectively; and r is the discount rate.

An online tool from the US National Renewable Energy Laboratory was used to calculate the levelized cost of electricity (LCOE) [15]. Like NPV, the LCOE uses the discounted costs of inputs for energy production over the life cycle of the project. It differs from NPV in that LCOE is expressed as a unit cost (\$/kWh) rather than an aggregated project value. The inputs for the LCOE calculator included the capital cost, operation and maintenance cost, capacity factor, and cost escalation rate derived from the RETScreen analysis. The LCOE equation used in the analysis is below [15]. Table 2 lists the main model parameters that were used to calculate NPV and LCOE in the RETScreen and National Renewable Energy Laboratory tools.

$$LCOE = \frac{\text{Capital Cost} \times CRF \times (1 - T \times D_{PV})}{8760 \times CF \times (1 - T)} + \frac{\text{Fixed O\&M}}{8760 \times CF} + \text{Variable O\&M} + \text{Fuel Price} \times \text{Heat Rate}$$

where CRF is the capacity recovery factor; T is the tax rate; D_{PV} is the present value of depreciation; CF is the capacity factor; and O&M is operations and maintenance.

3. Context: Kenya's energy sector

3.1. Energy and the tea industry

Tea is Kenya's leading export commodity. During the 2010–2011 season, Kenya produced 399 million kilograms (kg) of made tea and earned 97 billion Kenya shillings (US\$1.1 billion) in foreign exchange [16]. Tea processing requires a substantial input of energy in the form of electricity and thermal power. Each kilogram of made tea requires about US\$0.12 electricity, a cost that doubled from

2001 to 2010 [4]. Finding ways to reduce the cost of the electricity input for made tea, from cost effective and environmentally friendly sources, is a key part of the Tea Research Foundation of Kenya's strategic plan [17]. Reducing the production cost of tea can increase the profits for tea farmers, many of whom are small landowners and members of the KTDA cooperative. KTDA 500,000 member farmers cooperatively own 65 tea factories which produced 56% of Kenya's tea crop in 2010–2011 [16].

The Kenya tea sector is on the cusp of an energy transition that could affect not only the tea industry but also rural communities of the tea-growing regions. Tea farming regions could support a number of renewable energy technologies. The Greening the Tea Industry in East Africa Project (GTIEA) investigated the potential for small hydropower development to support tea factories [5]. The wet climate and hilly terrain make many, but not all, tea factory sites suitable for small hydropower. The Imenti Tea Factory, for example, recently installed a 920 kW hydropower system which provides stable, low-cost electricity to the factory. The factory has a power purchase agreement with the Kenya Power and Lighting Company and exports its surplus generation to the grid. This arrangement not only provides high-quality, reliable power to the factory, but also earns additional income through exporting electricity to the grid [4]. Wind power has not yet been explored as an energy option and its economic feasibility in these regions is unclear.

The tea-growing regions are poor. In the eastern region, near Mt. Kenya, the percentage of the population below the poverty line ranges from 24 to 44%. In the western region, the poverty rate ranges from 34 to 64% [18]. Improving access to energy services, including electricity, is an important component of poverty alleviation and reaching the MDGs. Expanding the electricity grid to rural homes is cost-prohibitive – most rural residents cannot even afford the grid connection fee (about US\$422) [3]. A transition to decentralized generation and delivery is required to bring modern energy services to rural Kenyans.

3.2. Previous pre-feasibility wind assessments

Wind energy development in Kenya is still in its infancy. There is little public information about Kenya's only operating wind farm at Ngong Hills to the southwest of Nairobi. A feasibility study was released for the proposed Corner Baridi wind farm also in the Ngong Hills. The 50 MW Corner Baridi project, consisting of twenty-five 2.0 MW turbines, has a total project cost of €109 million (\$144 million), or \$2891/kW. The cost model assumed a 10% interest rate, a feed-in-tariff of \$0.12/kWh, and carbon credit sales at \$28/tCO₂/year. The project's 10.23% internal rate of return (IRR), including carbon credits, was below the benchmark IRR of 10.38% [13]. Although the scale of the proposed Corner Baridi project is far larger than that for a tea factory, it does provide a local perspective on costs for wind energy development in Kenya.

Researchers in several African nations have also published pre-feasibility wind assessments but most of them have been in North Africa. El-Osta and Kalifa [19] used RETScreen energy analysis software to estimate the economic viability of a proposed 6 MW wind farm in Libya. Three different size wind turbines were considered (from 0.6 MW to 1.5 MW). El-Osta and Kalifa [19] estimated the total initial costs for the 0.6 MW configuration to be US\$1275/kW (US\$1631/kW in 2012 dollars). Other key model inputs included a 50% debt ratio, 20-year debt term, 7.5% debt interest rate, and a range of discount rates (6%, 8%, and 10%). The 0.6 MW configuration had the highest NPV, though all turbine sizes returned positive NPVs and thus were economically efficient.

Himri et al. [20] estimated the cost of energy from a hypothetical 30 MW wind farm at three potential locations in Algeria. Also using

Table 2
Main RETScreen cost model values. All monetary values are in 2013 US dollars.

Parameter	Choice	Source/rationale
Feasibility study	\$35,000	Author estimate
Development & engineering	\$90,000	[13], linear + 50%
Base load – wind turbine	\$410,000	Market price of turbine
Peak load – grid electricity	\$745/kW (\$244,360)	Derived from Ref. [4]
Transportation	\$275,000	[13], linear + 50%
Erection, civil works, commissioning, etc.	\$550,000	[13], linear + 50%
O&M parts and labor	\$40,000	[13], linear + 50%
Fuel cost escalation	5%	[4,11]
Inflation rate	5%	Target inflation rate of Central Bank [29]
Discount rate	10%	[22]
Project life	20 years	[13]
Debt ratio	70%	[13]
Debt interest rate	10%	[13]
Debt term	5 years	[5]

RETScreen, they estimated the initial cost of the wind farm at US\$42.7 million, or US\$1422/kW (US\$1520/kW in 2012 dollars). The analysis assumed an avoided cost of energy of US\$0.095/kWh, a US\$0.025/kWh renewable energy production credit, US\$5.00/ton greenhouse gas reduction credit, and a 12% discount rate. All of the scenarios resulted in positive NPVs. Himri et al. estimated the cost of energy from the wind farm to be US\$0.03–0.07/kWh.

Hamouda [21] investigated the economic feasibility of a single 1 MW turbine in Cairo, Egypt. Assuming a 900€/kW (US\$1187/kW) initial capital cost and an 8% discount rate, Hamouda found that such a project had a negative NPV and would not be economically efficient. Adjusting the discount rate to 5% and escalating the electricity tariff at 5% per year resulted in a positive NPV (€358,035 (US\$473,717)).

Diechmann et al. [22] used SWERA data to model small (11 kW) standalone and larger (100 kW) minigrid wind systems for distributed generation in Kenya and several African countries. The authors estimated the initial capital cost to range from US\$2780/kW for the 100 kW minigrid to US\$5370 for the 11 kW standalone turbine. The resulting cost of energy was estimated to be US\$0.14–0.17/kWh which would be a lower cost than grid expansion in about one-third of households.

These pre-feasibility studies suggest that under the right conditions – environmental, economic, and policy – wind energy can be a viable source of electricity in Africa. These assessments covered a wide range of scales, from 11 kW standalone turbines to 50 MW wind farms. One important lesson is that pre-feasibility assessments are highly sensitive to model assumptions and small changes in, for example, the discount rate can have large effects on the NPV. Two of the published studies included an East African location. There is a lack of literature on medium- and large-scale assessments for East Africa.

3.3. Energy transitions

The Kenya tea industry may be poised for an energy transition. A special issue of *Energy Policy* recently highlighted the growing body of literature in energy transitions. Writing in that special issue, Arnulf Grubler [23] identified three insights about energy transitions that are particularly relevant in this case.

Grubler's [23] first insight was the importance of energy end-use in driving energy transitions. As internal combustion engines and automobiles drove the growth of the oil industry and electric lighting drove the growth of electric utilities, so too will energy end-uses drive current energy transitions. Demand for high-quality, reliable, and clean electricity at Kenyan tea factories is driving investment in clean generation technologies. In past energy transitions, new demand for energy services was met with innovations in generation, efficiency, and falling costs in a virtuous cycle. Whether renewable energy investment at tea factories can catalyze such a virtuous cycle and have positive spillover effects on rural communities is unclear.

The second insight was that energy transitions usually unfold over decades, not overnight. There are, however, circumstances that can accelerate transitions. A niche market, for example, can

offer an opportunity for experimentation and learning [23]. The Kenya tea industry is a niche market and has the capital and expertise to embark on such an energy transition. Pre-feasibility assessments like this one can support emergent transitions like that of the tea sector.

Grubler's [23] third insight was regarding the successful scaling up of energy systems, both at the scale of individual generating units (e.g. wind turbines) and at the industry scale. Achieving economies of scale can drive down the price of electricity – but only if the pace is appropriate. The history of energy transitions is littered with premature attempts at scaling up and Grubler cautions against scaling up too early. A number of factors limit the scale of energy development at Kenyan tea factories, particularly at the unit level. For example, the logistics of transporting large turbine blades to rural tea-growing areas may be a practical limit on the size of a wind turbine. Another limitation is that KTDA is prohibited from selling power directly to customers via a minigrid. On the other hand, KTDA's cooperative structure may allow energy projects at several different tea factories to be bundled together rather than developed as standalone projects. By achieving industry-level scales, there may be opportunities to attract so-called “impact investors,” obtain better financing terms, and potentially sell carbon credits aggregated from multiple projects.

4. Results

4.1. Wind resource assessment

The SWERA data include both modeled wind speeds (50 m above ground) and modeled wind power density. The wind power density suggested a greater wind resource at the tea factories than did the wind speed (Table 3). Twenty four tea factories (28.9%) had wind resources rated Class 3 or better. With this result, Hypothesis H1₀ is rejected and the alternative hypothesis is accepted: 20% or more of the tea factories have Class 3 or better wind resources. The wind resource is greater in the eastern region, but there are fewer tea factories in the areas of suitable wind power densities as compared to the west. In the east, the five tea factories with either SWERA Class 3 (Moderate) or Class 4 (Good) wind resources had mean (SD) wind power density of 240.4 W/m² (62.4) (Fig. 4). The 19 factories in the western region with Class 3 resources averaged 203.9 W/m² (21.4) (Fig. 5). The most promising site is located east of Mt. Kenya in Meru County and has an estimated wind power density of 355 W/m² and a 6.3 m/s wind speed. The greatest wind resource in the western region was in Bomet County and had a wind power density of 240 W/m² and a 5.6 m/s wind speed.

4.2. Economic analysis

The tea factory in each region with the highest rated wind resource was selected for an additional economic assessment using RETScreen. The cost analysis and financial analysis were assumed to be the same for each region. The assessments only differed in the wind resource and local climate data.

Table 3
Wind speed and power density at tea farms.

Region	Number of farms	Mean wind speed (m/s) [SD]	Mean wind power density (W/m ²) [SD]	Number of tea farm sites rated “moderate” or better	
				Wind speed (>5.5 m/s)	Wind power density (>165 W/m ²)
East	39	3.2 [1.4]	69.7 [79.6]	3	5
West	44	4.1 [1.2]	135.8 [72.0]	2	19
Total	83	3.7 [1.3]	104.7 [82]	5	24

Fig. 4. Five tea farms in the east region have wind resources rated SWERA Class 3 (Moderate) or Class 4 (Good).

The total requirement for tea factory electricity was met with a combination of grid/diesel electricity and wind energy generation. The total initial cost for the wind turbine was \$1,488,425, or \$1984/kW. The capital cost of the supplemental grid/diesel electricity was \$233,360 and the total capital cost for electricity (turbine plus grid/diesel) was \$1,721,785.

Under the modeled conditions, the Meru County turbine produced 1,393,000 kWh of electricity. This corresponded to a capacity factor of 21.2% and accounted for 50.8% of the hypothetical tea factory's electricity requirement. The estimated LCOE for the Meru County turbine was \$0.156/kWh which was less than the current price of the grid and diesel-generated electricity (\$0.173/kWh).

The Bomet County turbine, under lower wind speeds, produced 1,068,000 kWh of electricity – 38.9% of the tea factory's required electricity. This production corresponded to a 16.3% capacity factor and an LCOE of \$0.202/kWh. The Bomet County turbine's LCOE was greater than the current price of grid and diesel-generated electricity.

Net present value is the best measure of a project's economic efficiency. Table 4 shows the base case NPV and other economic indicators for both the Meru County (east) and Bomet county (west) sites. The Meru County site results support Hypothesis 2_A, that wind energy is an economically efficient choice for Kenyan tea factories. The Bomet County site results, however, do not allow the rejection of the null hypothesis.

Pre-feasibility assessments have a high degree of uncertainty. The assumptions used in the calculations, from the choice of turbine to construction cost estimates to the choice of discount rate, all have an impact on the measure of the project's economic efficiency. The

results of the sensitivity analysis show that the Meru County (east) site is economically efficient (*i.e.* a positive NPV) over a wide range of model assumptions (Table 5). The Bomet County site, on the other hand, only showed a positive NPV under more optimistic assumptions. The hypothetical project achieved a positive NPV if the initial costs decreased by 10%, if the wind speed increased by 10%, or the grid/diesel electricity price increased by 10% (Table 6). The NPV calculations for both regions were most sensitive to the wind speed, electricity price, and to a lesser degree, initial cost. Changes in the debt interest rate and discount rate had modest impacts on NPV.

The economic analysis suggested that 5.8 m/s is the minimum wind speed necessary to obtain a positive NPV under the base case model conditions. A 9.6 m/s wind speed produced, under the model conditions, nearly the full amount of electricity required for the hypothetical tea factory. The 9.6 m/s wind speed corresponded to a 41.2% capacity factor.

4.3. Verification: Ngong Hills wind farm

There is evidence that the coarse spatial resolution of the SWERA data (25 km² grid) may underestimate local wind resources. The Ngong Hills wind farm, Kenya's first and only operating wind farm, lies south west of Nairobi. The wind farm comprises six Vestas V52 850 kW wind turbines for a total capacity of 5.1 MW [24]. The SWERA data estimated that the Ngong Hills area has wind speeds of 5–6 m/s which corresponded to SWERA Class 3 (Moderate) – similar to the wind speeds at the tea factories. The SWERA country guide for Kenya additionally explored the wind

Fig. 5. Nineteen tea farms in the western region have wind resources rated SWERA Class 3 (Moderate).

energy potential for Ngong Hills using fine-scale local data. The use of fine-scale data revealed a wind resource of 8–10 m/s at the site – substantially higher than the SWERA modeled data [25].

In 2010 the 5.1 MW wind farm generated 18,000 MWh of electricity [26]. RETScreen was used to back-calculate an average wind speed based on the power curve data of the turbines and the known output. An annual electricity output of 18,000 MWh corresponded to an annual average wind speed at 50 m of 10.1 m/s. This wind speed was consistent with the fine-scale analysis reported in the SWERA country guide described above. These findings also suggested a greater wind resource at Ngong Hills than predicted by the coarse scale SWERA model.

Taken together, the fine-scale analysis and the reported wind farm output suggested that, in some cases, SWERA data are conservative and may underestimate the actual wind resource at a particular site. If this is true for the tea-growing regions, then some particular sites with “moderate” wind resources, such as ridges smaller than the 25 km² grid size, may actually be able to support wind power. Additional site-specific analysis is needed determine whether this is the case at Kenyan tea factories.

Table 4
NPV and other indicators of economic viability for wind projects at the two sites.

Economic indicator	Meru county (east)	Bomet county (west)
NPV	\$515,779	\$–92,442
Annual life cycle savings	\$60,583	\$–10,858
After-tax equity IRR	15.2%	9.0%
Equity payback	8.4 years	10.9 years

5. Discussion

The objective of this project was to assess the potential of wind energy to support an energy transition at Kenyan tea farms and factories. Analysis of the countrywide SWERA data set indicated that 24 of the 83 (29%) tea factory sites analyzed have Class 3 or better wind resources, supporting Hypothesis 1A. There are more Class 3 tea factory sites west of the Rift Valley but they generally have lower wind speeds. On the east side of the Rift Valley, fewer tea factories have Class 3 wind resources, but those that do have higher wind speeds including one Class 4 site.

The second hypothesis that wind energy would be an economically efficient energy source at Class 3 (or better) sites, received some support. The site with the highest wind speeds, in Meru County, did result in a positive NPV which was robust across a wide range of

Table 5
Sensitivity analysis for the Meru County site. NPV was analyzed across $\pm 20\%$ in key model parameters. Figures in bold indicate a positive NPV.

Parameter	Meru county – NPV after parameter change				
	–20%	–10%	Base case (0%)	+10%	+20%
Initial cost	\$860,137	\$687,958	\$515,779	\$343,601	\$171,422
Debt interest rate	\$576,733	\$546,414	\$515,779	\$484,835	\$453,587
Discount rate	\$826,636	\$660,691	\$515,779	\$388,932	\$277,641
Wind speed	\$–536,780	\$–38,465	\$515,779	\$1,086,106	\$1,628,883
Electricity price	\$–361,541	\$249,489	\$515,779	\$782,070	\$1,064,024

Table 6

Sensitivity analysis for Bomet County site. NPV was analyzed across $\pm 20\%$ in key model parameters. Figures in bold indicate a positive NPV.

Parameter	Bomet county – NPV after parameter change				
	–20%	–10%	Base case (0%)	+10%	+20%
Initial cost	\$228,786	\$57,589	\$–92,442	\$–244,255	\$–397,520
Debt interest rate	\$–39,943	\$–66,057	\$–92,442	\$–119,252	\$–146,561
Discount rate	\$117,761	\$5156	\$–92,442	\$–177,177	\$–250,859
Wind speed	\$–953,984	\$–536,780	\$–92,442	\$373,357	\$899,730
Electricity price	\$–470,269	\$–274,026	\$–92,442	\$88,678	\$304,943

model assumptions. This suggests that, at the best sites, wind can be a viable choice for energy production. Not all Class 3 areas, however, can support economically efficient wind projects. Analysis of tea farms with the highest wind resources in the western region (Bomet County) resulted in a negative NPV in the base case. The NPV is small but positive under more optimistic assumptions. Resources in the lower range of Class 3 do not appear to be economically viable under the base case model assumptions used here.

The capital cost estimated here (\$1984/kW) is consistent with other capital cost estimates reported in the literature. As discussed in Section 3.2, pre-feasibility studies of similarly sized projects from North Africa ranged from about \$1100/kW to \$1600/kW. The Corner Baridi project, a much larger project but located in Kenya, had a capital cost of \$2891/kW. The World Bank reported that new wind energy projects installed in Sub-Saharan Africa in 2012 had an average capital cost of \$2400/kW [27]. A feasibility study for a 750 kW turbine in the US had capital costs of \$2133/kW [28]. An NREL analysis of mid-scale wind turbines estimated the installed cost of a 750 kW turbine to be \$2533/kW [30]. If the Meru site's capital cost were the same as the NREL estimate (28% higher than the base case), then the NPV would be a low, but positive, \$40,859.

Transportation is one of the largest costs, and also one of the most uncertain. It was difficult to obtain a reliable estimate of transportation costs because so few wind farms have been built in East Africa. In this model, turbine transportation costs (\$275,000) accounted for 18% of the total capital cost. Transporting turbines from Northern Europe, for example, may be cost-prohibitive even if the price of the turbine itself is quite reasonable.

This project evaluated wind resources using one particular turbine model (Goldwind S48,750 kW). One reason for this choice was that its output is a substantial proportion of the demand at a Kenyan tea factory, but not greater than it. A turbine of this size would not export electricity to the grid. A larger turbine, however, may be able to cover all the tea factory electricity needs and export electricity but the economic efficiency (and logistics) of such a configuration is unclear. Project-specific feasibility studies can determine the optimal turbine size for a given location.

This analysis used annual average values for wind speed but winds do vary seasonally. The SWERA country report for Kenya showed that, for a location in central Kenya, wind power production was highest from November to April [25]. The windy season corresponds to the high season for tea production (October–January and April–May). Grid power outages are most common during the high season with, on average, 31 h of power outages per month during these months [5]. This suggests that wind energy could be a suitable complementary power source for the tea factories. The diurnal fluctuations in the wind speeds in the tea-growing regions are presently unknown but will be necessary to fully understand wind's potential to power a particular tea factory.

The literature on energy transitions, particularly the insights of Grubler [23], provides a framework for understanding energy

transitions in Kenya's tea sector. End use demand drove many past energy transitions, such as automobiles driving the development of petroleum and lighting driving electric utilities, in a positive feedback loop. Similarly, end use demand in the tea sector is driving the transition to distributed, renewable energy in Kenya's rural tea-growing regions. Whether this development can catalyze a positive feedback loop with spillover benefits to energy-poor rural communities remains to be seen. Grubler noted that energy transitions play out over decades, not a matter of years. The energy transition in Kenya's tea sector is just underway and will undoubtedly take several decades to mature. Grubler's final insight was about the importance of scaling up, both at the individual unit level and at the industry level. The KTDA's cooperative structure may foster economies of scale not achievable at the level of individual farms. By bundling multiple factories' energy projects together, KTDA may be able to take advantage of better financing terms and carbon markets. This is worth further exploration.

6. Conclusions

This analysis showed that wind energy can be an economically viable choice for Kenya's tea factories in certain locations. No attempt was made to optimize the turbine model, capacity, or number. Additional site-specific analyses may show even greater returns under alternative project designs. While wind energy may be economically efficient at some Meru County locations, we did not compare wind energy to other self-generation options like small hydropower. It is possible that other on-site generation technologies may have a higher NPV than wind energy and thus may be more economically efficient.

The SWERA data were shown to be conservative and, in at least one case, underestimate the wind resource at a particular site. If this proves to be the case in Kenya's tea-growing regions, some of the Class 3 resources may be economically viable. This will clarify as more site-level data become available.

The communities in Kenya's tea-growing regions are generally poor. Improving access to modern energy sources, including electricity, is one step in alleviating abject poverty and achieving the MDGs. Though the tea factories may be building energy infrastructure in these rural areas, a new business model is necessary to bring energy services to the rural poor. What that will be, such as battery systems or standalone generation, and whether the tea sector will play a role remains unclear.

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