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Development of Small Wind Turbines

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Development of Small Wind Turbines

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Global warming is the greatest source of progress that the Humanity has never accomplished. The story starts today.

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Contents

| | |
|---|-----------|
| <u>ACKNOWLEDGEMENT</u> | iv |
| <u>CONTENTS</u> | v |
| <u>ABSTRACT</u> | ix |
| <u>FOREWORD</u> | 1 |
| <u>INTRODUCTION</u> | 3 |
| <u>THEORETICAL BACKGROUND</u> | 5 |
| Chapter 1: Small wind turbine design | 5 |
| 1.1. Generalities | 5 |
| 1.1.1. Blades | 5 |
| 1.1.2. Permanent magnet generators | 6 |
| 1.1.3. SWT operation | 6 |
| 1.2. Blade Element Momentum method | 8 |
| 1.2.1. 1-D momentum theory for an ideal wind turbine | 9 |
| 1.2.2. BEM | 11 |
| 1.3. Blade design for maximum power production performance | 15 |
| 1.3.1. Challenges, objectives, and assumptions | 15 |
| 1.3.2. PROCEDURE | 16 |
| 1.4. Blade design for starting and low wind performance | 18 |
| 1.4.1. Challenges, objectives and assumptions | 18 |
| 1.4.2. Procedure | 19 |
| 1.5. Application of small wind turbine design to decentralised power supply | 22 |
| 1.5.1. Turbulence model | 22 |
| 1.5.2. Wind turbine energy output calculation | 22 |
| Chapter 2: Computing SWT design with Matlab | 24 |
| 2.1. Blade design for optimal power production performance | 24 |
| 2.2. Blade mechanical properties | 25 |
| 2.3. Blade Element Momentum adapted to the determination of the operating conditions of a SWT rotor connected to a Permanent Magnet Generator | 25 |
| 2.4. Starting behaviour modelling | 27 |
| Chapter 3: Socio-economic evaluation of wind-based decentralised electrification projects | 29 |
| 3.1. Key cost and financing concept | 29 |
| 3.2. Analysis tools | 30 |

INPUTS **32**

| | |
|--|----|
| Chapter 4: Inputs | 32 |
| 4.1. Blades | 32 |
| 4.1.1. Airfoil selection background | 32 |
| 4.1.2. Airfoil profile | 33 |
| 4.1.3. Airfoil lift and drag data | 33 |
| 4.1.4. Selected materials | 36 |
| 4.2. Generators | 36 |
| 4.2.1. General characteristics | 36 |
| 4.2.2. Power curve | 37 |
| 4.3. SWT operation in rural Kenya | 38 |
| 4.3.1. Energy requirements for an isolated school in rural Kenya | 38 |
| 4.3.2. Prevailing wind conditions in Kenya | 39 |
| 4.3.3. Wind data time series input | 40 |

**SUITABILITY OF SMALL WIND TURBINES FOR DECENTRALISED
ELECTRIFICATION IN RURAL KENYA** **42**

| | |
|---|----|
| Chapter 5: The need for rural electrification in Kenya | 42 |
| 5.1. General background | 42 |
| 5.1.1. Energy sources and electrification rate in rural Kenya | 42 |
| 5.1.2. Cost of energy | 43 |
| 5.1.3. Rural electrification status and policy | 43 |
| 5.2. The challenges of electrification and modern energy service provision in rural Kenya | 44 |
| 5.2.1. Poverty in rural Kenya | 44 |
| 5.2.2. The complex connection between access to electricity and development | 45 |

| | |
|--|----|
| Chapter 6: A wind-based decentralised electrification experience in Kenya: Esilanke Primary School pilot project | 47 |
| 6.1. Background | 47 |
| 6.1.1. General information | 47 |
| 6.1.2. Socio-economic situation of Esilanke community | 47 |
| 6.1.3. Energy situation | 49 |
| 6.1.4. Wind resource | 52 |
| 6.2. Project methodology | 52 |
| 6.2.1. General strategy | 52 |
| 6.2.2. Timeframe | 52 |
| 6.2.3. Measures to ensure project sustainability | 53 |
| 6.3. Installed system | 55 |
| 6.3.1. The KenTec 1000 wind turbine | 55 |
| 6.3.2. Power control system and storage | 56 |
| 6.3.3. Appliances | 56 |
| 6.4. Performance | 57 |
| 6.4.1. Simulation of the expected energy production | 57 |
| 6.4.2. Energy consumption | 58 |
| 6.4.3. Technical sustainability | 58 |
| 6.5. Financial viability | 59 |
| 6.5.1. Project cost | 59 |
| 6.5.2 Willingness to pay | 60 |
| 6.5.3. Prospects for income generating activities | 60 |
| 6.5.4. Financial and cost-benefit analysis of wind-based decentralised electrification projects | 61 |
| 6.6. Conclusion on the expansion of wind-based electrification pilot projects in rural Kenya | 65 |

| | |
|---|------------|
| Chapter 7: Manufacturing and selling SWT in Kenya | 66 |
| 7.1. The Kenyan SWES technology | 66 |
| 7.1.1. The Kijito windpumps | 66 |
| 7.1.2. The WindCruiser wind turbines | 69 |
| 7.2. The SWES market in Kenya | 70 |
| 7.2.1. Background | 70 |
| 7.2.2. Market prospects | 70 |
| 7.2.3. Limitations to market expansion | 71 |
| 7.3. Conditions for a viable development of SWES manufacturing activities in Kenya | 71 |
| 6.3.1. Reducing manufacturing costs | 71 |
| 7.3.2. Guaranteeing performance and system quality | 72 |
| 7.3.3. Promoting wind energy solutions in Kenya and lobbying | 72 |
| 7.3.4. The importance of developing key-partnerships | 72 |
| Chapter 8: Conclusion on SWT suitability for decentralised electrification in rural Kenya | 74 |
| 8.1. Great prospects but obstacles to overcome | 74 |
| 8.2. Proposed guidelines and implementation strategy for developing wind-based decentralised electrification in rural Kenya | 75 |
| DEVELOPMENT OF SMALL WIND TURBINES FOR OPTIMAL POWER PRODUCTION AND STARTING PERFORMANCE IN KENYAN WIND CLIMATES | 78 |
| Chapter 9 : Model validation | 78 |
| 9.1. Methodology | 78 |
| 9.2. Power production performance | 81 |
| 9.3. Starting performance | 81 |
| Chapter 10: Performance of the NC 600W wind turbine | 83 |
| 10.1. Power production performance | 83 |
| 10.2 Starting performance | 85 |
| 10.3. Conclusion on Newcastle 600W wind turbine performance | 86 |
| Chapter 11: Analysis of design choice effects on SWT performance | 88 |
| 11.1. Considered designs | 88 |
| 11.2. The effect of pitching | 89 |
| 11.3. The effect of yawing power regulation | 90 |
| 11.4. The effect of changing the number of blades | 91 |
| 11.5. The effect of changing the airfoil | 93 |
| 11.6. The effect of increasing blade length | 94 |
| 11.7. The effect of changing the generator | 97 |
| 11.8. The effect of blade design method | 98 |
| 11.9. The effect of changing the design criteria | 99 |
| 11.10. Design suitability for electricity provision in rural Kenya | 101 |
| Chapter 12: Proposed guidelines for designing and manufacturing small wind turbines adapted to operation in Kenyan wind climates | 102 |
| 12.1. Key points about SWT design | 102 |
| 12.2. Proposed guidelines | 105 |
| 12.2.1. Objectives to achieve | 105 |
| 12.2.2. Useful small wind turbine sizes for rural electrification in Kenya | 105 |
| 12.2.3. Adapting Kenyan small wind energy system technology | 106 |
| 12.2.4. Material selection, power equipment supply and local manufacturing | 107 |
| 12.2.6. Design criteria | 107 |
| 12.2.7. Strategy recommendations | 108 |

| | |
|--|-------------------|
| <u>PROJECT EVALUATION</u> | <u>110</u> |
| Chapter 13: Study limitations, lessons learned and future projects | 110 |
| 13.1. Study limitations | 110 |
| 13.2. Lessons learned | 111 |
| 13.3. Future projects | 112 |
| <u>CONCLUSION</u> | <u>114</u> |
| <u>REFERENCES</u> | <u>116</u> |
| <u>APPENDICES</u> | <u>I</u> |
| Appendix I: map of Kenya | II |
| Appendix II: wind climates of Kenya | III |
| Appendix III: Esilanke data, courtesy of KenTec | X |
| Appendix IV: DWEK Concept paper | XVII |
| Appendix V: Chord and twist distribution | XXII |
| Appendix VI: Details about design choice effects on SWT performances | XXVII |
| Appendix VII: Questionnaires delivered to Esilanke's community | XXXIII |

Abstract

In Sub-Saharan rural Africa, access to electricity is a critical issue. The present study has analysed under which conditions Small Wind Turbines (SWT) decentralised electrification projects would become technically, socially, economically and financially viable in rural Kenya. Based on the analysed manufacturing, operation and maintenance constraints of Kenya, some guidelines are then proposed to designing Small Wind Turbine adapted to high power production and starting performance in Kenyan wind climates.

In March 2007 a 1kW China-imported wind turbine was installed in Esilanke Primary School by the Kenyan windpump manufacturer Bobs Harries Engineering Ltd for the KenTec-Windgen wind-based decentralised electrification pilot project. The case study at Esilanke Primary School has shown that due to the context of high energy expenditure in rural areas, Small Wind Turbines is an appropriate solution capable to induce much development opportunity. Indeed from a technical point of view, the energy system and SWT management learning process has been very well assimilated by the school staff. The amount of energy produced exceeds the school requirement for most of the year. Some energy shortage (a few days to a few weeks a year) might however happen during the low wind season. Due to this excess wind power, connecting wind-based electrification to productive uses of electricity has been enhanced. At the school the community is now proposing mobile battery charging. The generated income has already enabled to collect sufficient amount for next battery distilled water replacement. The project has induced several socio-economic benefits as kerosene cost reduction, development of morning/evening classes, access to computer and modern education standards. On a more general financial point of view, the high front costs of SWT project are relatively high and could constitute an obstacle to a large expansion of SWT in poor rural areas. The study has also highlighted the requirement of an appropriate technical local environment as a key to make such a project affordable and guaranteeing technical sustainability. In the situation of Kenya, where several industrial stakeholders have been involved in wind energy technology for up to 30 years, this study concludes that Kenya has a particularly favourable situation for a large development of SWT projects. More accurate industrial strategy, SWT supply chain development, wind energy promotion campaign, improvement of wind resource knowledge, financial facilities for SWT investments are five key areas where progress are still necessary to stimulate SWT market growth.

Regarding the design of small wind turbines adapted to operation in Kenyan wind climates, the study has demonstrated that a well-designed 300W wind turbine can already provide 60% of basic rural Kenyan school electricity needs (2kWh/day) in low wind climate, and up to 90% if the rotor is oversized for the given generator. In high wind climate, the wind turbine would produce much more than the basic needs. A small wind turbine rated at 600W at 9m/s provides 130% of rural Kenyan school electricity needs in low wind climate. From the optimal design for power production, some designing adjustments would be needed to improve starting performance. One important conclusion is that high power production and starting performances are not antagonist objectives: increasing chord length distribution, R_{tip} or blade number are interesting strategies to meet those both objectives. Adjusting root design is decisive. The project enhances that the generator choice is a key step in the SWT design process.

Therefore the global conclusion of the project is that small wind turbines are appropriate for decentralised electrification projects in rural Kenya. Provided local and national, industrial and public synergies are enhanced in the energy, water and rural electrification sectors, SWTs could become a powerful lever of development in Kenya, and beyond in all East Africa.

Foreword

Global warming is today's world challenge and its consequences will generate tomorrow's crises. The phenomenon is ineluctable, for the worst and for the best. One can still dream about the Humanity managing to counteract the effects of global warming; at best the rich countries will mitigate some aspects in their green garden.

Is there still hope in October 2007 events about the emergence of a world consciousness and technologic breakthrough? Perhaps.

The rich countries have finally understood that their waster behaviour mortgages their economic vibrancy; and with the coming crises there is much business to do. For sure global warming will be a lucrative business for some of us. It will generate much profit as water shortage, famine, rural exodus and wars. But there are key questions to make it a successful enterprise. Why to get involved, what to do with the generated profit and as always, what is the value of money?

Fortunately there are still on Earth some places where people have only heard about the terrific headbutt of a glorious football star and still dream about watching the final of next football World Cup. They might invest in a TV set. But since there are not only clever and responsible people above the Mediterranean line, they are probably already thinking about how their community could get organised themselves for raising their economy up. They are thinking about the cost of charcoal, kerosene, the information about health hazards, the hundreds of dollars they put every year to operate and maintain the nice diesel pump that was donated a few years ago. They have water, not much during the dry season, but at least here the ground water is clean. They also know that people nearby do business with simple projects, like charging mobile phone batteries. They all have mobiles but there is no electricity here. The national grid is not far, but who will extend the line by 10kms for a 1000 scattered people community? No, the solution will not come from outside. They go to the capital city; they have even been in a cyber-café surfing on the Web. World is beautiful, terribly beautiful. Progress, progress, world is going the right direction. There is even a World Bank! Imagine: a World Bank! They know it. A World Bank!

World is big, world is small. It is amazing to imagine that this beautifully uncomfortable feeling is shared by people so far away. Everybody will feel it, but some of us more than others. There they know that there is still hope in this world. They know how much getting connected is the key of their future. But they do not know that tomorrow, even more than today, they will have to make their own way.

At best, the rich countries will mitigate some aspects of global warming for their green garden. There will be technologic breakthroughs and the present time is a fascinating period for science. It will be costly. But some of us will do business on it. Global warming will even be a convenient pretext for a new protectionist deal! The ones that polluted for decades, for centuries, will now make pay it by the people that are not lucky to get developed today. In French we say: "Mieux vaut être riche et bien portant".

Why to get involved, what is the value of money?

Wind energy is fashion. It is a free energy. It does not pollute and wind industry creates much employment, in many countries. Wind energy systems are getting big and go offshore not to annoy the peaceful life of European citizens. Whales might one day complain but they will need to eat much genetically-modified plankton and grow up; because today offshore human-designed wind turbines weigh already a couple of wealthy blue whales... As far as I am concerned, those gigantic oceanic windmills, and their smaller land cousins, are much more elegant than the nuclear power stations and high-tension masts that run all over France as the second and third more interesting country's features after the Tour Eiffel.

On top of all those assets, wind energy benefits can be huge on pollution savings. In 2006 the 3000 megawatts installed in Denmark have enabled to save 3.4 million ton CO₂, which corresponds to 0.6 ton CO₂ per Dane [01]. Including external impacts, wind energy becomes actually one of the cheapest power options.

When considering the energy and pollution situation in Africa with respect to rich countries, the facts tell much about the story: Africa has contributed and is contributing very little to global warming. Today Africa accounts for 2–3% of the world's carbon dioxide emissions from energy and industrial sources, and 7% if emissions from land use (forests) are taken into account [02].

However some other facts should cause questioning. First it is striking to realize that a single kerosene lamp, which is the most used lighting mean in rural Africa, generates about 0.15 to 0.3 ton CO₂ per year. Second the biomass-based energy resource is a dramatic cause of pollution and environmental and health-related issues. The United Nations' Food and Agriculture Organization (FAO) estimates that CO₂ emissions from the production and use of fuelwood and charcoal in Kenya exceeded 30 million tons in 1996. Wood and charcoal stoves in Kenya produce up to 10 kg-C per day on a 20 year global warming potential and non-CO₂ emissions from charcoal stoves about 5.5 kg-C in 20-year CO₂ equivalent units [03].

As capita average, a Kenyan uses an energy amount equivalent to 3% of Dane's energy use. But the greenhouse gas emitted by a Kenyan represents about 5% of the ones emitted by a Dane [04]. Current Africa's energy portfolio and trend is not sustainable: even though energy use is very low in Africa today, in the future polluting potential due to fossil and biomass energy sources is very important.

When considering that global warming consequences will affect dramatically the most vulnerable populations on Earth, the accumulation of today's poverty situation and tomorrow's recurrent acute crises will make human development very uncertain in rural Africa.

Pollution, development and peace are obviously interconnected issues. There are no several strategies to continue living in peace on this world; whether major social and technological revolutions enable to move forward to low energy consumption and fully environment-friendly economy, or responsibility becomes a widely-shared human characteristics of the present time.

Introduction

In its guide to energy's role in reducing poverty: "Energizing the Millennium Development Goals" [1], the United Nations Development Programme highlights how much energy is a key of development. Electricity is referred as essential for modern communication, supporting modern industry, and the provision of public services such as public lighting, education, and health care. Given that on Earth at least 1.6 billion people have no access to electricity, the International Energy Agency estimates that a total of USD 200 billion worth of investment in electricity will be needed to help halve the proportion of people living on less than USD 1 a day by 2015 [2]. UNDP enhances that this amount is in addition to the USD 5.8 trillion needed just to meet existing projections in electricity demand [1].

It is a tough challenge to meet those figures; but it is a much more difficult challenge to make those investments environmentally friendly and economically viable for the developing countries.

In Kenya, 80% of the rural households earn less than USD 1/day/capita. Only about 1% of the rural population have access to electricity [3]. As an equatorial country where it is dark by around 6.30pm everyday, there is considerable demand for lighting throughout the year. A variety of fuels are used: while many families will to some extent use light from the open fire, most low-income homes rely on kerosene in simple wick lamps (around 95% of rural homes are reported to have access to kerosene, around 90% of whom use this fuel for lighting) [4]. There is therefore very little contribution of electricity to economic development in rural areas while electricity can be a powerful catalyser of development when productive uses are connected or induced.

Small wind turbines have some noticeable advantages that should make them become an important part of a coherent and efficient rural electrification strategy. First, small wind turbines have benefited from the growth of the wind energy sector. Nowadays, small wind turbines are mature technology. Second, small wind turbines are available in plenty of sizes, all of them being interesting for rural electrification. The lowest range: about 300-500W are suitable for electricity provision of rural households; around 1-2kW, electric needs of rural schools and other public institutions are covered; 5kW wind turbines are ideal size for village mini-grid project. Above 5kW, small wind turbines can be connected to existing diesel generators and therefore save much polluting emissions. Rural small industries, farming activities, service business could also be interested in any of those sizes.

The energy production of small wind turbines meets the electric needs of Africa's rural areas. The capacity to enhance productive uses of electricity with wind-based rural electrification project is the reason why small wind turbines constitute a very interesting solution for efficient rural development programmes.

However the context of rural Africa is very demanding. There are many aspects to analyse before going to design a SWT adapted to operating in rural Africa. Indeed often local technical expertise is lacking, therefore power generation systems have to be robust and require little maintenance. Furthermore poverty situation implies low cost systems in order to be affordable by the majority of rural households and communities. High efficiency and quality are also incontrovertible when targeting commercial prospects. The system adequacy with the wind resource is a decisive aspect of small wind turbines performance. In such areas moderate wind climates are prevailing; those wind regimes implies a special design. Starting and safety are also key issue of proper SWT design. Most small wind turbines rely indeed on self-starting.

Developing small wind turbines with high starting and power production performance is the main challenge of SWT design. Therefore the wind energy engineer has to take all those parameters and objectives into account and keep them in mind all along the SWT design process.

This project, carried out in partnership with the Kenyan windpump manufacturer Bobs Harries Engineering Ltd (BHEL), aims at contributing to the development of small wind turbines adapted to operation in rural Kenya. Bobs Harries Engineering Ltd has been manufacturing the Kijito windpumps since 1979. Their experience has shown that wind energy is a solution that can much improve the living standards in rural areas. After 30 years of activity in windpumping, BHEL wishes to get involved in wind power generation. This project has therefore been oriented by this wish and aims at bringing new light on the efficiency of the current Kijito windpumps, the opportunity to use this technology for power generation and how their performance would compete with modern SWT designs.

Since the engineer work is not only to design new system but to design new system useful for the society, this project has much insisted on studying the conditions of viability of small wind turbine project and market in Kenya prior to move to the design step.

Thanks to the wind-based electrification pilot project developed by the Danish-Kenyan partnership KenTec-Windgen and funded by the Danish International Development Agency, much valuable input has been provided to this Master's Thesis project.

From Esilanke case study and the field work periods In Kenya, this project has focussed on identifying the technical, financial and socio-economical barriers to a large development of small wind turbine projects for rural electrification in Kenya. Particular stress has been put on defining prevailing wind climates of Kenya and target wind resource for wind-based rural electrification projects in Kenya. Those inputs have then been used to analyse what are the most adequate SWT designs for operation in Kenyan wind climate. Finally, guidelines for the design of small wind turbines operating in rural Africa are proposed.

This Master's Thesis report is divided into five parts: the first part is dedicated to the theory, the second one presents the inputs used in the analysis of the most adequate SWT designs for operation in Kenyan wind climates, the third part assesses the suitability of small wind turbines for decentralised electrification in rural Kenya, the fourth part focuses on the development of small wind turbines for optimal power production and starting performance in Kenyan wind climate, finally the fifth part is devoted to project evaluation.

Theoretical background

Chapter 1: Small wind turbine design

1.1. Generalities

1.1.1. Blades

Blades are a key part of any wind energy systems. Indeed blades are in charge of extracting the power from the wind. A key characteristic of small wind turbines is that there is no powered system to start them: SWTs are self-starting. Therefore on top of targeting high power production performance, the blade design of SWTs must guarantee high starting performance.

As it is presented in details in section 4.3, the target wind resource is the low to medium wind climate of East Africa. Therefore, design wind speed is much lower than the one for multi megawatt wind turbines and ranges from 7 to 11 m/s according to design power.

Consequently rotor size must be adapted to this wind climate constraint. A requirement is to get as close as possible to the Betz limits at the design wind speed while still keeping high starting performance. For 7 to 11 m/s wind speed, the following table specifies the wind kinetic power (in Watts) that can be transmitted to the generator within a disc of a given radius. C_p is set to 0.40.

| V_d | R = 0.75m | R = 1m | R = 1.25m | R = 1.5m | R = 1.75m | R = 2m |
|--------|-----------|--------|-----------|----------|-----------|--------|
| 7 m/s | 143 | 254 | 397 | 572 | 779 | 1017 |
| 8 m/s | 214 | 380 | 593 | 854 | 1163 | 1518 |
| 9 m/s | 304 | 540 | 845 | 1216 | 1655 | 2162 |
| 10 m/s | 417 | 741 | 1158 | 1668 | 2271 | 2966 |
| 11 m/s | 555 | 987 | 1542 | 2220 | 3022 | 3947 |

Table 1.1 Wind kinetic power for several rotor radius and wind speed at $C_p = 0.4$

Given the considered generators (rated power from 300W to 1kW), it appears that V_d must be at least 9 m/s. Blade length can be as small as 0.75m long. This brief calculation does not take into consideration the generator characteristics, indeed there are always energy conversion loss between the wind mechanical power inputted into the generator and the output power delivered to the load. When defining the design point, the input wind power should meet the generator output power divided by the generator efficiency.

Concerning starting, blade design should maximise the stationary torque. The root part is the area where most of this torque is created. Therefore suitable blade design for starting focuses on the root geometry.

1.1.2. Permanent magnet generators

Permanent magnet generators is the most used technology for small wind turbines below 2kW. Even though they have suffered from high magnet costs for a long time, the recent improvements make them more and more affordable. Nowadays, Chinese manufacturers like Ginlong sell 1.5kW PMG sample unit for 300 USD.

For higher sizes of small wind turbines, induction generators can become more advantageous since installing electronic control systems becomes a more cost-effective option. Therefore from 5kW, the rotation speed of small wind turbines using induction generators can be controlled thanks to a controller coupled to the generator. Furthermore brake system can be included.

The main advantage of PMGs is their varying rotation speed which enables to track optimum C_p for most wind speeds below V_d . Typical PMG rotation speeds are 100-1000 rpm. These high rotation speeds enable to build SWT without any gear systems. Indeed tip speed ratio ($\lambda = \omega R_{tip} / U_0$) of 1m radius rotor operating at 600rpm in 9 m/s wind speed is 7, which is a typical suitable value for 3 blade rotors. The table below presents the tip speed ratios of 1m, 1.5m and 2m radius SWT operating at several rotation speeds in 7, 9 and 11 m/s wind speeds

| λ | 1m | | | 1.5m | | | 2m | | |
|-----------|-------|-------|--------|-------|-------|--------|-------|-------|--------|
| | 7 m/s | 9 m/s | 11 m/s | 7 m/s | 9 m/s | 11 m/s | 7 m/s | 9 m/s | 11 m/s |
| 300 rpm | 4.5 | 3.5 | 2.9 | 6.7 | 5.2 | 4.3 | 9.0 | 7.0 | 5.7 |
| 500 rpm | 7.5 | 5.8 | 4.8 | 11.2 | 8.7 | 7.1 | 15.0 | 11.6 | 9.5 |
| 700 rpm | 10.5 | 8.1 | 6.7 | 15.7 | 12.2 | 10.0 | 20.9 | 16.3 | 13.3 |

Table 2.2 Tip speed ratio for several rotation speeds, wind speeds and rotor radii

However the main disadvantage of PMG is their high energy loss (from 5% at low rotation speeds up to 50% at high rotation speeds). The PMG power vs. rotation speed is a key input parameter for designing a suitable rotor capable to both take advantage of the generator characteristics and the considered design wind speed.

Regarding starting behaviour of small wind turbines, the torque of wind on blades will have to overtake the PMG cogging torque in order to start blade rotation. Typical cogging torques for 500W to 1.5kW PMGs is 0.3 to 0.6 Nm.

1.1.3. SWT operation

Target wind resource

The operating height of small wind turbines has a major impact on the target wind resource. Indeed hub height is generally comprised between 5 and 10m for 300W to 2kW wind systems. At those heights, wind resource is much affected by ground characteristics: roughness and obstacles. The closeness to ground is

therefore a limiting factor for the available wind energy. In good wind resource area, typical mean wind speed at 10m height is 4.5 to 7 m/s. In absolute scale, those values would be referred as low and medium wind resource for multi megawatt wind parks projects; for small wind turbine projects, a 7 m/s mean wind speed denotes a high wind resource site.

Compared to multi megawatt wind turbines operating at 50m and above, small wind turbines can not target the same wind resource. Therefore it is useless to target 15 m/s rated wind speed and realistic values for rated wind speed of SWT are around 9 m/s.

Due to this low to medium wind resource target and the higher SWT production cost (in USD/kW), one could argue that cost of electricity will be much higher for a 1kW wind turbine than for a 1MW wind turbine. It is definitively true that scale economy and higher wind resource yields (much) lower cost of electricity, but no one should forget that cost of electricity is a relative concept which varies from a place to another, from country to country, from continent to continent. Therefore the economic suitability of small wind turbines can not be determined without taking into consideration the energy resource portfolio, environment constraints and economy of the area where they will operate.

As demonstrated in Part 3, small wind turbines are a pertinent source of electricity in any remote area of Africa endowed with sufficient wind resource. Remoteness is a key characteristic for SWT operation. On top of requiring robust design, it induces the idea that small wind turbines will be a suitable option in any area where they are relatively more advantageous compared to the current other available energy resources.

The context of this research work, taking advantage of wind energy to provide electricity in rural Kenya, highlights that current energy sources of Kenyan rural households are very polluting and dramatically costly. Therefore low and medium wind resources are plainly compatible with cost effective small wind turbine projects in rural Kenya.

Based on the available energy resources available for electricity production in remote areas, both in developed and developing countries, and the environment constraints induced by climate warming, low and medium wind resource suitability for small wind turbine projects could actually be extended to any remote area on Earth, the degree of remoteness and the local energy, environment and economy situations, defining the level of suitability.

Self starting

Starting is a key concept in small wind turbine design. Most commercial small wind turbines (<2kW) are self starting.

Two arguments plead for designing small wind turbine relying on self starting. The first one is the cost of installing a motorized system for starting blade rotation on small wind turbines. The second one comes from the fact that most small wind turbines operate in remote areas where technical support and spare parts availability might lack. One way to ensure reliability is to design system using simple and robust technology.

Provided suitable blade design, it is possible to achieve excellent starting performance only thanks to the torque created by the wind on blades.

To start rotation, a wind peak of typically 5-7 m/s will be needed to generate enough torque on blades to overcome the resistive torques from the generator and the drive train. The main resistive torque is the generator cogging torque. Once the wind torque exceeds the resistive torques, blades start rotating and accelerate. To produce power the generator requires a certain minimum rotation speed. The acceleration period T_S occurring from the time when wind torque on blades exceeds the total resistive torque to the time when rotation speed reaches the minimum value required for power production is an important characteristic of starting behaviour of small wind turbines. T_S can vary from a few seconds to a few minutes according to the considered wind speed. If this wind peak does not last enough so that rotation speed has not reached the minimum value required by the generator for power production, then blades will start decelerating and power production will be delayed to the sufficiently long next wind peak period. Starting behaviour can also be characterized with U_S the wind speed necessary to overtake the total resistive torque.

It is one goal of this study to investigate proper blade design for high starting performances. T_S and U_S will be used to assess starting performance. The objective is to minimize them. To introduce what will be more

detailed in section 1.4., starting performance is very sensitive to blade root design. Indeed most of the blade wind torque is generated at the root sections while the tip sections contribute to a small amount of the total blade torque during starting.

Power production

At power production, wind energy is extracted by the blades and transformed into electric energy in the generator. Target wind resource, generator characteristics, blade design are the main considerations to design an optimized small wind turbines for power production. Regarding blade design, it is interesting to note that contrary to starting, most of the torque is produced at the outer sections of the blades (next to tip). It is also important to remind that the purpose of this study is to design a small wind turbine suitable for providing electricity to a rural school in Kenya. As presented more in details in Esilanke project case study (Chapter 4), the objective annual energy output is kWh (corresponding to 2 kWh daily energy output).

Power regulation strategy

Safety of small wind turbines will highly depends on the design of their power regulation strategy. It is a particularly important issue at high wind speeds. It must ensure that loads do not reach their maximum admissible values.

For small wind turbines, furling is a common control strategy. The tail fin is attached to the nacelle with an offset enabling the rotor to furl out once wind speed excess the design yaw wind speed (about 10-15 m/s). It has the main advantage of being very simple but will yield reduced power production performance due to constant yaw offset at low wind speeds.

More advanced control strategy is possible with the installation of an electronic controller which will adjust the rotation speed to present wind speed. Advanced control strategy becomes cost-effective for higher small wind turbine sizes (from 5kW).

It is out of the scope of this study to include a control strategy in the design process. However for the considered SWT sizes, furling system would be probably the most adapted and the easiest to manufacture in Kenya.

1.2. Blade Element Momentum method

The classical Blade Element Momentum method (BEM) from Glauert is the core model used for designing small wind turbines for high power production and starting performance.

The 1-D BEM is a simple model which enables to evaluate accurately the power performance of a wind turbine. It only requires information on blade root and tip radii, chord and twist distributions and selected airfoils.

The blades are divided in a certain number of sections (typically 10 to 30 sections) where the local forces are derived. To be able to solve the equations of conservation considering the forces applying on each blade element, the air flow is modelled as annular streamtubes corresponding to those blade elements.

The main model assumptions are no radial dependency and constant forces acting on each blade annular element. To correct the second assumption which is only valid for an infinite number of blades, the Prandtl's tip-loss factor is needed. This correction enables to carry out calculation for finite a number of blades.

It is useful to start with the 1-D momentum theory for an ideal wind turbine before going into BEM. Indeed the main results derived rotor wise will be later applied on the blade elements.

1.2.1. 1-D momentum theory for an ideal wind turbine

Let's model the rotor as an ideal frictionless 1D-disc. No rotational velocity in the wake and constant air density is assumed.

Let's define also the wind velocities: U_0 upstream, U at the rotor plane and U_1 far in the wake. It is expected that the rotor disc will slow down the wind speed and streamlines will diverge. This wind speed drop traduces the energy extraction operated by the blades on wind. It also induces the pressure drop over the rotor originating the thrust force applied by the rotor on the air flow.

The variation of the axial wind velocity and pressure are illustrated on the following figure.

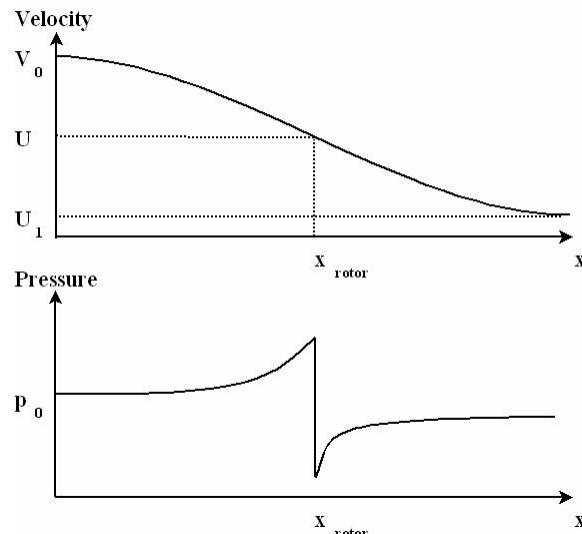


Figure 1.1. Axial velocity and pressure up- and downstream of a rotor

The thrust force can be defined as:

$$T = \Delta p A \quad (1.1)$$

where $A = \pi R^2$ is the area of the rotor.

Assuming a stationary, incompressible and frictionless flow with no external forces, the Bernoulli equation can be introduced to relate pressures and wind speeds upstream to just in front of the rotor, and just behind the rotor to far downstream in the wake.

$$p_0 + \frac{1}{2} \rho_{air} U_0^2 = p + \frac{1}{2} \rho_{air} U^2 \quad \text{and} \quad p - \Delta p + \frac{1}{2} \rho_{air} U = p_0 + \frac{1}{2} \rho_{air} U_1^2 \quad (1.2)$$

The pressure drop can therefore be derived easily: $\Delta p = \frac{1}{2} \rho_{air} (U_0^2 - U_1^2)$ (1.3)

To proceed the conservation of mass and momentum, let's define the control volume as follow:

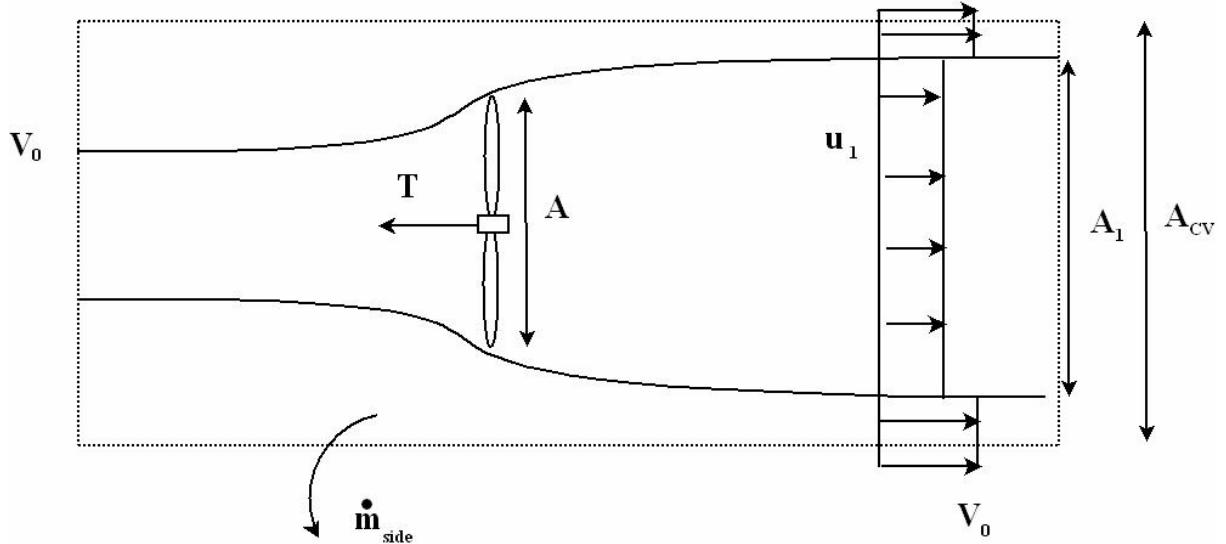


Figure 2.2. Circular control volume around a wind turbine

The control volume has a circular cross section with an area A_{CV} .

By applying the conservation of mass on this control volume, we get the equation:

$$\rho_{air} A_1 U_1 + \rho_{air} (A_{CV} - A_1) U_0 + \dot{m}_{side} = \rho_{air} A_{CV} U_0 \quad (1.4)$$

$$\text{and therefore obtain } \dot{m}_{side} = \rho_{air} A_1 (U_0 - U_1) \quad (1.5)$$

Focussing now on the circular control volumes defined by A and A_1 , A and A_1 we can also relate A and A_1 as:

$$\dot{m} = \rho_{air} A U_0 = \rho_{air} A_1 U_1 \quad (1.6)$$

By applying the conservation of axial momentum on a circular control volume and reminding the assumption, the general equation gets much simpler:

$$\frac{\partial}{\partial t} \iiint_{CV} \rho_{air} U d(vol) + \iiint_{CV} U \rho_{air} V \cdot dA = F_{ext} + F_{pres} \quad (1.7)$$

where dA is a vector pointing in the direction normal to an infinitesimal part of the control surface and having a length equal to this element. F_{pres} is the axial component of the pressure forces acting on the control volume and $d(vol)$ denotes an incremental part of the control volume.

The stationary flow assumption implies that the first term is zero. Given that the pressures far upstream and downstream are equal to the same atmospheric value and since the control volume cross sectional area is constant, the pressure force between the end planes of the control volume is zero. We therefore get:

$$\rho_{air} U_1^2 A_1 + \rho_{air} U_0^2 (A_{CV} - A_1) + \dot{m}_{side} U_0 - \rho_{air} U_0^2 A_{CV} = -T \quad (1.8)$$

Combining equations (1.5), (1.6) and (1.8) yields:

$$T = \rho_{air} U A (U_0 - U_1) = \dot{m} (U_0 - U_1) \quad (1.9)$$

Combining (1.1) and (1.3) and replacing the thrust in (1.9) enables to connect the different axial speeds as:

$$U = \frac{1}{2}(U_0 + U_1) \quad (1.10)$$

It would be now interesting to get a direct relationship between U and U_0 .

The air passing through the rotor decelerates. This deceleration is modelled thanks to the axial induction factor a as:

$$U = (1 - a)U_0 \quad (1.11)$$

and therefore $U_1 = (1 - 2a)U_0$ (1.12)

Frictionless flow assumption implies that there is no internal energy loss and the Power caught by the blades can be found by using the integral energy equation on the control volume:

$$\dot{P} = m\left(\frac{1}{2}U_0^2 + \frac{p_0}{\rho_{air}} - \frac{1}{2}U_1^2 - \frac{p_0}{\rho_{air}}\right) = \frac{1}{2}\rho_{air}UA(U_0^2 - U_1^2) \quad (1.13)$$

Introducing the above expression for U_0 and U_1 yields:

$$P = 2\rho_{air}U_0^3a(1-a)^2A \text{ and } T = 2a\rho_{air}U_0^2(1-a)^2A \quad (1.14)$$

The power and thrust coefficients can be derived as:

$$C_P = \frac{P}{P_{avail}} = \frac{P}{\frac{1}{2}\rho_{air}U_0^3A} = 4a(1-a)^2 \quad (1.15)$$

$$\text{and } C_T = \frac{T}{\frac{1}{2}\rho_{air}U_0^2A} = 4a(1-a) \quad (1.16)$$

and by differentiating C_P with respects to a , it can be easily demonstrated that C_P has a maximum of 16/27 for $a = 1/3$; this is the Betz limits.

Although for an ideal turbine there is no rotation in the wake, the effect of rotation is an important matter of real wind turbines. The Euler's turbine equation relates the power and the tangential velocities as:

$$\dot{dP} = m\omega rC_\theta = 2\pi r^2\rho_{air}\omega UC_\theta dr \quad (1.17)$$

where C_θ is the azimuthal component of the absolute velocity after the rotor. Similarly to the axial induction factor a , the tangential factor a' is introduced to model the loss of kinetic energy contained in the rotating wake as:

$$C_\theta = 2a'\omega r \quad (1.18)$$

Introducing it into equation and integrating dP from 0 to R yields:

$$P = 4\pi\rho_{air}\omega^2U_0 \int_0^{R_{tip}} a'(1-a)r^3 dr \quad (1.19)$$

1.2.2. BEM

Thrust and torque on a blade element

For an annular section of an ideal rotor, the conservation of momentum is:

$$dT = 2\pi r\rho_{air}U(U_0 - U_1)dr \quad (1.20)$$

Setting the rotational velocity upstream to zero and C_θ in the wake, the conservation of angular momentum is:

$$dM = \dot{m}rC_\theta = 2\pi r^2\rho_{air}UC_\theta dr \quad (1.21)$$

Introducing the axial and tangential induction vectors defined in equations (1.11) and (1.12) yields:

$$dT = 4\pi r \rho_{air} U_0^2 a(1-a) dr \quad \text{and} \quad dM = 4\pi r^3 \rho_{air} U_0 \omega (1-a)a' dr \quad (1.22) - (1.23)$$

Velocities on a blade element

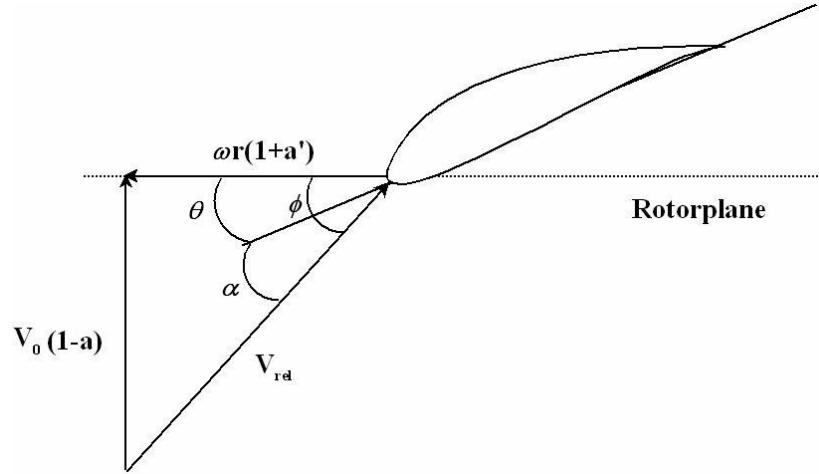


Figure 3.3. Velocities at the rotorplane

U_{rel} is the relative local velocity seen by the blade element. Therefore it is the vector summation of the wind speed at the rotor plane and the rotor rotation speed. Its norm is:

$$U_{rel} = \sqrt{((1-a)U_0)^2 + ((1+a')\omega r)^2} \quad (1.24)$$

According to potential flow theory, a and a' are not independent for angles of attacks below stall since the reacting force is perpendicular to the local velocity seen by the blade. Therefore the total induced velocity must be in the same direction as the force and thus be perpendicular to the local velocity.

From this, the flow angle ϕ , the angle between the plan of rotation and the relative velocity, can be derived as:

$$\tan \phi = \frac{(1-a)U_0}{(1+a')\omega r} = \frac{a'\omega r}{aU_0} \quad (1.25)$$

and the relationship between a and a' can be established:

$$x^2 a'(1+a') = a(1-a) \quad (1.26)$$

$$\text{where } x = \omega r / U_0 \text{ is the local speed ratio} \quad (1.27)$$

All angles are local, i.e. defined at a section of the blade. θ is the total local twist angle and α the angle of attack. The flow angle, the twist angle and the angle of attack are related through: $\alpha = \phi - \theta$

The total local twist angle is the summation of the local twist angle and the blade pitch angle.

$$\theta = \theta_{twist} + \theta_{pitch} \quad (1.28)$$

The local twist angle is inherent to blade design while the blade pitch angle can refer, in the case of small wind turbines, to the action of rotating the blade by a few degrees when mounting it on the hub (for other purposes like improving starting performance for example).

Forces acting on a blade element

A blade element is assumed to behave as an airfoil. Therefore the force applied by the wind on the blade element can be divided into two perpendicular components: the drag acting in the direction of U_{rel} and the lift perpendicular to it. R is the resulting force from lift and drag forces. F_T is the tangential component of R (parallel to rotor plane axis) and F_N is the normal component (perpendicular to rotor plane axis).

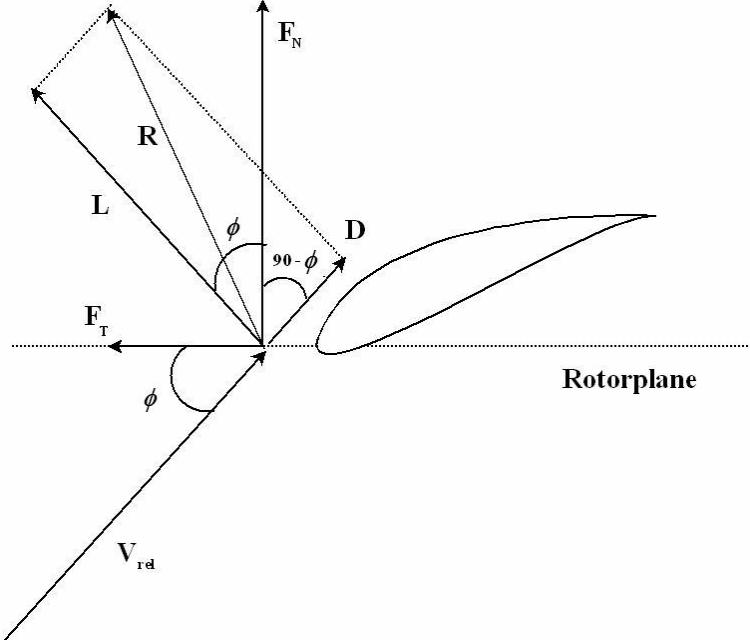


Figure 4.4. Local forces on a blade element

Lift and drag forces can be derived from the lift and drag coefficients (C_L and C_D). Indeed for most airfoils, C_L and C_D have been measured and are therefore available.

C_L and C_D are function of the angle of attack α , the Reynolds number Re and the Mach number Ma . The Mach number is the ratio the between the wind speed and the speed of sound and the Reynolds number at a blade section is $Re = c U_{rel} \nu_{air}$. For a wind turbine, the Mach dependence can be neglected. Due to large range of rotation speeds, Reynolds number is an important matter for small wind turbines.

Lift and drag forces are derived from C_L and C_D as:

$$L = \frac{1}{2} \rho_{air} U_{rel}^2 c C_L \quad D = \frac{1}{2} \rho_{air} U_{rel}^2 c C_D \quad (1.29) - (130)$$

where c is the chord

F_N and F_T to L and D as:

$$F_N = L \cos \phi + D \sin \phi \quad F_T = L \sin \phi - D \cos \phi \quad (1.30) - (131)$$

All forces are per unit length.

Those forces can be rewritten as normalized expression:

$$C_n = C_L \cos \phi + C_D \sin \phi = \frac{F_N}{\frac{1}{2} \rho_{air} U_{rel}^2 c} \quad (1.32)$$

$$C_t = C_L \sin \phi - C_D \cos \phi = \frac{F_T}{\frac{1}{2} \rho_{air} U_{rel}^2 c} \quad (133)$$

The normal force and the torque are linked to C_N and C_T as:

$$dT = BF_N dr = \frac{1}{2} \rho_{air} B \frac{U_0^2 (1-a)^2}{\sin^2 \phi} c C_n dr \quad (1.34)$$

$$dM = rBF_T dr = \frac{1}{2} \rho_{air} B \frac{U_0^2 (1-a) \omega r (1+a')}{\sin \phi \cos \phi} c C_t r dr \quad (1.35)$$

Prandtl's tip-loss factor

Prandtl's tip-loss factor is required to correct the assumption of infinite number of blades. The Factor F is introduced in dT and dM equations (1.22) and (1.23):

$$dT = 4\pi r \rho_{air} U_0^2 a (1-a) F dr \quad \text{and} \quad dM = 4\pi r^3 \rho_{air} U_0 \omega (1-a) a' F dr \quad (1.36) - (1.37)$$

where:

$$F = \frac{2}{\pi} \cos^{-1}(e^{-f}) \quad f = \frac{B}{2} \frac{R-r}{r \sin \phi} \quad (1.38) - (1.39)$$

Equalling equations (1.22) and (1.36) for dT and equations (1.23) and (1.37) for dM yields:

$$a = \frac{1}{(4F \sin^2 \phi / \sigma C_N) + 1} \quad \text{and} \quad a' = \frac{1}{(4F \sin \phi \cos \phi / \sigma C_T) - 1} \quad (1.40) - (1.41)$$

$$\text{where } \sigma \text{ is the solidity and defied by: } \sigma(r) = \frac{c(r)B}{2\pi r} \quad (1.42)$$

The simple momentum theory breaks down when the axial induction factor gets larger than approximately 0.4. The Glauert correction, applied on the Thrust coefficient, is an empirical way to fit with measurements. The expression given by Spera is:

$$C_T = \begin{cases} 4a(1-a)F & a \leq a_c \\ 4(a_c^2 + (1-2a_c)a)F & a > a_c \end{cases} \quad (1.43)$$

Recalling that C_T is by definition: $C_T = \frac{dT}{\frac{1}{2} \rho_{air} U_0^2 2\pi r dr}$ and using (1.34) for dT

A new expression for the induction factor by equalling those two C_T expressions:

$$a = \frac{1}{2} \left[2 + K(1-2a_c) - \sqrt{(K(1-2a_c)+2)^2 + 4(Ka_c^2 - 1)} \right] \quad (1.44)$$

$$\text{where } K = \frac{4F \sin^2 \phi}{\sigma C_N} \quad (1.45)$$

1.3. Blade design for maximum power production performance

1.3.1. Challenges, objectives and assumptions

The methodology of designing a blade for maximum power performance consists first in determining the design operating conditions (defined with U_d and ω_d) and then the geometry of the blade.

Defining the operating conditions at which the blade is designed is a key first step. Indeed $C_L(\alpha, Re)$ and $C_D(\alpha, Re)$ are function of α , Re function, themselves function of respectively U_0 , ω and the twist angle θ for the former and U_0 and the chord length c for the later.

At that point, it appears that actually the determination of operating conditions and blade geometry are interconnected matters.

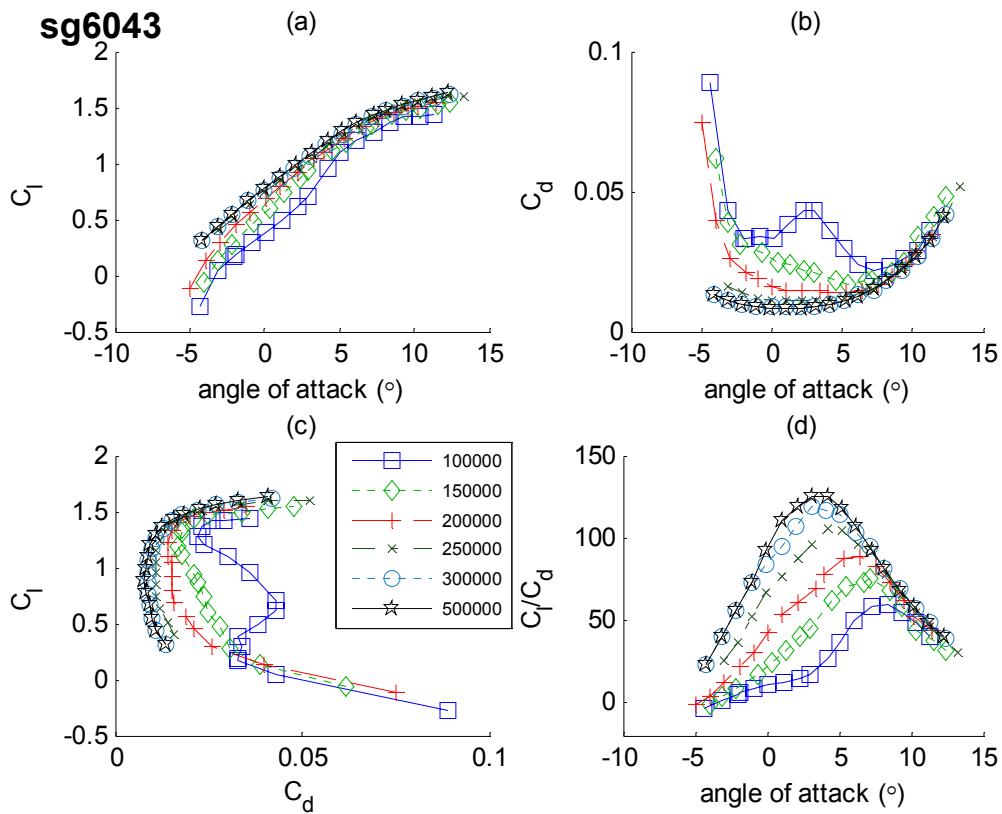


Figure 5.5. Lift and drag coefficients for the airfoil SG 6043

To briefly explain the interconnected issues, as seen on graph (d) of Figure 1.5, it exists therefore a combination of α , Re where the ratio C_L/C_D is maximum and including ϕ where the tangential force is maximum. Furthermore the rotation speed connects torque and power: for given tangential force, the higher the rotation speed, the higher the power. The values of the rotation speed ω and the incoming wind speed U_0 will also intervene in the derivation of the flow angle.

Once the local chord c is known, the Re number can be calculated and once the local twist angle θ_{twist} is derived, the angle of attack is computed and therefore $C_L(\alpha, Re)$ and $C_D(\alpha, Re)$ can be determined.

On an absolute scale, the objective is to have power performance as close as possible to the Betz limit, i.e. C_P above 0.5. It is however important to connect this absolute objective to the target power output.

With small wind turbines, the importance, *and difficulty*, of designing blade for maximum power production is enhanced by the impossibility to install a motorised pitch system. Therefore the angle of attack can not be adjusted by pitching the blade. However, the varying speed characteristic of Permanent Magnet Generators offers the opportunity to take advantage of this property for keeping the angle of attack as close as possible to the optimum value.

The first step is to determine the design U_d resulting from the wind climate where the turbine is expected to operate, as mentioned earlier climates of 4.5-7 mean wind speeds are the most likely for small wind turbines.

The IEC standard [5] specifies the following relationship between the hub-height average wind speed U_{ave} and the U_d .

$$U_d = 1.4 U_{ave} \quad (1.46)$$

The second step is to determine the design power output of the wind generator P_d . It is clear that the limited kinetic energy contained and extractable from the wind means that U_d and P_d can not be randomly picked and P_d results from U_d .

Third, introducing P_d and the design rotation speed ω_d means that actually a generator must be chosen. ω_d results from P_d .

The operating conditions could be sum up within the tip speed ratio λ but this would exclude the Re dependency of C_L and C_D when designing the blade, that is why U_d , P_d and ω_d need to be determined first. Then the designed tip speed ratio λ_d is derived. We will see in 1.3.2 that the choice of the tip speed ratio is actually a key input to get as close as possible to the Betz limit. Therefore the choice of the operating parameters: U_d , P_d , ω_d and λ_d result from the same logic and the determination of one parameter can not be dissociated to its implications on the other ones.

1.3.2. Procedure

Once those design parameters have been determined, the procedure consists in maximizing the expression :

$$f(a, a') = a'(1-a) \quad (1.47)$$

contained in the C_P equation from (1.19) while still satisfying the relationship established in (1.26).

From (1.26) a' is also a function of a , thus for a given x the problem reduces to seeking the (a, a') combination yielding $df/da = 0$.

$$\frac{df}{da} = (1-a) \frac{da'}{da} - a' = 0 \quad \Leftrightarrow \quad \frac{da'}{da} = \frac{a'}{1-a} \quad (1.48)$$

Another expression for da'/da is provided by differentiating equation (1.26) with respect to a which yields:

$$\frac{da'}{da} = \frac{1-2a}{(1+2a')x^2} \quad (1.49)$$

and replacing x^2 in (1.49) thanks to (1.26) yields to the final relationship between a and a' :

$$a' = \frac{1-3a}{4a-1} \quad (1.50)$$

It is important to remember that those equations are valid only when the flow is attached to the blades, i.e. for angle of attacks below stall, which is obviously the case when seeking the optimal aerodynamics airfoil performance.

At that point, it is now possible to link the choice of the tip speed ratio λ to the derivation of the power coefficient C_P .

The tables below provides the numerical relationship between a, a' and x (Table 1.3).

| a | a' | x |
|------|--------|--------|
| 0.25 | Inf | 0 |
| 0.26 | 5.5000 | 0.0734 |
| 0.27 | 2.3750 | 0.1568 |
| 0.28 | 1.3333 | 0.2546 |
| 0.29 | 0.8125 | 0.3739 |
| 0.30 | 0.5000 | 0.5292 |
| 0.31 | 0.2917 | 0.7535 |
| 0.32 | 0.1429 | 1.1545 |
| 0.33 | 0.0313 | 2.6193 |

Table 3.3 The numerical relationship between a , a' and x

From this table the interesting point is the convergence of a to $1/3$ with increasing speed ratio (which consisting with the simple momentum theory for an ideal rotor).

From an energy conversion point of view it is better to select λ_d greater than 6. Indeed with λ_d beyond 6, there is only a small amount of energy is lost due to rotation for high tip speed ratios and it is possible to reach C_p very close to the Betz limit. The relationship between a and a' enables to determine the optimal characteristics of the air flow around the blades. The next step is therefore to link those parameters to the determination of the blade geometry.

Combining equations (1.50) and (1.26) yields the optimum relationship between a and x :

$$16a^3 - 24a^2 + a(9 - 3x^2) - 1 + x^2 = 0 \quad (1.51)$$

Once this relationship is satisfied, the flow angle can be derived as:

$$\tan \phi = \frac{(1-a)}{(1+a')x} \quad (1.52)$$

Prior to compute the optimum local twist angle θ_{opt} , the airfoil must be selected and the optimum value for the local angle of attack α_{opt} must be determined.

The goal is to maximize the tangential force, or its dimension-less value, the C_t .

$$C_t = C_L \sin \phi - C_D \cos \phi$$

The procedure is to compute C_D / C_L and determine the angle of attack yielding to the minimum value of the drag-lift coefficient ratio. The values of the lift and drag coefficient corresponding to that are referred to $C_{L,opt}$ and $C_{D,opt}$.

Due to the Reynolds dependency for C_L and C_D , U_d and ω_d are not enough to calculate Re but the chord length c_{opt} is also needed. Therefore computing α_{opt} and c_{opt} are within this methodology interconnected. It means that a first value for α_{opt} is derived based on Re guess. Then this first value for α_{opt} will be inputted to compute c_{opt} , and back this c_{opt} value will be used to recalculate Re , and so on until all values converge. On a loop process, both α_{opt} and c_{opt} are derived.

The optimum chord is found from equation using the optimum values for a and a' :

$$\frac{c(x)}{R_{tip}} = \frac{8\pi a x \sin^2 \phi}{(1-a)BC_n \lambda} \quad (1.53)$$

1.4. Blade design for starting and low wind performance

1.4.1. Challenges, objectives and assumptions

As it has been mentioned several times, pitch adjustment is very rare for small wind turbines and most small wind turbines are self-starting. Therefore when the turbine is stationary, the angle of attack is very high and close to 90° . To start rotating, the aerodynamic torque must exceed the resistive torque of the generator and the drive train. While the aerodynamic torque will scale as BR^3 (from equation 1.35), it appears that the resistive torque will decrease less rapidly than R^3 , enhancing thereby the starting issue for small wind turbines.

Wood presents in his book [6] the typical example of a 2bladed 2.5m radius 5kW turbine and a 3bladed 0.97m radius 0.6kW turbine. The 5kW turbine has a total resistive torque of 1Nm while the 0.6kW turbine has a 0.36Nm one. The BR^3 ratio is 0.197 ($\sim 1/5$) while its resistive torque ratio is 0.36 ($\sim 1/3$). It means that between those two turbines while the aerodynamic torque is divided by 5, the resistive torque is only divided by 3.

Permanent Magnet Generators requires a minimum rotation speed to produce power. Therefore starting is not only characterized by the starting wind speed, U_S , but also by the duration of the period from the time when the aerodynamic torque exceeds the resistive torque to the time when rotation speed exceeds its minimum value for power production. This period is called the starting period, T_S .

From the previous analysis for power production performance, we have seen that the angle of attack is a key for power production. When the angle of attack is high, C_D dominates and the aerodynamic torque is small, when the angle reduces, C_D / C_L decreases as well down to the optimum point at α_d . Therefore as long as angles of attack are high, the aerodynamic torque will be small and the turbine will accelerates slowly. This period of slow acceleration is referred as the “idling period”. Its duration is a critical parameter for self-starting SWT blade designers. When the angle of attack gets close to the optimum value, the blades will start accelerating fast.

The notion of starting wind speed is complex and not always easy to define. Indeed, starting can cover several configuration cases and concepts as it is presented below.

- The turbine is stationary; wind speed is very low, 2-3 m/s. A wind speed peak of 6m/s occurs and last sufficiently long so that blades accelerates slowly; after 40-120 seconds the turbine starts producing power.
- The turbine is producing power but wind speed is low, 4-5 m/s and drop to 3 m/s, due to rotation inertia the turbine is still rotating fast enough and power production continues
- Continuing the previous case, wind speeds drops again to 2.5m/s. Rotation speed goes down below the minimum value for power production. Therefore power production stops but the blades continue rotating slowly. A wind speed peak of 5m/s occurs; since the blades are still rotating, the angle is much smaller than when stationary and therefore a 5m/s wind speed is enough to reach the minimum rotation speed for power production.
- Last and continuing the previous situation, wind speed drops again to 1.5 m/s and the turbine decelerates and finally stops rotating.

The first case refers to the starting wind speed as we referred it in this study: the turbine is stationary and we are seeking the minimum wind speed when rotation speed excesses its minimum value for power production. In that case the cut-in wind speed, U_{cin} , and the starting wind speed are identical.

The second and the fourth cases refer to the cut-out situation, which is not easy to define since it is connected to the actual operating situation when wind speeds drops.

The third case highlights the influence of the rotation speed on the cut-in wind speed as well.

In practice the cut-in wind speed, U_{cin} , covers a range of wind speeds comprises between the cut-out, U_{cout} , wind speed and the starting wind speed, U_S .

The first main assumption is to suppose that starting is a quasi-steady process. This assumption is justified by the duration of the idling period which is the longest and most critical part of the total starting period. Wood claims that for the hundreds of measured starting sequences that were analysed, there is no evidence that unsteady effects are significant [7].

The second main assumption is that no significant momentum is extracted during starting and therefore the induction factors a and a' are neglected.

Therefore the analysis is based on the modification of the BEM method presented above where the resulting differential equation $d\omega/dt$ for is integrated using standard fourth order Runge-Kuta equation method to determine the angular velocity as a function of time.

While power production performance is governed by blade design and generator characteristics, starting and low wind performance is determined by the rotational inertia of the blades, the generator and drive train resistive torques. In this study, the generator cogging torque will be considered as the main resistive source and assimilated to the total resistive torque.

1.4.2. Procedure

Lift and drag coefficients at high angle of attack and low Re numbers

In his PhD thesis, Wright specifies that for the Re range occurring during starting sequence ($10^4 - 10^5$) “aerofoil performance is significantly affected by the behaviour of a flow separation bubble that covers much of the aerofoil surface so lift and drag prediction is difficult and very sensitive to the flow conditions.” He highlights the phenomenon at low angles of attack.

At so low Re and high α , it is difficult to find data. Extrapolations are needed which alter the result reliability.

The method developed by Wright in his PhD thesis [8] for determining C_L and C_D at low Re high α yielded to very consistent results with measurements. Therefore this present work has used the same methodology.

For the considered airfoil, the C_L and C_D available at the lowest Re are used as input. Typically, data are available for $Re = 60\,000-80\,000$ and covers a range of α from -5° to 15° .

This data are then combined with the results from Ostowari and Naik [9] for the NACA4418 for $15^\circ < \alpha < 90^\circ$ at $Re = 250\,000$. This first estimate corresponds to an infinite aspect ratio (AR). It is referred as estimate (a).

However Aspect Ratio effects are quite important for starting and C_D is expected to be lower at high α when including those effects. For a blade the aspect ratio is defined as the length of the blade (l) squared, divided by the planform area (S).

$$AR = l^2/S \quad (1.54)$$

For this second estimate, the data from Ostowari and Naik for the NACA4418 for $AR = 9$ ($15^\circ < \alpha < 90^\circ$ at $Re = 250\,000$) are combined with the available information for the considered airfoil $-5^\circ < \alpha < 15^\circ$ at $Re = 60-80\,000$). This estimate is referred as estimate (b).

In his PhD Thesis, Wright improves this result by weighting it with the Viterna equations applied to the considered airfoil. The Viterna equations require determining the angle of attack, lift and drag coefficients at stall. Since stall occurs above 15° , available data do not cover stall behaviour. It is therefore quite hazardous to extrapolate stall characteristics from the available data for the considered airfoil.

Even though using this weighting method, Wright gives much more weight to the Ostowari data, resulting in very close values between the weighted outputs and the original NACA4418 for $AR = 9$ for $\alpha > 30^\circ$.

We will see that estimate (b) provide best starting sequence simulations.

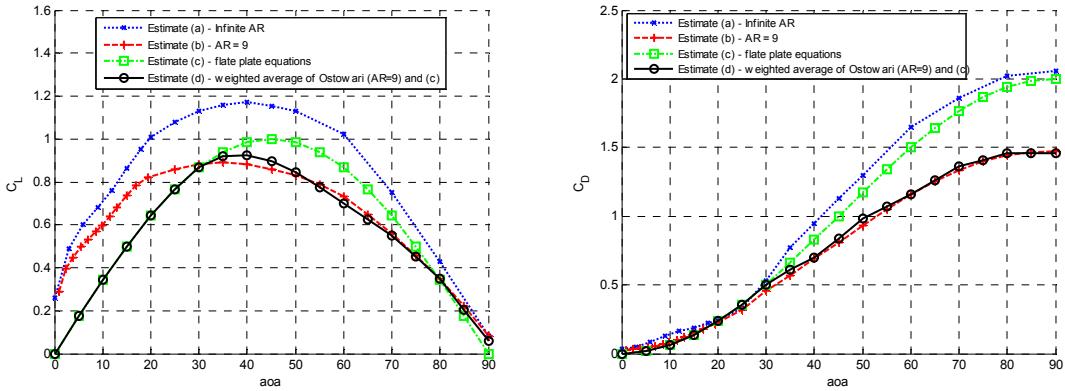


Figure 6.6. Lift and drag coefficients used in the starting behaviour modelling method

Another estimate can be made from the aerodynamic characteristics of a flat plate at high α . Indeed close to 90° , the aerodynamic behaviour becomes independent to airfoils and flat plate equations provide fairly good results:

$$\begin{aligned} C_L &= 2 \sin \alpha \cos \alpha \\ C_D &= 2 \sin^2 \alpha \end{aligned} \quad (1.55)$$

The method is proposed by Wood [10] who showed that for $\alpha > 45^\circ$ (infinite AR) those equations provides good fits for three sets of airfoils. It is referred as estimate (c). However lift behaviour is much underestimated for $\alpha < 45^\circ$. In the case of starting, and considering especially the idling period, the critical issue is the high angle of attacks, thus the good fits for $\alpha > 45^\circ$ is of major interest while the inaccuracy for $\alpha < 45^\circ$ is secondary.

A fourth estimate is introduced which is simply built from Ostowari data for $AR = 9$ and estimate (c). Below 30° , the flat plate generic equations are used, beyond 60° the Ostowari data for $AR = 9$ is used, between 30° and 60° an interpolation is computed.

Estimation of the starting wind speed U_S

Wood in [10] has developed a method to calculate the starting wind speed U_S .

From the local torque equation rewritten here as:

$$dM = rBF_T dr = \frac{1}{2} \rho_{air} B U_{rel}^2 c (C_L \sin \phi - C_D \cos \phi) r dr$$

For the idling period, let's assume true the following relationship

$$\alpha \approx \pi/2 - \theta \quad (\text{only exactly true at starting})$$

which induces: $\sin \alpha \approx \cos \theta$ and $\sin \phi \approx 1$

Solving for the flat plate C_L and C_D equations, the expression for the local torque gets simpler as:

$$dM = rBF_T dr = \frac{1}{2} \rho_{air} B (1-a)^2 U_0^2 c \sin(2\theta) r dr \quad (1.57)$$

Equalling the local torque with the previous dM expressions in (1.21) from the the conservation of angular momentum gives: $a' = a \tan \theta$ (1.58)

Equalling equation (1.22) and (1.34) as

$$4\pi r U_0^2 a (1-a) = \frac{1}{2} B U_{rel}^2 c C_n \quad (1.59)$$

enables to derive an approximate value for a with the abovementioned relationship between α and θ and the flat plate C_L and C_D equations.

$$a \approx \frac{1}{2} \sigma \cos^2 \theta \quad (1.60)$$

For small wind turbine blades, typical θ values are: $-5^\circ < \theta < 30^\circ$ and $\sigma < 0.2$ and both decrease from root to tip, and thus $a' < a \ll 1$.

Therefore the approximation of neglecting the induction factors is justified.

The aerodynamic torque can be integrated:

$$M = \frac{1}{2} \rho_{air} B U_0^2 \int_{R_{hub}}^{R_{tip}} c \sin(2\theta) r dr = \frac{1}{2} \rho_{air} B U_0^2 R_{tip}^3 I_{cp} \quad (1.61)$$

where I_{cp} is the “chord-pitch” integral defined as:

$$I_{cp} = \int_{r_h}^1 c \sin(2\theta) r dr \quad (1.62)$$

(in the chord-pitch integral, r refers to radius length normalised by R_{tip})

To derive the starting wind speed, U_S , let's assume that at U_S the aerodynamic torque equals the resistive torque of the generator and the drive train, M_{res} . Thus:

$$U_S = \left(\frac{2M_{res}}{\rho_{air} B U_0^2 R_{tip}^3 I_{cp}} \right)^{1/2} \quad (1.63)$$

If we also assume that the generator cogging torque is the main contribution for the total resistive torque, then:

$$U_S = \left(\frac{2M_{cog}}{\rho_{air} B U_0^2 R_{tip}^3 I_{cp}} \right)^{1/2} \quad (1.64)$$

Estimation of the starting period T_S

The assumption that no power is extracted during starting implies that the aerodynamic torque is used only to accelerate the blades and therefore the following differential equation applies at any time during starting:

$$\frac{d\omega}{dt} = \frac{(M - M_{res})}{J} \Leftrightarrow \frac{d\lambda}{dt} = \frac{R_{tip}(M - M_{res})}{J U_0} \quad (1.65)$$

This differential equation is solved with a standard Runge-Kutta method.

Only uniform density blades are considered in this study. The rotor inertia J of the rotor about turbine axis, is given by:

$$J = B \rho_b \int (y^2 + z^2) dx dy dz \quad (1.66)$$

Assuming that centroids lie along the z-axis (radius direction), J can be rewritten as:

$$J / (B \rho_b) = \int r^2 dx dy dz + \int y^2 dx dy dz = J_1 + J_2 \quad (1.67)$$

J_1 is expected to dominate since $c/R_{tip} \ll 1$. Defining A as the dimensionless area of the airfoil section divided by the chord length c , J_1 can be written as: $J_1 = A \int (cr)^2 dr$ (1.68)

J_1 is solved through trapezoidal integration.

For J_2 , an approximate expression is developed by assuming rectangular blade section with thickness t' . Thus $A = t'/c$ and centroids are along the z-axis. A new coordinate system (x', y') is introduced where y' lies along the chord line.

$$J_2 \approx \int_{-c/2}^{c/2} dy' \int_{-t/2}^{t/2} dx' (\cos^2 \theta_{twist} y'^2 + \sin^2 \theta_{twist} x'^2 + 2 \cos \theta_{twist} \sin \theta_{twist} x' y') = \frac{t' c^3 \cos^2 \theta_{twist} + t'^3 c \sin^2 \theta_{twist}}{12} \quad (1.69)$$

1.5. Application of small wind turbine design to decentralised power supply

1.5.1. Turbulence model

The Kaimal spectrum is used to generate realistic turbulence.

$$S_{uu}(f) = u_*^2 \frac{52.5/U}{(1+33n)^{5/3}} \quad (1.70)$$

where f is the frequencies at which the spectrum is estimated

u_* reflects the turbulence intensity set to 10% ($u_* = TI \times U$)

z is the hub height (10m)

U is the considered mean wind speed for the time series (m/s)

$n = f \times z / U$

For a given mean wind speed U , the spectrum is estimated at the frequencies f defined as:

The Nyquist frequency is defined as

$$f = l \times f_s / N \quad (1.71)$$

with $l = 1, \dots, N/2$, N is the number of discrete wind speed values calculated from the time series as $N = T/dt$.

$f_s = 1/dt$ is the sampling frequency ($dt = 10s$)

This spectrum is then inputted into an inverse discrete Fourier transform to generate a Time Series. The analysis of the wind climates of Kenya has been effectuated prior to time series construction. More information about Kenyan wind resource is presented in Chapter 4.

1.5.2. Wind turbine energy output calculation

The wind turbine energy output is based on Hansen's book, Aerodynamics of wind turbines, [11].

The annual energy production is computed from the power curve of the small wind turbine and the Weibull parameters (A, k) describing typical Kenyan wind climates.

As described in the European Wind Atlas [12], from the Weibull distribution the probability $f(V_i < V_0 < V_{i+1})$ that the wind speed lies between V_i and V_{i+1} is calculated from:

$$f(V_i < V_0 < V_{i+1}) = \exp\left(-\left(\frac{V_i}{A}\right)^k - \exp\left(-\left(\frac{V_{i+1}}{A}\right)^k\right)\right) \quad (1.72)$$

The total annual energy output can then be computed as:

$$AEO = \sum_{i=1}^{N-1} \frac{1}{2} (P(V_{i+1})P(V_i)) \times f(V_i < V_0 < V_{i+1}) \times 8760 \quad (1.73)$$

Chapter 2: Computing SWT design with Matlab

Matlab code has been used to build the different programmes to simulate power production and starting performance.

2.1. Blade design for optimal power production performance

Given design wind speed V_d and tip speed ratio λ_d , the root radius R_{root} and rotor radius R_{tip} , and the aerodynamic properties of the selected airfoil as $C_L(Re, \alpha)$ and $C_D(Re, \alpha)$ tables, this subroutine determines optimum chord and twist distribution. A schematic version is presented below.

```
INPUTS: Vd, λd, RROOT, RTIPI, airfoil data: CL(Re, α), CD(Re, α)
OUTPUTS: chord(r), θ(r)
for normalised radius = root:tip
    STEP 1: Compute x
        x = normalised radius × λd
    STEP 2: Compute a and a'
        for a = 0.2:0.4
            (x,a) relationship = 16 × a3 - 24 × a2 + a × (9-3 × x2) - 1 + x2
        end
        find (x,aopt) relationship = 0
        a'opt= (1 - 3 × aopt) / (4 × aopt-1)

    STEP 3: Compute φ(r) and Ut
        φ = atan((1 - aopt) / ((1 + a'opt) × x))
        Ut = Vd × sqrt((1 - a)2 + ((1+ap) × x)2);

    STEP 4: Determine maximal CN curves as function of (Re,α)
        CN,MAX (Re, α) = f( (CL, CD, Re, α)AIRFOIL , φ)
    STEP 5: Initialize CN,OPT
        CN,OPT = 0.8

    STEP 6: Compute chord(r) and θ(r)
        while chordGUESS ~= chord
            chordGUESS = 8 × pi × a × x × sin(φ)2 × Rtip / ((1 - a) × B × λd × CN,OPT)
            Re = Ut × chordGUESS / v
            find (CN,OPT, αOPT) = CN,MAX (Re, α)
            chord = 8 × pi × a × x × sin(φ)2 × Rtip / ((1 - a) × B × λd × CN,OPT)
        end
        θ = φ - αOPT
end
```

2.2. Blade mechanical properties

The blade mechanical properties subroutine enables to determine some key parameters that are later used for modelling the starting behaviour or carry out the load test as described in the IEC standard for small wind turbines [5]. The inputs are the airfoil geometry description as a table of (x,y) coordinates, the blade geometry (chord and twist distribution, blade lengths) and the material desnity. It is possible to input two different airfoils but the material must be uniform all over the blade. The subroutine outputs are the mass of the blade, the (x,y) coordinates of the centre of gravity for each section and the radius coordinate of the blade centre of gravity, the second moment of inertia I_x and $I_{x'}$, the rotational moment of inertia about the turbine axis J , the blade section areas, the blade planform area. Furthermore a rectangular root section can be computed and the same properties as for the aerodynamic sections can be derived for the root.

In the present report, only the computation of the rotational moment of inertia about the turbine axis J is presented. Due to lack of time it has not been possible to take as much advantage of this subroutine as wished. The original goal was to incorporate load testing for the blade design in an SWT optimization tool. Therefore accurate knowledge of the mechanical properties was needed. Unfortunately, though an optimization tool has actually been built, time has lacked to analyse the results properly.

The computation of rotational moment of inertia about the turbine axis J is effectuated with equations 1.66 to 1.69 and it is later used in the Starting behaviour modelling subroutine.

2.3. Blade Element Momentum adapted to the determination of the operating conditions of a SWT rotor connected to a Permanent Magnet Generator

The Blade Element Momentum subroutine is the chore part for determining the power production performance of the wind turbine. It requires the blade geometry (chord and twist distributions, root and tip radii, airfoil aerodynamic properties) and the operating conditions (U_0 , ω) as inputs. It enables to calculatesvarious outputs. The most important for wind turbine operation analysis is the power curve $P(V_0)$, the local torque $dM(r)$, Reynolds number $Re(r)$, and angle of attack $\alpha(r)$.

The particularity of this BEM subroutine is that the operating conditions are partially known when launching the code. Indeed instead of setting the rotation speeds $\omega = f(V_0)$, the code requires generator curves as $P_{gen,OUT} = g_1(\omega)$ and $P_{gen,IN} = g_2(\omega)$. The subroutine also accepts one of the two generator power curve and the generator efficiency curve $eff_{gen} = g_3(\omega)$. For each desired U_0 , the subroutine will equal the mechanical wind power caught by the blades and the input generator electric power $P_{gen,IN}$, and therefore determine the operating rotation speed $\omega(V_0)$ and the power curve $P(V_0)$, where P relates to this output generator electric power corresponding to $P_{gen,IN}$.

Some special features have been added to simulate small wind turbine operation as yaw offset, and the inclusion of Re influence in the determination of the blade aerodynamic properties.

INPUTS: V_0 , R_{ROOT} , R_{TIP} , $chord(r)$, $\theta(r)$, airfoil data: $C_L(Re, \alpha)$, $C_D(Re, \alpha)$, yaw offset = $yf(V_0)$, $P_{gen,OUT} = g_1(\omega)$, $P_{gen,IN} = g_2(\omega)$.

OUTPUTS: $P(V_0)$, $\omega(V_0)$, $dM(r)$, $Re(r)$, $\alpha(r)$

for $V_0 = V_{0,CUTIN} : V_{0,STOP}$

STEP 1: Compute $V_{0,eff}$

$$V_{0,eff} = V_0 \times \cos(yf(V_0))$$

for $\omega = \omega_{MIN} : \omega_{MAX}$

STEP 2: compute generator electric input power

```

Interpolate  $P_{gen,IN} = g_1(\omega)$ 
for  $r = R_{root} : R_{tip}$ 
STEP 3: initialize  $a$  and  $a'$ 
 $a = a' = 0$ 
while  $a$  and  $a'$  have not converged
STEP 4: compute the flow angle  $\phi$ 
 $\phi = \text{atan}((1-a) \times V_{0,eff} / ((1 + a') \times \omega \times r))$ 
STEP 5: compute the local angle of attack angle  $\alpha$ 
 $\alpha = \phi - \theta$ 
STEP 6: compute the relative wind velocity  $V_{rel}$ 
 $V_{rel} = (1-a) \times V_{0,eff} / \sin(\phi)$ 
STEP 7: compute the local Reynolds number
 $Re = \text{chord} \times V_{rel} / \nu$ 
STEP 8: determine the local lift and drag properties
Interpolate  $C_L(Re, \alpha)$ ,  $C_D(Re, \alpha)$ 
STEP 9: compute  $C_n$ 
 $C_n = C_L \times \cos(\phi) + C_D \times \sin(\phi)$ 
STEP 10: compute Prandtl's tip loss factor
Eq(1.38)
STEP 11: compute the induction factors  $a$  and  $a'$ 
Eq(1.40) and Eq(1.41)
STEP 12: compute Glauert correction
Eq(1.43)
end (a  $a'$  convergence loop)
STEP 13: compute the local force on the blade
 $C_n = C_L \times \cos(\phi) + C_D \times \sin(\phi)$ 
 $C_t = C_L \times \sin(\phi) - C_D \times \cos(\phi)$ 
 $F_n = \frac{1}{2} \times \rho_{air} \times V_{rel}^2 \times \text{chord} \times C_n$ 
 $F_t = \frac{1}{2} \times \rho_{air} \times V_{rel}^2 \times \text{chord} \times C_t$ 
STEP 14: compute the blade torque and thrust assuming linear
variation of the local forces between two following blade sections
Eq(1.37) and Eq(1.38)
end (blade section computation at  $r$ )
STEP 15: compute the rotor power and thrust
 $P_{ROT} = B \times \omega \times M$ 
 $T_{ROT} = B \times T$ 
STEP 16: determine whether generator and rotor operating points are
matching, and if yes compute operating rotation speed and wind
turbine power curve
if  $P_{ROT} = P_{gen,IN}$ 
 $P(V_0) = P_{gen,OUT}$ 
 $\omega_{OP}(V_0) = \omega$ 
end
end (rotation speed loop)
end (wind speed loop)

```

2.4. Starting behaviour modelling

The starting behaviour subroutine enables to compute the behaviour of the small wind turbine during starting sequence. The main outputs are the rotation speed, torque, Reynolds number and angle of attack as function of time. It requires a wind speed time series, the blade geometry and the knowledge of the generator resistive torque as inputs.

Assuming no flow deceleration through the blade (induction factors are set to 0), the torque generated by the wind on the blades M_{ROT} is equated to the product of the rotational moment of inertia J and angular acceleration ω . To start rotating, the blades will need to overcome the cogging torque of the generator $M_{RES,STAT}$ which is assumed to provide most of the resistive torque. When the aerodynamic torque exceeds the generator cogging torque, the net torque is the subtraction of the aerodynamic torque by the generator rotating torque $M_{RES,ROT}$.

The resulting ordinary differential equation for $d\omega/dt$ is solved with a standard fourth order Runge Kutta method to determine the angular velocity as a function of time. The following schematic code is the function called by the Runge Kutta solver Ode45.

```
INPUTS: V0(t), RROOT, RTIPI, chord(r), θ(r), J, yaw offset = yf(V0), MRES,ROT,  
MRES,STAT
OUTPUTS: ω(t), dM(t,r), Re(t,r), α(t,r)
```

STEP 1: compute the tip speed ratio

$$\lambda_{eff} = R_{tip} \times \omega(t) / (V_0(t))$$

for r = R_{root} : R_{tip}

STEP 2: Compute the local speed ratio

$$X = \lambda \times r / R_{tip}$$

STEP 3: compute the flow angle φ

$$X_{min} = 1e-3$$

if X > X_{min}

$$\phi = atan(X)$$

else

$$\phi = \pi/2$$

end

STEP 4: compute the local angle of attack angle α

$$\alpha = \phi - \theta$$

STEP 5: compute the local lift and drag properties using one of the following method

Method (a) interpolated airfoil data for infinite AR

Interpolate C_L(Re, α), C_D(Re, α)

Method (b) interpolated airfoil data for finite AR

Interpolate C_L(Re, α), C_D(Re, α)

Method (c) generic flat plate equations Eq(1.55)

$$C_L = 2 \sin(\alpha) \times \cos(\alpha)$$

$$C_D = 2 \sin^2(\alpha)$$

STEP 6: compute the local force on the blade

$$C_n = C_L \times \cos(\phi) + C_D \times \sin(\phi)$$

```

 $C_t = C_L \times \sin(\phi) - C_D \times \cos(\phi)$ 
 $F_n = \frac{1}{2} \times \rho_{air} \times V_{rel}^2 \times chord \times C_n$ 
 $F_t = \frac{1}{2} \times \rho_{air} \times V_{rel}^2 \times chord \times C_t$ 
end (blade section computation at r)

STEP 7: compute the blade torque assuming linear variation of the
local forces between two following blade sections
Eq(1.35)
end (blade section computation at r)

STEP 8: compute the rotor torque
M_ROT = B * M

STEP 9: compute the net torque
if  $\omega = 0$ 
    M_NET = M_ROT - M_RES,STAT
else
    M_NET = M_ROT - M_RES,ROT
end

STEP 10: compute the rotational acceleration
d  $\omega$  / dt = M_NET / J

```

Chapter 3: Socio-economic evaluation of wind-based decentralised electrification projects

3.1. Key cost and financing concept

Financing wind-based rural electrification is a demanding process. Indeed due to the size of the power generation system, investments can be high, especially when considering community or village power supply. Typical small wind turbines range from 2kW to 20kW for community/village power supply. The price of a 2kW wind turbine would be at least USD 2000. Including battery storage and installation cost, final project investment will be multiplied by 3 to 8 depending on whether local skills and expertise are available locally or would need to come from the capital city.

There is many ways to finance such projects. Not only cooperation aid funds are available, but Governments are also supporting community's electrification project through national programmes. When projects are funded from external donors/programmes, financing generally concerns the system and a part of the installation; the community has to participate in the installation and is in charge of covering the O&M costs.

But communities could also be interested in investing themselves in power generation systems. Indeed accessing modern energy like electricity is a big improvement for the socio-economic situation of rural communities.

The energy expenditure represent generally around 25% of rural household incomes and those energies (mostly fossil as wood, charcoal, kerosene...) are very inefficient and polluting. Electricity can also play a key catalysis role for rural development by enabling communities to set up new / enlarge productive activities. Therefore investing in modern energy supply can become much financially attractive for rural communities.

To be sustainable and yield development, a wind-based decentralised electrification project should meet those three economy criteria:

- Investing in a decentralised power generation system must be affordable,
- End users should be willing to pay
- The induced benefits should make the investment financially worth for the end users.

The affordability barrier is a main issue for small wind turbines which can be too costly investment for rural communities.

End user willingness to pay for operating and maintaining the system or for the provided services generated by electricity supply is a success key. It denotes strong community's involvement and let expect positive impact on economy.

The induced benefits are numerous. From an economy point of view, electricity is able to drive various new business service activities: battery charging, shop centres, communications... It also impacts public services positively, as for example morning/evening classes, street lighting (security), rural health centres.

When electricity allows rural households to change their very polluting kerosene lamps with electric lights, it reduces the indoor pollution and therefore family's health situation gets improved. This is a typical external benefits induced by electricity access.

Considering external effects relates to the cost-benefit analysis where the project is evaluated through the point of view of the society as a whole; while financing aspects focus only on project implementation and the stakeholders directly involved in the project.

3.2. Analysis tools

The net present value (NPV) of a project calculates the value today of every expenditure which results from the project. Comparing NPV of different projects enables to determine which one is the most valuable, expressed as ‘value today’. A negative NPV means that the project is too expensive for the investors/end-users.

The formula to calculate the NPV is

$$NPV = \sum_{i=1}^N \frac{Values}{(1 + d)^i} \quad (3.1)$$

where:

d is the discount rate;

i is the counter for the period;

N is the total number of periods for the payment.

Discount rate is a key input for financing calculation since it affects the evolution of project value. It is not easy to determine the right value for a rural community that is the reason why the discount rate has been set to 10%, which traduces the current inflation level in Kenya. It is important to realise that the appropriate choice of technology and the appropriate design of the project depend on the discount rate.

The internal rate of return (IRR) calculates the discount rate that will make the net present value of the project equal to zero, when that discount rate is applied for the NPV calculation. When the IRR is higher than the selected discount rate for the end-users/investors of the project, the project becomes financially attractive to them. It means that they will get more profits by investing in the project than using their money as the way they do today.

The IRR is calculated through an iterative method where a first value for the NPV is calculated from a guessed discount rate and so on until the NPV gets zero.

When the investment amount is limited, then the IRR is much useful since it enables to rank different project according to their return on investment; if there is no financing limit, then the NPV provides useful information on how much projects contribute to the economy.

The annualised total cost transforms the sum of one-time investment expenditure and a number of (equal size) operational expenditure to an annuity. Calculation of annualised total cost requires knowledge of the total investment expenditure, the investment lifetime, and the yearly operational expenditure as well as agreement on the discount rate.

If annualised revenues are larger than annualised costs, it means that the project will provide more value to the end-users/investors than the situation without the project. It is often used to assessing financial viability of an investment project.

Annualised costs (AC) are calculated using the standard amortization formula:

$$AC = \frac{I \times d}{(1 - (1 + d)^{-N})} + O & M \quad (3.2)$$

where:

I is the total investment expenditure

d is the discount rate

N is the lifetime of the project

O&M are the annual O&M expenditures.

To assess the financing of wind-based electrification project, NPV will be first calculated to determine whether enough economic benefits are globally generated. When NPV is negative, it means that the project will not generate enough economic benefits, and therefore the investment is too expensive.

Then the AC will be calculated to determine the viability of the investment. If annualised costs are larger than annualised revenues, the community will have difficulty to finance the project.

Finally the IRR is analysed to assess how much the project is profitable for the community.

Inputs

Chapter 4: Inputs

4.1. Blades

4.1.1. Airfoil selection background

The selection of airfoils has been based on two criteria: simulating performance of Kenyan wind turbines and inputting modern airfoils designed for low Re .

Indeed the “flat plate with camber” airfoil corresponds to blade design of Kijito windpumps while the NACA4412 is used by Craftskills Enterprises for their Windcruiser wind turbines. Modern airfoils are SG 6040, SG 6041, SG 6043 and SD 7062.

The SG series was designed by Professors Mickael Selig (S) and Phillippe Guiguere (G) of the University of Illinois at Urbana-Champaign specifically for small wind turbines. Their design parameters are presented in Table 4.1. SG 6040 is a root airfoil with large thickness (16%) and low design Re (200000) while the two other ones are designed for power extraction with therefore a smaller thickness (10%) and differ with design Re inducing high camber for SG 6043. SG 6041 and SG 6043 are more adapted to the outer part sections of the blades.

| Airfoil | t/c (%) | Camber (%) | Design C_L | Design Re |
|---------|---------|------------|--------------|-------------|
| SG 6040 | 16 | 2.5 | 1.1 | 200000 |
| SG 6041 | 10 | 2 | 0.6 | 500000 |
| SG 6043 | 10 | 5.5 | 1.2 | 300000 |

Table 4.1. General characteristics of SG 6040, 6041 and 6043 airfoils

Airfoil SD 7062 (S: Selig, D: Donovan) is also studied since its adequacy for small wind turbine global performance has been demonstrated by the wind energy group of Newcastle University in several studies [6]. It is also used in the model validation step when comparing power production and starting performance of the blade designed by the wind energy group of Newcastle University for their 600W wind turbine. SD7062 has the main advantages to have quite high thickness (14%) while relatively high design C_L (1.2). It is therefore a good compromise for starting and power production performance.

4.1.2. Airfoil profile

Here are presented the profiles of the tested airfoils.

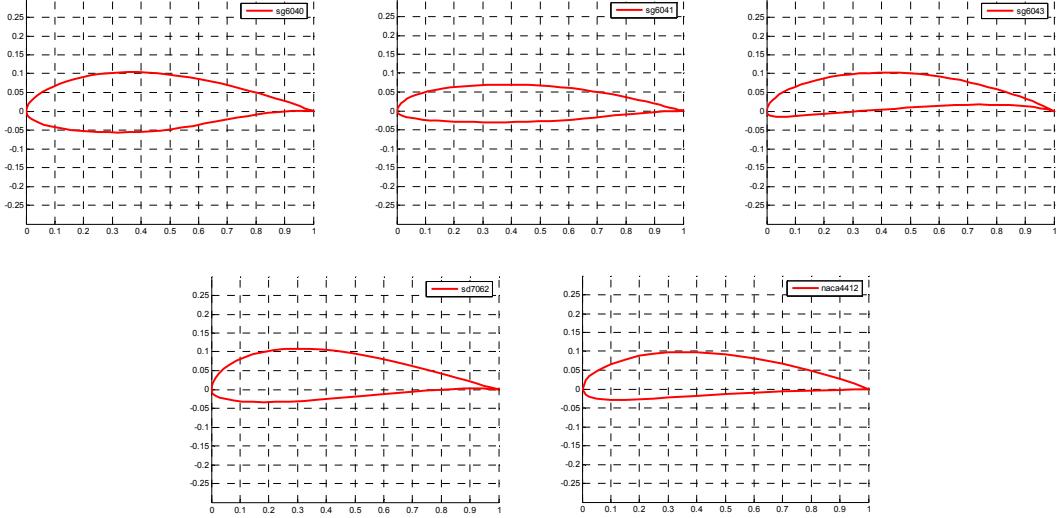


Figure 4.1. Profile of the tested airfoils

4.1.3. Airfoil lift and drag data

The lift-drag data have been provided by Wood [6] for the NACA, SG and SD airfoils. The flat plate with camber data are provided by Batchelor in [13].

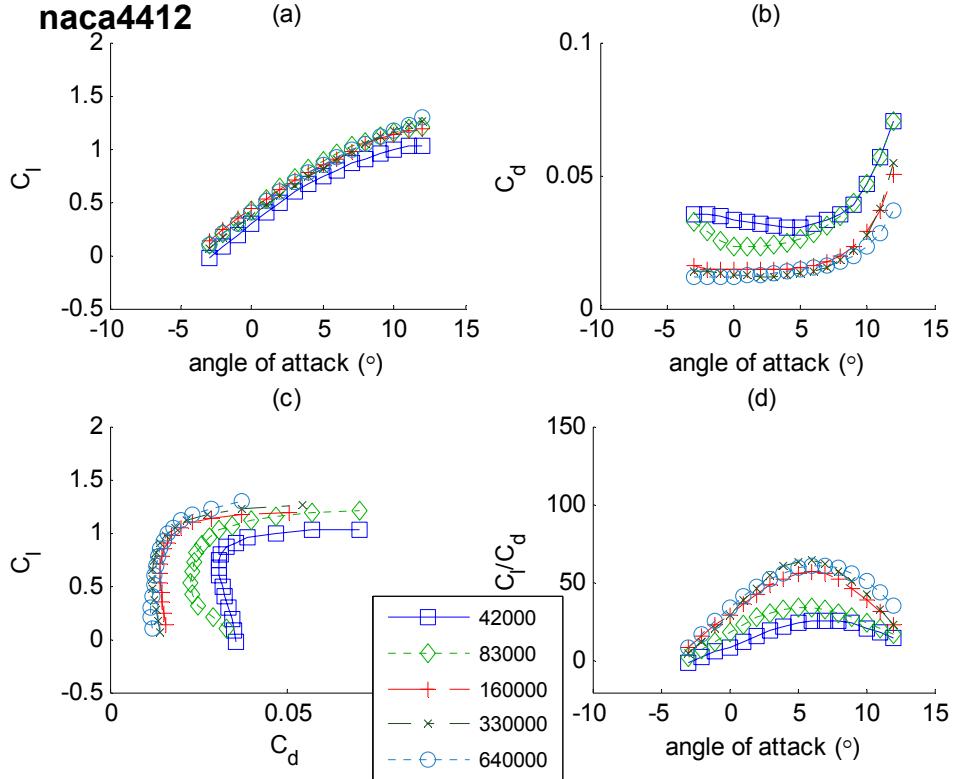


Figure 4.2. Lift Drag properties of the NACA 4412

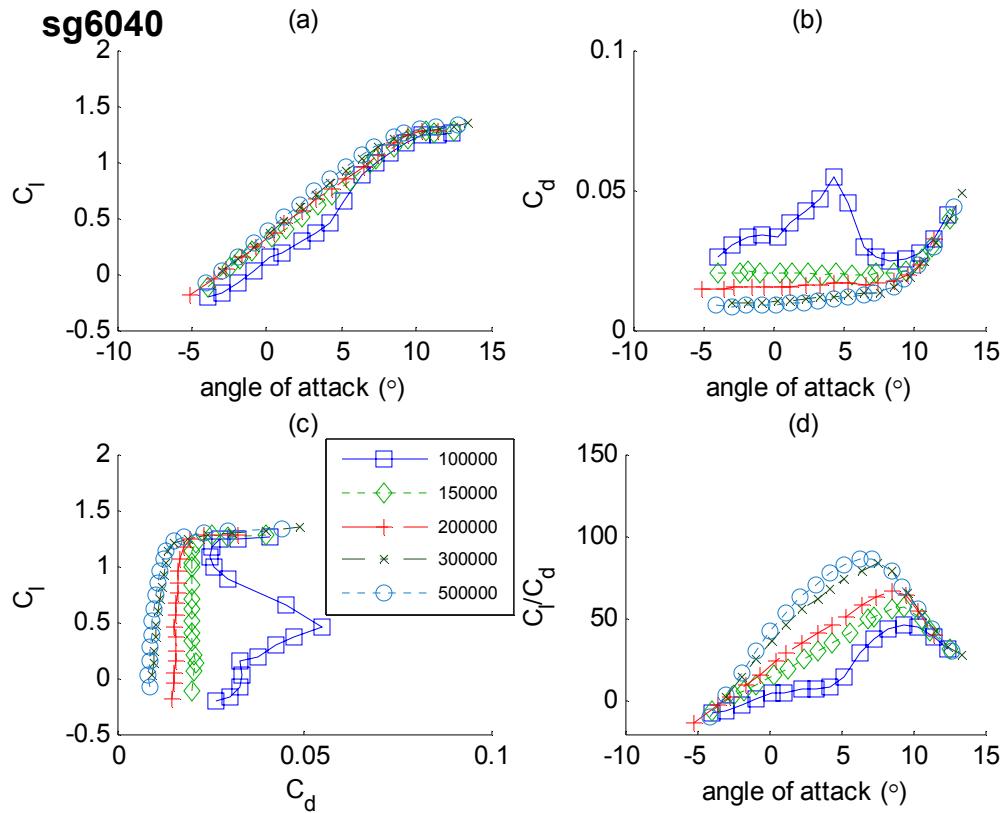


Figure 4.3. Lift-drag properties for the SG 6040

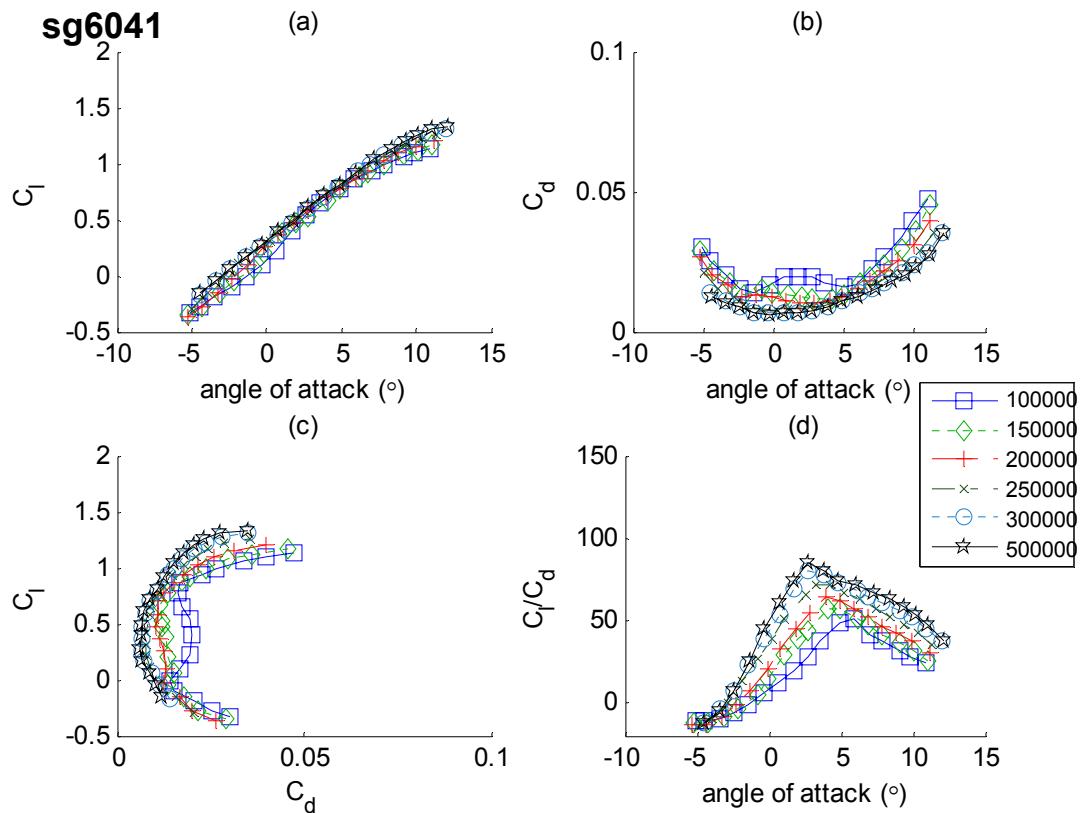


Figure 4.4. Lift-drag properties for the SG 6041

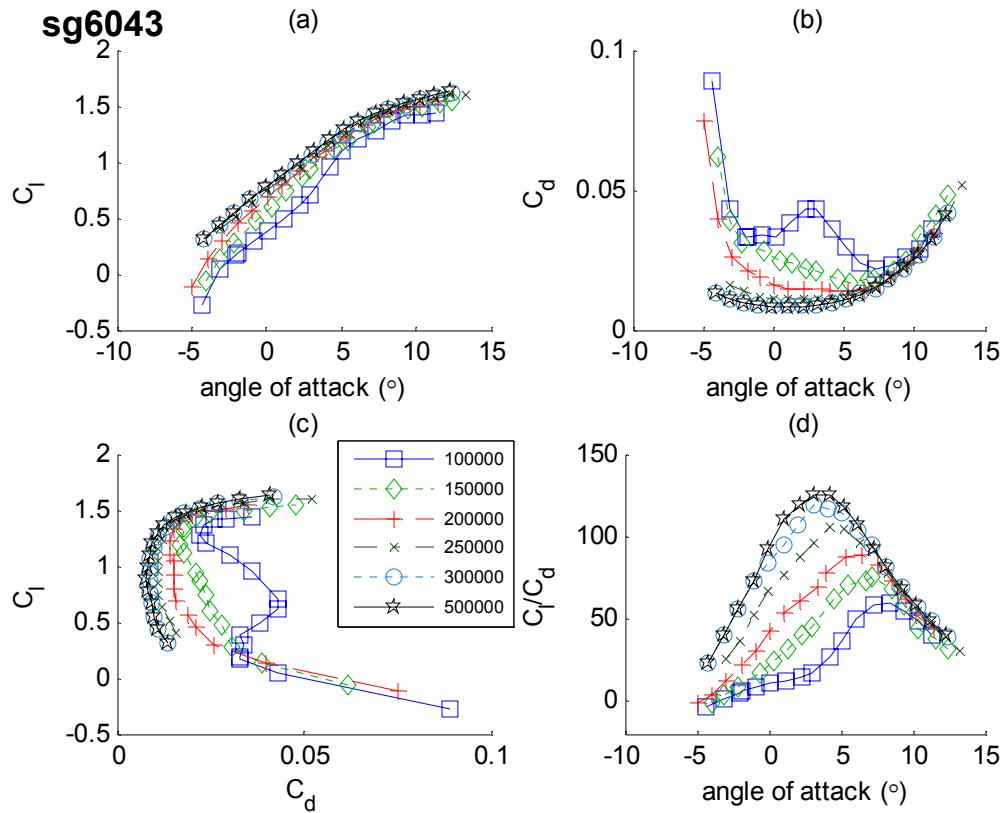


Figure 4.5. Lift-drag properties for the SG 6043

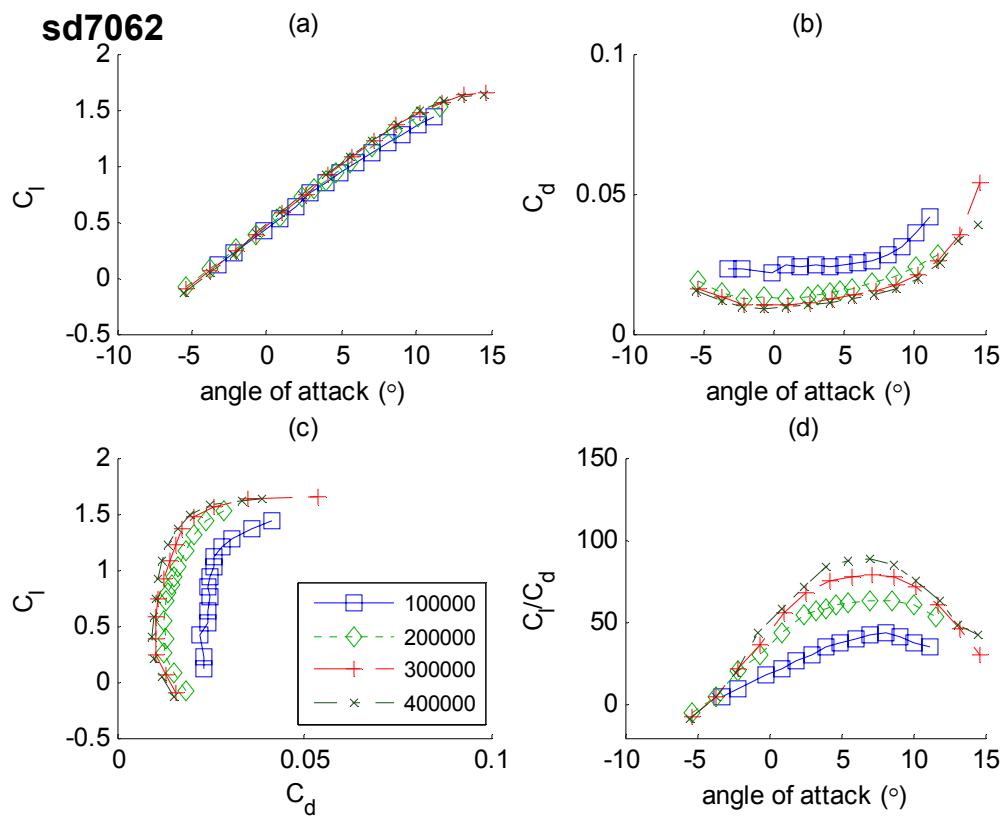


Figure 4.6 Lift-drag properties for the SG 6040

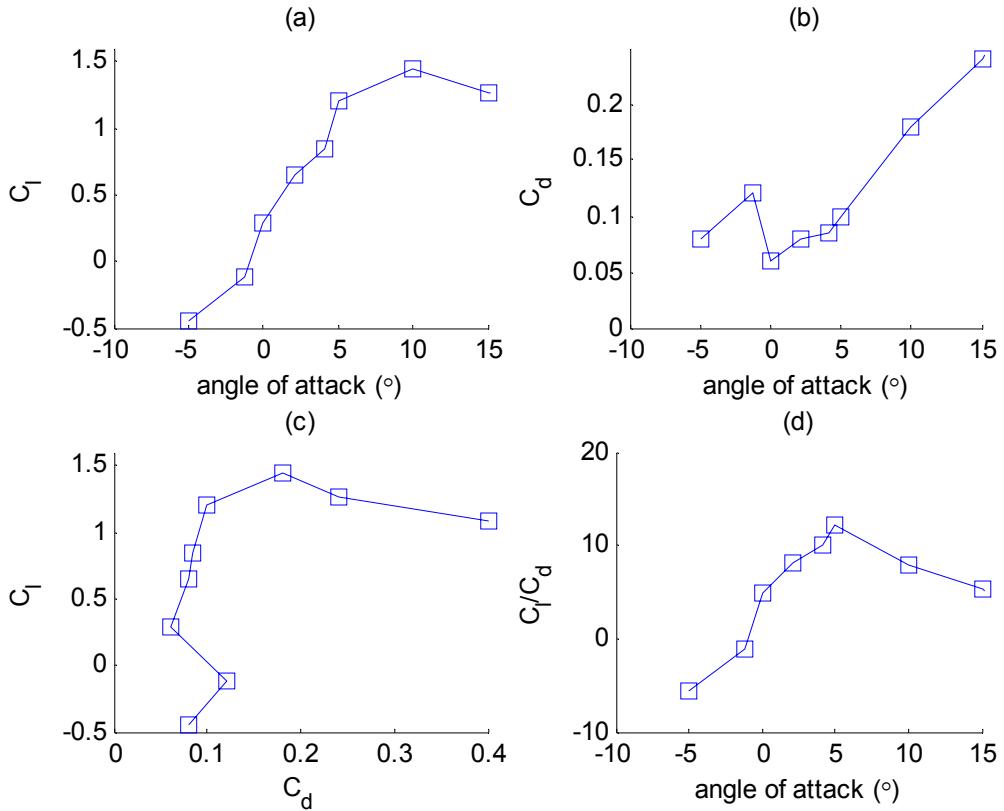


Figure 4.7. Lift-drag properties for the flat plate with camber airfoil

4.1.4. Selected materials

The two materials selected targets easy manufacturing in Kenya. Therefore pine wood and steel are the two materials considered for blade manufacturing.

Furthermore pine wood has been tested at Newcastle University [14] and has shown excellent mechanical performance.

The density of pine wood is 550 kg/m^3 and density of steel has been set to 7800 kg/m^3 .

4.2. Generators

4.2.1. General characteristics

Two generators have been tested in the present reports. Both of them are referred as 600W rated permanent magnet generators (PMG) but the Newcastle one is better rated at 300-400W and the Windmission as one as 800-900W. Wood book [6] and Windmission website [15] can be consulted for complementary information.

Those generators have been used at the University of Newcastle and in Denmark by the Danish SWT manufacturer Windmission. They have good reliability quality.

Generator characteristics and power curves are presented below.

| | | | |
|-------------------------|------------------------------|------------------|------------------|
| Generator | | Newcastle 600W | Windmission 600W |
| Power generation source | | Permanent Magnet | Permanent Magnet |
| Starting | Cogging torque [Nm] | 0.36 | 0.6 |
| Power production | Minimum rotation speed [rpm] | 268 | 160 |
| | Maximum rotation speed [rpm] | 1070 | 913 |
| | Advised P_r [W] | 300-600 | 600-1000 |

Table 4.2. Characteristics of the tested generators

4.2.2. Power curve

Newcastle PMG 600

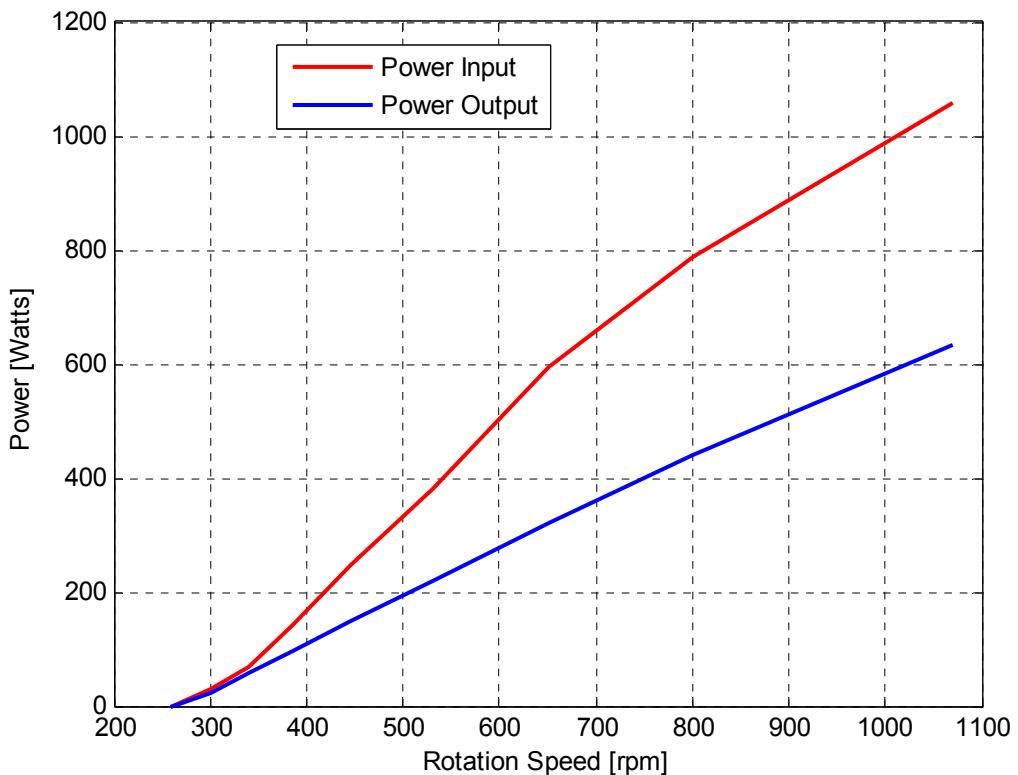


Figure 4.8. Power vs. rotation speed curve for the Newcastle 600W PMG

Windmission 600W

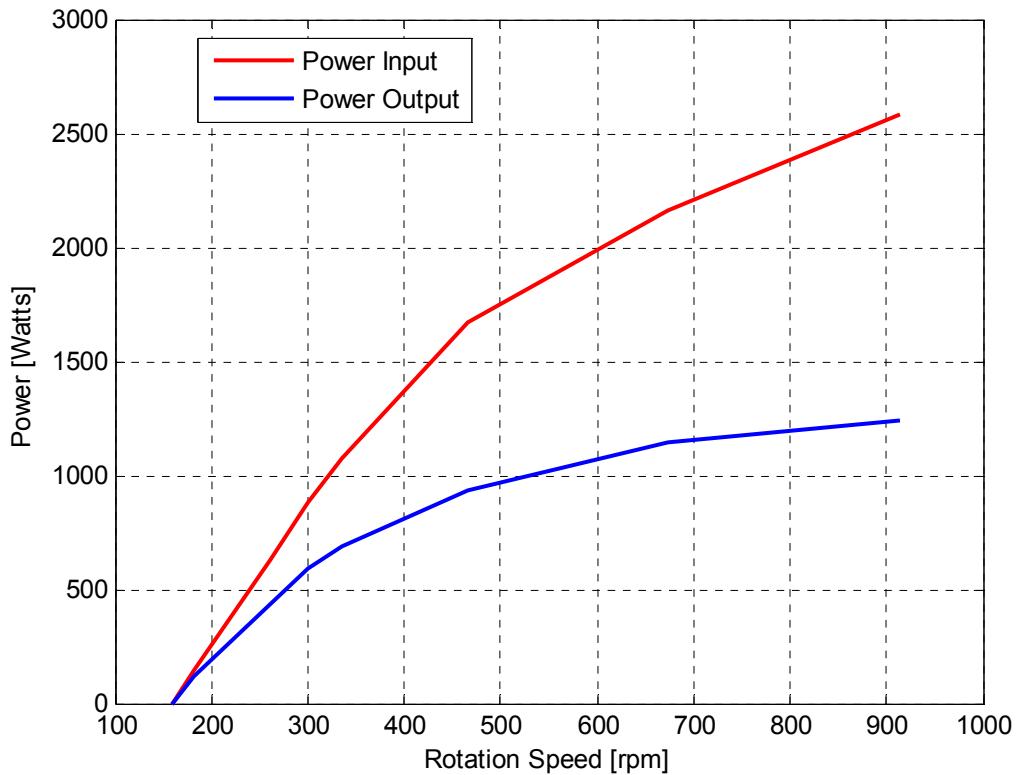


Figure 4.9. Power vs. rotation speed curve for the Windmission 600W PMG

4.3. SWT operation in rural Kenya

4.3.1. Energy requirements for an isolated school in rural Kenya

Most rural schools do not access electricity. As it is described more in details in Esilanke case study, the first electric need concern lighting. Indeed current most common lighting source is kerosene lamps that generate much polluting emissions and are therefore harmful to health and climate.

When accessing electricity, many needs appear very quickly. It concerns communication (mobile), entertainment (radio, TV...), business... Schools are very demanding to get computer and sufficient amount of power to extend power benefits to community level through the organisation of powered events, like ceremonies, weddings... Starting some income generating business activities based on power access is also an important way to ensure financial sustainability.

The school energy requirement model used in this study is based on Esilanke school case study. Daily energy need is 2kWh and details are summarized in the next table.

| Room | Appliance | Number | Use | Consumption | |
|---------------------------|-----------------------------|---------|-------------------------------|------------------------------|---|
| | | | | Daily energy use (Wh/day) | Hours of use |
| Office block (2 rooms) | Fluorescent Lights – 11W | 3 | Morning Evening work | 165 | 6-8am, 6-9pm |
| | Computer | 1 | Day | 600 | 6-12pm |
| Class rooms B, C | Fluorescent Lights – 11W | 4 | Morning Evening classes | 265 | 5-8am, 5-8pm |
| | Fluorescent Lights – 36W | 2 | | 430 | |
| Class rooms D, E | FL 11W | 4 | Morning classes | 130 | 5-8am |
| Battery charging | Mobile phones | Up to 8 | Day | Up to 400 | Depending on wind and battery charge state |

Table 4.3. Power consumption model for a Kenyan rural school

4.3.2. Prevailing wind conditions in Kenya

Wind map of Kenya

In Kenya, large and local topography effects much affect the wind resource. Indeed Kenyan altitudes vary from sea level (along the coast) to 5199m (Mount Kenya). The large East-to-West altitude gradient generates temperature gradients and contributes therefore to create a large hill effect from the sea cost to the edge of the Rift Valley. On the wind map shown here below, the inland greenest areas correspond actually quite precisely to the edge of the Rift Valley. The geography of Kenya can be found in Appendix I. In the North the very high wind potential (yellowish and reddish areas) is due to the combination of two effects. This area corresponds to a large highland (> 1000m) corridor between the central Kenya Mountains (2500-5000m) and the Ethiopian plateau (3000-4000m). Winds blowing from the Indian Ocean are trapped into this corridor; this phenomenon is reinforced by the warm climate of the up North dry areas of Sudan and further the Sahara desert. On the mountainous spots, wind resource can be amazingly huge. In Marsabit, measurements at 10m high have shown an average wind speed of more than 11m/s!

The wind map of Kenya is the result of the SWERA-GEF project (*Solar and Wind Energy Resource Assessment*) funded by the United Nations Environmental Programme [16]. Risoe National Laboratory is a project partner and was in charge of the wind map of Kenya. The simulated wind resource of Kenya is currently being validated.

The red to yellow colours refer to very high wind potential, green to medium potential and blue to low potential. The presented map shows average wind speed contours at 50m high.

The main limitation of the map were: 1) the wind flow model had to be adapted to Equator wind flow characteristics, the very large mesh (10km) is not suitable for taking into account local topography effect, and the difficulty to find reliable measurements for validating the map. It is therefore likely that the map underestimates the wind resource on the highest wind potential areas. However the general wind climate pattern agrees with the local experience and few available measurements.

Winds are mainly blowing from East to West. Monsoon phenomenon generates seasonal variations of the wind resource.

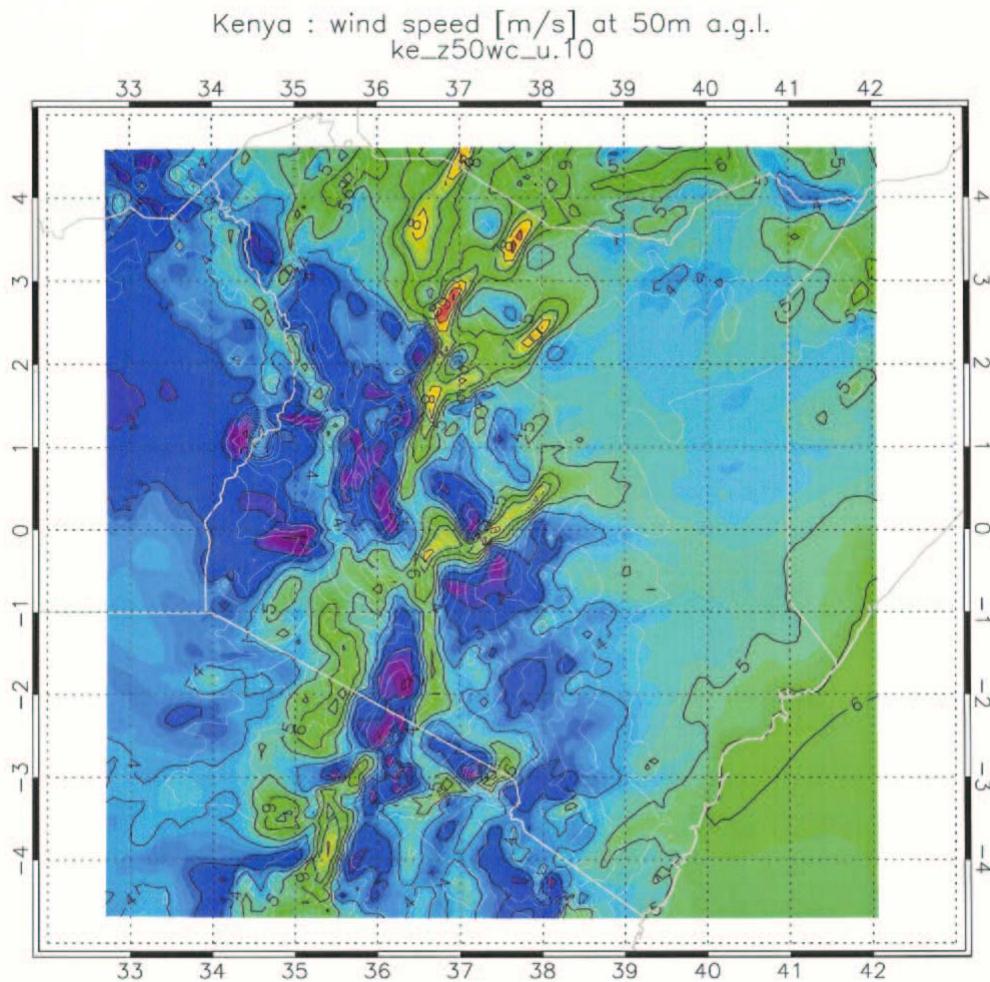


Figure 10. Simulated wind map of Kenya

To conclude, wind climate of Kenya is very good on the North West quarter and along the Rift Valley edges. For those areas average wind speed should be at least 6m/s at 10mhigh, and potentially much above for some spots.

Along the coast a medium wind resource is expected with average wind speed between 4-6 m/s at 10 m-high.

For the other parts of the country, wind resource is expected to be quite low, expect for specific hilly spots. Wind data measurements are still too scattered to allow comprehensive modelling of Kenyan wind resource.

4.3.3. Wind data time series input

The information about energy requirements for rural schools and the analysis of Kenya's wind climates has yielded the construction of two typical wind regime corresponding to low and medium-high wind climates. More details about Kenyan wind climates is presented in Appendix II.

For each wind climate, the Weibull characteristics, daily time series and starting sequence are presented.

| | Low wind regime | High wind regime |
|-----------------------|-----------------|------------------|
| A [m/s] | 3.66 | 7.76 |
| k | 2.24 | 2.53 |
| Mean wind speed [m/s] | 3.50 | 6.89 |

Table 4.4. Weibull characteristics of low and medium-high wind climates of Kenya

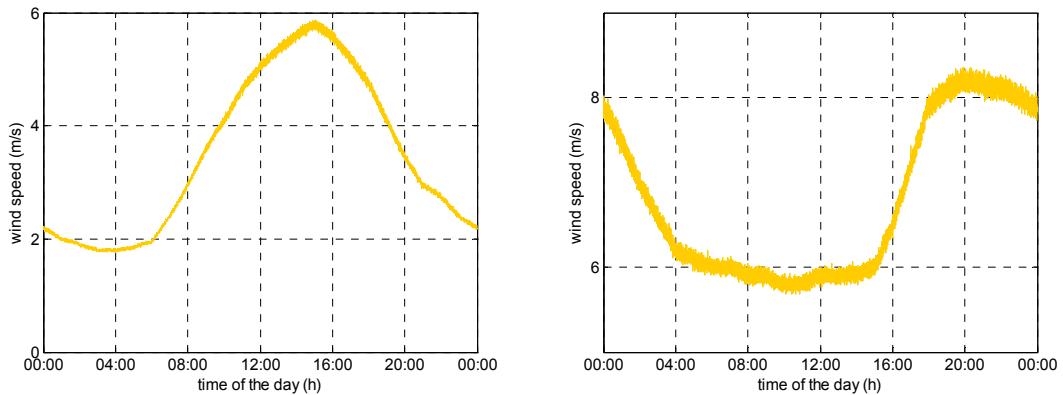


Figure 21. Wind speed daily time series for low and medium-high wind climate

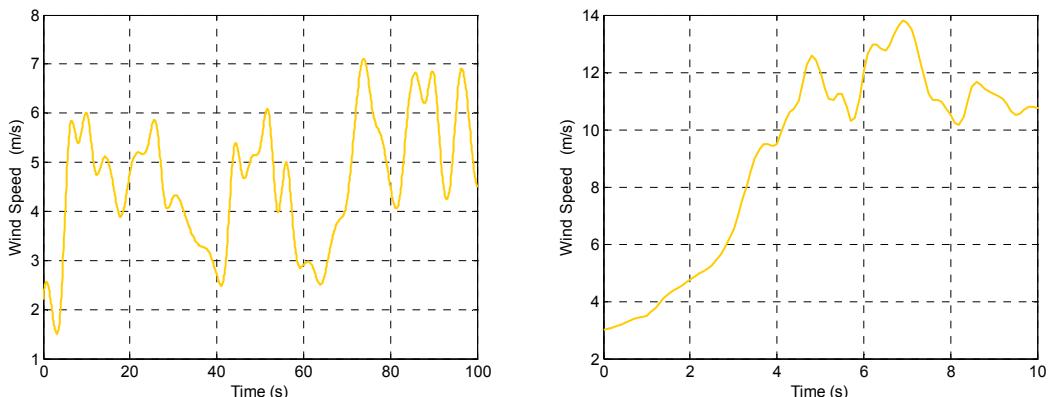


Figure 32. Wind speed starting sequences for low and medium-high wind climate

Suitability of small wind turbines for decentralised electrification in rural Kenya

Chapter 5: The need for rural electrification in Kenya

5.1. General background

5.1.1. Energy sources and electrification rate in rural Kenya

Traditional biomass (wood and charcoal) is the prevailing energy source (82%) in rural Kenya [3]. Indeed due to their low financial capacities, rural households and small enterprises prefer non-commercial forms of energy. Access to modern energy, like electricity and petroleum products, is expensive and unaffordable. About 1% of Kenyan rural households have access to electricity.

This household energy portfolio has much negative consequences on health and environment: abundant use of biomass is a serious cause of respiratory illnesses [17] and deforestation in the rural areas.

| | Firewood (43.8 %) | Charcoal (46 %) | Wood Wastes (0.6 %) | Farm Residue (6.4 %) | Electricity (0.7 %) | Kerosene (2.2 %) | LPG (0.2 %) | Total Demand (100 %) |
|---------------------|----------------------|--------------------|---------------------------|----------------------------|------------------------|---------------------|----------------|----------------------------|
| Rural Household | 89.4 % | 46.2 % | 61.9 % | 99.5 % | 8 % | 53.1 % | 5.6 % | 80 % |
| Urban Household | 2.3 % | 36.5 % | 38.1 % | 0.5 % | 61.8 % | 46.3 % | 66.7 % | 13 % |
| Cottage Industry | 8.3 % | 17.3 % | 0 % | 0 % | 30.2 % | 0.7 % | 27.7 % | 7 % |
| Total | 100 % | 100 % | 100 % | 100 % | 100 % | 100 % | 100 % | 100 % |

Table 5.1. Annual Energy Consumption in Households and Cottage Industry [18]

Electrification rate through grid extension is particularly low in Kenya. From the creation of the Rural Electrification Programme (REP) in 1973, only about 100000 new metered customers have been connected to the grid (91069 in 2004,[19]). With a budget of KSh 1 billions in 2001, the Rural Electrification

Programme has only connected 5000 new customers; the cost of connection has been multiplied by 5 between 1993 and 2001.

Therefore the rural dwellers have progressively lost the hope to see the grid coming one day to their house, settlement or village. That is one of the reasons why the wealthiest segment of the rural population has often chosen the solar photovoltaic option. In Kenya there are today more than 120000 Solar Home Systems (SHSs) installed and 20000 new SHSs are installed each year. The average size is around 50 Wp and enables to power a few lights, a radio and a TV black and white. A key figure to understand the inappropriateness, or failure, of the hitherto Rural Electrification policy is that over 50% of the Kenyan PV systems are located within 5 kilometres to the nearest grid lines [20].

5.1.2. Cost of energy

The table presented below summarizes the typical energy options and costs in rural Kenya. It is particularly interesting to notice the gap about the cost of energy between electricity option (isolated grid, mini grid, home systems) and the inefficient dry cell and kerosene options. On monthly average and whatever the solutions, rural households have to spend considerable amount for their energy needs compared to their income. Up to 25% of the income can be spent into energy expenditure.

| | Rural Electrification Programme Isolated grid | Independent mini-grid | | Home solutions | |
|---|---|-----------------------|-----------------------|---|-----------------------|
| | | Diesel-based | Hydro-based | 12VDC solar-home system and battery-based systems | Dry Cell and kerosene |
| Power delivery capacity | 0-100s kWh/month | | | <6 kWh/month | >0.5 kWh/month |
| Appliances | Capacity to power most appliances (provided rural people can afford them) | | | Lights, TV, radio, cell phone, small motors | Kerosene lamp radio |
| kWh cost | Production | Cons. tariff | > US\$ 0.16-0.21 /kWh | US\$ 0.16-0.21 /kWh | +- US\$ 0.5/kWh |
| | US\$ 0.3/kWh | US\$ 0.11/kWh | | | |
| Real monthly costs paid by consumers | US\$ 5-20 | | US\$ 10-50 | US\$ 5-50 US\$ 2 (low maintenance) US\$ 5-15 in fee-for-service | US\$ 5-15 |

Table 5.2 Current main power providers in isolated areas of Kenya [20]

To complement this information, electricity tariff is countrywide KSh 8/kWh (USD 0.1/kWh). About line extension, the Sessional Paper 2004 form the Kenyan Parliament reports that “it costs more than KShs.1.2 million (USD 15000) on average to construct a kilometre of an 11kV or a 33kV line. Thus, the average cost of supplying a rural consumer was KShs.180000 (USD 2250), which is about seven times the national per capita income in 2002.” [19].

5.1.3. Rural electrification status and policy

The Rural Electrification policy has been managed by the Ministry of Energy since 1973 through the Rural Electrification Programme (REP). REP has mainly consisted in grid extension around the national grid and the seven isolated grids. Those isolated grids refer to seven remote cities of Kenya (mainly in the North). The Kenyan utility company KPLC (Kenya Power and Lighting Company) has been much involved as they are in charge of power transmission and distribution and responsible for power supply of the isolated grid of Northern Kenya. The REP revenue comes from a 5% levy imposed on each customers supplemented by donors funding which accounts for 18% of the total budget in 2003 [19].

REP’s impact has been very small in terms of new connected customers and therefore some reforms have been undertaken for the last five past years. Those reforms take place in the global modernization of Kenya’s energy sector.

Those reforms started on 1997 with the Electricity Power Act (EPA). They target the liberalization of the market (separation of transmission/distribution to generation activities into two different companies, partial privatization of KPLC and opening market to Independent Power Producer). The Electricity Regulatory Board (ERB) was effective the same year.

However the reforms on rural electrification have been a bit slower. A Rural Energy Task Force was launched by the MoE in 2003 to identify the rural electrification challenge and how to overcome them [19]. Then the Sessional Paper no. 4 on Energy has initiated major reforms on rural electrification, especially regarding the creation of the Rural Electrification Authority and the permission and support of private mini-grids and communities' investment in rural power generation and supply.

This new policy has become official with Energy Act 2006 which stipulates free licensing for private initiatives on isolated generation and distribution below 3000 kW [21]. The Bill will also transform the Electricity Regulatory Board into an Energy Regulatory Commission, in order to cover all sub-sectors and to reinforce the regulator's independence. Finally, the Bill will create an independent Rural Electrification Authority to manage the Rural Electrification Programme and the Rural Electrification Fund.

The Rural Electrification Authority, "will promote use of renewable energy sources including but not limited,.... wind, and taking into account specific needs of certain areas including the potential for using electricity for irrigation and in support of off-farm income generating activities"

Under Part V of the Act, the Minister may exercise his powers to promote the development and use of renewable energy through:

- Formulating a national strategy for coordinating research in renewable energy;
- Promoting the development of appropriate local capacity for the manufacture, installation, maintenance and operation of basic renewable technologies
- Promoting international co-operation on programs focusing on renewable energy source
- Promoting the utilization of renewable energy sources for power generation

Though legally created, the Rural Electrification Authority is not effective yet. A Rural Electrification Master Plan is also ongoing and expected to be ready by April 2008. In order to determine the least cost option for each area of Kenya, it will emphasize the use of Renewable Energies for Rural Electrification.

5.2. The challenges of electrification and modern energy service provision in rural Kenya

5.2.1. Poverty in rural Kenya

Relying mainly on agriculture and farming, the rural economy generates intermittent low incomes. Therefore most of the Kenyan poor households (87%) live in the rural areas and subsistence farmers represent 50% of the poor of Kenya (IPAR, 2002a; GOK, 2003). Virtually 100% of Kenyan rural households live below the poverty line of US\$ 2 per capita per day and still 80% are even below the US\$ 1 per capita per day [22].

These economical difficulties are exacerbated by the increasing population: the rural segment of Kenya's population has risen from 11 million (48% of the population) in 1990 to 17 million (56% of the population) in 2001 [3].

Conjugated to the previous drawbacks, distances to urban centres and poor infrastructures make access to modern technologies and services difficult. Therefore access to clean water, sanitation, indoor air pollution, health services are recurrent problems.

This very low income situation is an important drawback to access modern energy systems and services. However as it will be shown in Esilanke case study (Chapter 6), the current cost of energy and the will to access electricity make decentralised electrification possible and financially attractive even in very poor areas.

5.2.2. The complex connection between access to electricity and development

Electricity is a powerful vector of development. It induces new potentialities for modern services: security (street lighting), education (extension of studying time to dark morning and evening hours, modern education means), water access (pumping) and quality (purification devices), health (vaccination, refrigeration), media and communication...

At the economy level, electricity access yields higher profitability of most private service, industry and farming business activities. It is a strong vector of productive and income generation activities.

Furthermore providing modern energy services impacts the social life and well-being by benefiting the living quality, health and gender equality. Among many other related positive effects, one can emphasize that switching illumination from paraffin to electric lights reduces the indoor air pollution; electric water pumping or maize grinding offers new available time for women to dedicate to more productive and valuable activities; accessing media and information is a strong mean of gender equality and other modern values diffusion into rural households; enjoying TV, radio, recharging easily its mobile phone or going to a hair-saloon are important improvement of the well-being and living conditions for those who live in remote areas.

Evaluating service demand (individual, collective, multi-sectorial), their evolution and uncertainty, and the characteristics of the beneficiaries, customers or end-users from the origination the project is a prerequisite of any effective and efficient rural electrification strategies. Indeed investing in modern electricity supply systems usually generates high upfront costs for rural communities. Developing service and business activities around electricity generation is an appropriate strategy to make such projects financially viable. The objective is therefore to anticipate and/or initiate synergies between economic and human development.

However many rural electrification examples show that there is unfortunately no direct link between electricity access/supply and economical growth. The idea of access to electricity being an engine of economy growth in rural Africa is at least unobvious or even wrong. Indeed even if this access offers new potentialities for modern services development, it is a complex combination of factors that enables the effective use of electricity to stimulate economic growth. Access to electricity is therefore not an engine of economy growth but a catalyst.

In his study of Mpeketoni case (Kenya) on “How important is modern energy for micro-enterprises? – Evidence from rural Kenya” [23], Charles Kirubi reports that “the findings at Mpeketoni reveal that access to electricity, in combination with simultaneous access to markets and other infrastructure (road, communication, schools etc), have contributed to robust growth of SMEs in clear and compelling ways”. He for instance demonstrates “that productivity per worker and gross revenues per day increased on order of 200% for both carpentry and tailoring as the result of access to electricity”. The vibrancy of the local economy is seen as a key vector of the success of this diesel generation power supply project developed in Mpeketoni; even though power tariff is very high (US\$ 0.30/kWh).

However he also notes that many other electrification projects led to disappointing development results due to the weaker ability of the local endogenous economy to use electricity supply as growth catalyst. It quotes the case of Watu 1 settlement which shares some important characteristics with Mpeketoni but suffers from more arid conditions which result in the absence of vibrant agriculture market. While Watu 1 is connected to the national grid and therefore enjoys much lower tariff (US\$ 0.11/kWh), the catalyst effect of electricity access on economic growth has been much more limited.

The Kenyan solar photovoltaic experience provides another perspective on rural electrification process. As mentioned earlier the solar photovoltaic market has quickly grown in Kenya to reach 120 000 Solar Home System (SHS) installed since the beginning of the drop in prices at the late 1980s. This rural electrification process has been driven by households' wish to access modern media (TV) and supported by active commercial initiatives. Even though the installation of SHS are very high in Kenya (around US\$ 20/Wp,

i.e. US\$ 1000 for a typical 50Wp SHS [20], this solar photovoltaic rush traduces how individual wishes to access modern services and technologies can be an important engine of rural electrification. It also demonstrates that a solution which fits the local demand and its socio-economic characteristics can be diffused widely. Unfortunately the solar photovoltaic option being expensive, it has only benefited the wealthiest fringe of the rural households. Another drawback of this high cost is the limitation of PV electricity to small-scale end uses (lighting, radio, communication, small-scale pumping and refrigeration, etc): PV electricity is not adapted for productive purposes. It is for example not possible to use PV electricity for welding, grinding maize or charging batteries commercially.

Those examples highlight the fact that cost of electricity and impact of electricity access are relative concepts that must be related to the current and prospective socio-economic, energy and infrastructure situations.

They also enhance two main electrification alternatives to grid extension: isolated household electrification and community electrification. Though those decentralised alternatives are more expensive than grid extension, in the context of rural Africa where getting electricity from the national grid is a very uncertain option, both of them have much interest.

Isolated household electrification systems (like SHS) have the main advantage to be easily connected to commercial activities since they only result from individual choices. But this can also be a risk when individuals can not access exact information on system quality, performance and applicability.

Community options require community commitment: common strategies, decision process accepted by the whole community, project management at community level. Therefore community options are much more complicated to set up but on the other hand bring much higher benefits for socio economic development since they can induce productive uses of electricity.

Both of them also require appropriate legal framework in order to guarantee system reliability (through standard) and stimulate the market.

The next section will provide some complementary perspective on this electrification/development issue based on the case study of the wind-based decentralised electrification at Esilanke Primary School.

Chapter 6: A wind-based decentralised electrification experience in Kenya: Esilanke Primary School pilot project

6.1. Background

6.1.1. General information

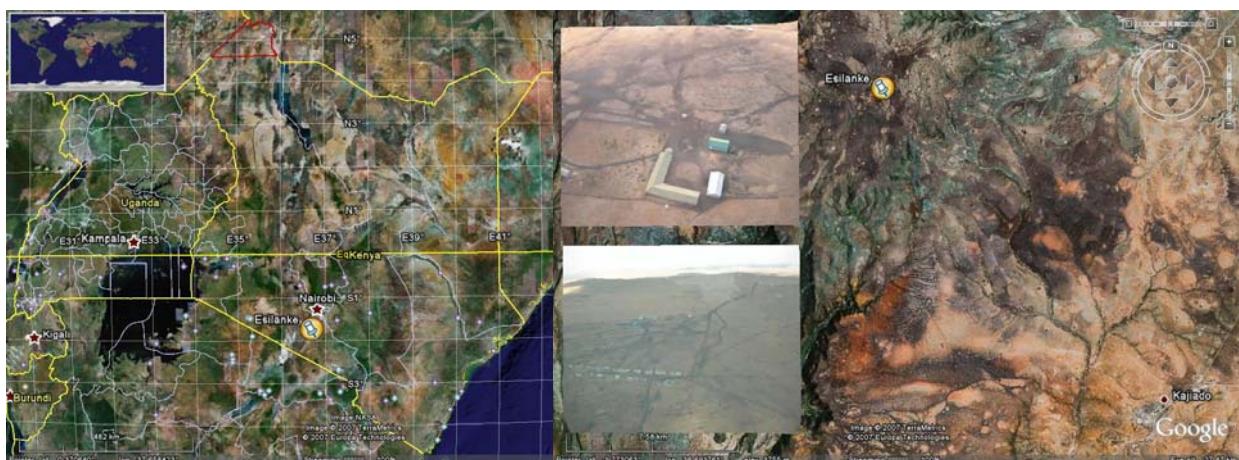


Figure 6.1. Aerial views of Esilanke Primary school

The electrification of Esilanke Primary School is a project developed by the Danish wind energy consulting company KenTec and its Kenyan partner Windgen under their B2B Danida programme.

The ultimate goal of this project is to assess the feasibility and the conditions of viability of wind-based decentralised electrification in rural Kenya towards dissemination in all areas of Kenya endowed with sufficient wind resource.

KenTec/Windgen selected the Primary School of Esilanke community located in Kajiado District, 50km South East of Nairobi. The coordinate position of the primary school is: 1°42'55.98" S, 36°41'10.56"E. Prior to the electrification, Esilanke did not have electricity. The closest grid point is Kajiado town, 15km away.

This electrification project uses a 1kW wind turbine imported from China. The generated electricity charges batteries. It constitutes one of the first wind rural electrification projects in Kenya.

The Kenyan windpump manufacturer Bobs Harries Engineering Ltd (BHEL) was in charge of the installation which was completed on the 8th of March 2007.

Baptiste Berges, student in Master in Wind Energy at the Technical University of Denmark and working on the development of small wind turbines for rural electrification in Kenya with BHEL, provided engineering support for the installation and assessed project sustainability in August 2007.

6.1.2. Socio-economic situation of Esilanke community

The information provided in this chapter is based on the analysis of the survey carried out for the purpose of the Master Thesis in August 2007 plus complementary information from the survey by Empiris Group in June-July 2006. Complementary information about water situation has been provided by Mr. Samuel Njanka, representative of Esilanke community.

Population

Esilanke community counts 104 families and about 1000 inhabitants. Polygamy is dominant with families counting between 1 and 6 wives per husband with an average of 2.1. Esilanke Primary School welcomes about 200 pupils.

Households are very scattered. Only 20 families (200 inhabitants) live in Esilanke village. Most families are located within a five 5km radius around the village but the furthest families are 10km away. People usually walk between 15 and 50 min to get Esilanke village.

Esilanke Primary School is 0.5km away from the village. It means that some pupils have to walk up to 2hours to reach the school/come home.

Living conditions

People live in shanties and primitive houses. The demanding climate (cold nights, rain/dry seasons) makes life tough. The rain seasons occur in October-November and April-June. Indoor air pollution is a serious problem due to polluting source of energy for lighting, cooking and heating as kerosene, charcoal, cow dung or wood.

The issues reported by Esilanke families are presented in the following table. It is very interesting to note that 97% reports “access to sufficient amount of water” as an important issue while only 66% reports the cost of water as an issue. Cost of energy is also an important issue for 82%.

| Sample of 38 families | An important issue | A moderate issue | A minor issue | Not an issue |
|---|--------------------|------------------|---------------|--------------|
| Access to sufficient amount of clean water for drinking/cooking purposes | 37 | 1 | | |
| Access to sufficient amount of clean water for hygiene purposes | 36 | 1 | | 1 |
| Access to health care | 32 | 3 | 2 | 1 |
| Cost of energy | 31 | 1 | 4 | 1 |
| Access to sufficient amount of food for the whole family | 30 | 2 | 2 | 1 |
| Financial resources of the family | 30 | 5 | 1 | |
| Business opportunities | 30 | 4 | 2 | 1 |
| Cost of food | 29 | 2 | 0 | 2 |
| Access to electricity | 29 | 3 | | 2 |
| Access to sufficient amount of water for farming purposes | 29 | 7 | 1 | 1 |
| Health / Diseases | 28 | 3 | 3 | |
| Energy | 28 | 7 | 2 | |
| Security | 28 | 6 | 1 | 2 |
| Development of Esilanke Community | 27 | 2 | 1 | 1 |
| Infrastructures (Roads, transportation means...) | 25 | 2 | 2 | 2 |
| Cost of water | 25 | 3 | 2 | 2 |
| Telecom network | 21 | 3 | 5 | 1 |

Table 6.1 Issues in Esilanke community

Water access

Water is a serious issue in Esilanke community, especially during the dry season.

The main water source is the community's 60m-deep borehole situated half a km from Esilanke village. A 3kVA diesel pump provides an average of 12000 L/day during the dry season and 6000L/day during the rain season. Water is used for household, school and farming. Most of the amount is used for cattle water supply (4500 heads) and a small amount refills the school water tank when needed. During the dry season 70000 L/month are devoted to household needs.

The diesel pump generates high O&M costs since it consumes 20L/day during the dry season (10L/day during the rain season), which correspond to a fuel cost of 42000 KSh/month (USD 626/month) during the dry season. To finance it, 20L for household water needs are charged KSh 5 (USD 0.075), farmers have to pay KSh 5/month/cow head and a fee of KSh 10/pupil/term is paid by families for school water needs.

A team is in charge of diesel supply, system O&M and collecting payment. Water is available at two taps: one in the village for household needs and another one outside the village for farming water.

Rain water is another widespread water resource in Esilanke community. At the school, rain water is collected and refills two water tanks. The few families who live next to spring can also enjoy that complementary water source.

A reservoir was built next to the village but water stagnation and scarcity make it inappropriate even for farming purposes.

Infrastructures

Infrastructures are quasi- nonexistent in Esilanke community; therefore Esilanke is a very isolated community. Roads are not tarmac. During the rain seasons (November-December, April-June), access is very difficult. A matatu (Kenyan car or small bus public transportation mean) is going from the nearest city, Kajiado, to Esilanke twice a day.

Only one shop in Esilanke village has electricity thanks to a diesel genset. The nearest grid point is about 15km away.

Telephone network is available on the top of the hills about 1km from Esilanke village but accessing telephone network is an issue on most Esilanke area.

Esilanke Primary School is the unique public building.

Economic activity

Farming (milk production) is the main activity of Esilanke community which owns a total of 4500 cows.

There are 15 shops in Esilanke village, among them are: two butcheries, two agro-vegetable shops, two barbers, three hotels and one mobile charging place. No industry is present.

In the neighbourhood, Kajiado town is the big centre of economic activity. Five other settlements are located in the vicinity of Esilanke.

6.1.3. Energy situation

Prevailing sources of energy and corresponding population proportions are :

- for lighting: kerosene (paraffin) lamps (93%), candles and electricity as solar-battery or stand-alone battery (5%) and wind power for teachers' families accommodated at school (2%)
- for cooking and heating: cow dung (83%), charcoal (79%) and wood (50%)
- for entertainment: on top of the very few families enjoying electricity (4%), 19% have reported using dry cell batteries for powering radios.

Household income and energy expenditures

In the Empiris survey, 32% of the families are classified as very good economic status, 38% as good, 26% as average and 4% as poor. The survey of August 2007 has enabled to specify and complement this information.

| Unit Cost | KSh |
|-------------------------|----------------|
| 1 bundle wood | free to 75-100 |
| 1L paraffin | 50 |
| 1 sack cow dung | free to 100 |
| 1 sack charcoal | 400 |
| 1 pair dry-cell battery | 55 |

Table 6.2 Typical unit cost of energy sources

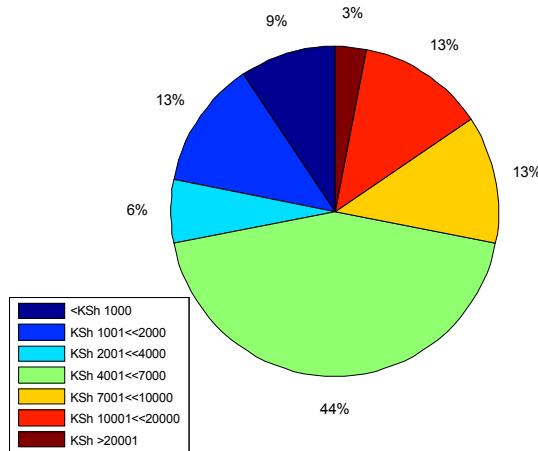


Figure 6.2 Monthly family income in Esilanke Community (28 family sample)

| Cost of Energy for | Sh/month | Nb of families |
|--------------------|----------|----------------|
| Lighting | 982 | 26 |
| Entertainment | 1570 | 6 |
| Mobile com. | 337 | 23 |
| Cooking + Heating | 2067 | 27 |

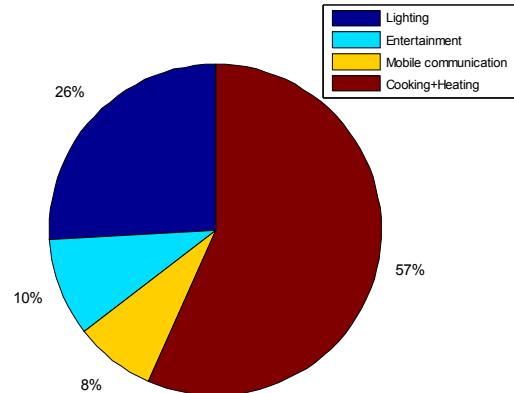


Table 6.3 Family energy expenditures - top

Figure 6.3 Weighted shares of the Cost of Energy - right

| | Min | Max | Weighted average | Percentage of families | | | | 100% |
|--------------------------|-----|------|------------------|------------------------|------------|------------|-------|------|
| | | | | % | | | | |
| Lighting | 200 | 2400 | 912 | <500 | 500<<1000 | 1000<<1500 | >1500 | |
| | | | | 32% | 32% | 11% | 25% | |
| Entertainment | 0 | 4000 | 336 | 0 | 0<<500 | 500<<1500 | >1500 | |
| | | | | 79% | 11% | 4% | 7% | |
| Communication | 0 | 800 | 277 | <0 | 0<<200 | 200<<400 | >400 | |
| | | | | 4% | 25% | 46% | 25% | |
| Cooking + Heating | 400 | 9200 | 1994 | <1000 | 1000<<2000 | 2000<<4000 | >4000 | |
| | | | | 29% | 39% | 21% | 11% | |

Table 6.4 General statistics on family energy expenditures (sample of 28 families)

Attitude to electricity access opportunity

The Empriris survey concluded that “95% of the residents want electricity while 5 want but fear to operate. 60% are able to contribute something to help the installation. Another main conclusion was the ability of most Esilanke resident to pay monthly fees for service access and O&M. Furthermore 80% are willing to pay 5000KSh (USD 75.5) or more for the installation. All institutions including schools, dispensaries and churches are ready to cooperate.”

The August 2007 survey confirms this positive attitude about electricity access.

As presented in the above tables, energy is very costly in the remote areas of Kenya. Access to electricity remains however a complicated enterprise. Indeed except the school where most of the power is used locally, the only close place is the village shop which owns a diesel generator. While most of Esilanke families have mobile phones, charging their battery is not easy. Charging services is not always available in the shop. To charge their mobile batteries, residents usually go to the closest towns (Kajiado, Kiserian, Isinya). Even though cost of charging is only KSh 20 (USd 0.30), cost of travelling in matatu is as high as KSh 150 (USD 2.24), making thereby mobile charging very expensive.

It is therefore not surprising that almost all Esilanke households are willing to access local electricity supply and services. It is economically sensitive for them.

A suitable situation for project expansion

When analysing the cost of energy for Esilanke families, it turns to be that KSh 1526/month (USD 22.74) is paid for energy sources that electricity could substitute (kerosene and candles, dry-cell batteries for radio, *lighting, entertainment, and communication*). This amount is dramatically high, especially compared to the reported average income: KSh 7078/month (USD 105.5). The cost of energy that could be substituted by electricity represents 22% of the monthly average income while the total cost of energy represents in average 50% of the monthly income. This is a very high percentage since common value in rural Africa is 25% maximum. Answering the questions about their income was not easy for Esilanke families since incomes are fluctuating with season and weather, therefore some uncertainty is expected.

Consequently the potential for transferring some of the energy costs to an investment for electricity supply is very high. It concerns cost of energy for lighting, mobile communication and entertainment.

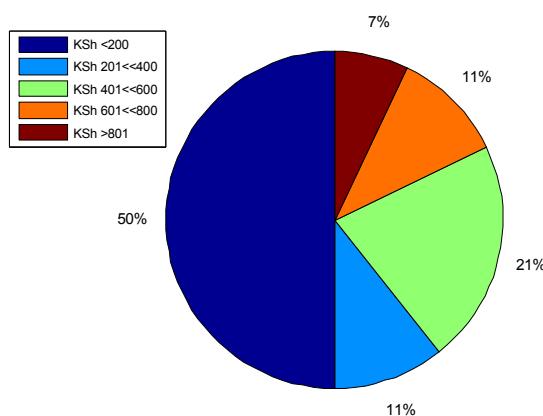


Figure 6.4 Monthly amount that families are ready to pay for the O&M fees resulting from electricity access

6.1.4. Wind resource

Esilanke area benefits from the natural asset of being on the edge of the Rift Valley. It is located about 2km from the top of the Rift Escarpment.

A huge hill effect applies on the highlands bordering the Eastern side of the Rift Valley. It results from the prevailing East wind direction and the gradual elevation from sea level on the cost to around 2000m high at the Escarpment.

The wind data used in this project are based on the extrapolation from the 4year measurements on the NGong Hills site. The mean wind speed is 6.89 m/s. Esilanke's wind resource is characterized by the Weibull parameters: $A = 7.76$ m/s and $k = 2.532$.

It is affected by strong seasonal variations: January to April and September to December are the high wind seasons (MWS = 7.89 m/s) while May to August is the low wind season (MWS = 4.55 m/s).

More information is provided in Appendix III.

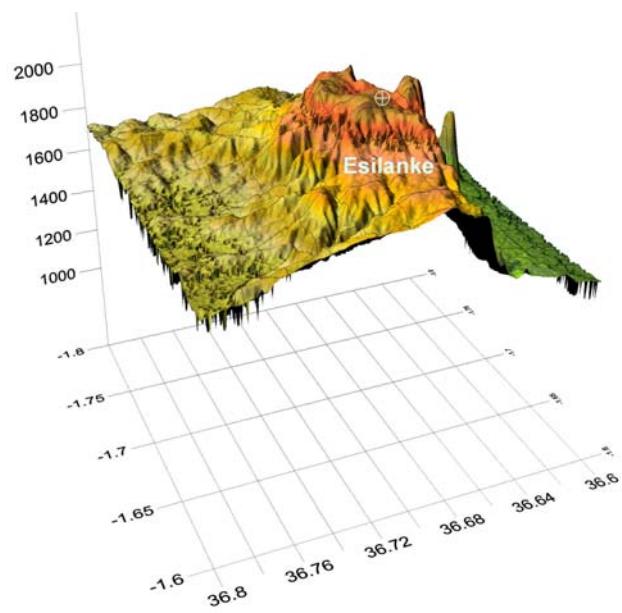


Figure 6.5 Relief view of Esilanke area

6.2. Project methodology

6.2.1. General strategy

The ultimate goal of this project is to assess the feasibility and the conditions of viability of wind-based decentralised electrification in rural Kenya towards dissemination in all areas of Kenya endowed with sufficient wind resource.

Therefore a lot of effort has been put into project evaluation and monitoring. Collaboration and information exchange with the local partner and the end-users has also been a key of the evaluation process.

Concerning the economy of the project, the power system and the appliances were donated by KenTec/Windgen. The community is responsible for financing the operation and maintenance cost. Indeed as pilot project, the upfront investment costs are high. Within the current state of development of small wind energy systems in Kenya, such a project is not affordable by poor rural community like Esilanke.

The lack of knowledge about the wind resource, the newness character and the absence of local skills has contributed to enhance those high costs. That is the reason why all the project philosophy has been to transfer capacity to Esilanke community in order to guarantee local management and project sustainability. Therefore once the system installed, some training sessions to power system O&M and energy consumption management have started and are continuing all along the first year of the project. On top of training, each visit is the opportunity to exchange information with the end-users and evaluate project sustainability.

6.2.2. Timeframe

First sem. 2006: Identification of Esilanke community by KenTec/Windgen from wind resource information and after analysis of the development project proposal presented by Samuel Njanka, representative of Esilanke Community.

- October 2006: Importation of wind power system from China
 Preliminary engineering studies
- January 2007: Foundation for the wind turbine tower and cabling of the school by BHEL team
- Mars 2007: Completion of the installation: erection of the turbine, finalising power system and appliances installation by BHEL team
 Capacity building: first training to power system O&M and energy consumption management



Figure 6.6 Installation of the wind turbines in Esilanke Primary School

- August 2007: Project evaluation with Esilanke community 5 months after installation
 System maintenance by BHEL team together with school staff
 Capacity reinforcement: second training to power system O&M and energy consumption management
- February 2008: Project impact assessment
 Evaluation of Esilanke capabilities
 System maintenance by BHEL team together with school staff
 Final training

6.2.3. Measures to ensure project sustainability

Simple and energy-efficient technology for facilitating the access-to-electricity learning process

Wind battery charging is a simple technology which requires little maintenance. Therefore it is adapted to the conditions of a rural community accessing electricity and the subsequent learning process on power management.

Power generation, supply and distribution have been secured to prevent pupil access (fencing the wind turbine area, underneath power cable, locked room for power control system and battery storage, high location for switches). The safety lamps and alarms inform the school staff about overloading or low battery state-of-charge.

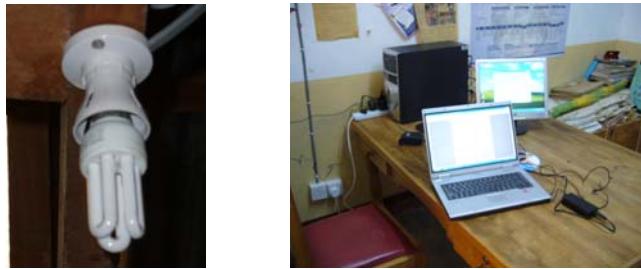


Figure 6.7 Appliances installed at Esilanke school

The appliances (11W energy saving lights) have been selected to minimize power consumption and therefore facilitate energy management. Complementary 36W fluorescent lights have been installed to ensure proper lighting conditions in classrooms. Uninterruptible Power Supply equipment has been installed between the computer and the switch in order to prevent computer equipment damaging if power quality gets temporarily bad. Originally all rooms were equipped with 36W fluorescent lights but the school reported high energy consumption and therefore most of those fluorescent tubes were replaced with energy saving lights in August 2007.

Mobilizing Kenyan wind technology skills and expertise

The Kenyan windpump manufacturer Bobs Harries Engineering Ltd (BHEL) has been chosen for their ability to provide proper expertise for system installation and maintenance. Indeed BHEL has about 30 years of experience in windpump manufacturing, installation and maintenance.

The presence of a Kenyan wind industrial partner is an important component for ensuring sustainability. Furthermore BHEL has the will to move on wind power generation system. This project was therefore the opportunity for the company to develop its wind power skills.

Progressive school staff training to power system O&M, energy consumption management and project sustainability

It is important to realize that prior to this project almost all the whole community did not have any knowledge about power system management.

In Mars 2007: the first training session happened and was dedicated to power system O&M and energy consumption management; enhancing the operation principle of the wind power supply system and the safety measures (battery water level, system alarms, sensitizing pupils to electricity hazards, using proper appliances).

Due to his interest in understanding power system operation and his participation to the installation of the system, teacher Kenneth Gitonga was appointed to be in charge of managing the power system and reporting daily energy consumption and issues.

The system was delivered with a computer system. Therefore computer lesson were provided with the ulterior target to incorporate the computer into the energy management strategy.

In August 2007, a second training session happened. Five months after installation, the learning process of access-to-electricity has produced very satisfying results. Therefore this second training has focussed on improving project sustainability and providing the means for Esilanke school to ensure themselves the sustainability.

Indeed it was very interesting to note that Professor Kenneth Gitonga had acquired an almost complete understanding of the operation principle of the power system and the role of each device. The effort implemented by the school staff to manage their power consumption according to the available wind

resource was also a great point of satisfaction. Technical training had consisted in reinforcing and enlarging the school staff skills so that an O&M team is effective.

While no computer skills were available within Esilanke community prior the project, the school staff has learned very quickly how to use the computer (most was self-learning) so that they were able to use Word software and print school papers.

This new knowledge has been capitalised into developing an Excel-based “Help for decision on Power Management Strategy” tool. This Excel tool was one arm of the “Being aware, controlling, anticipating” methodology to help the school staff to manage their energy consumption.

The methodology has also focussed on disseminating the power situation information to all Esilanke Primary School community, especially to the pupils. Therefore the school information board is now used to report the daily power situation, the information on morning/evening class opening and the daily guidelines decided by the school staff.

On top of reinforcing the school staff technical skills and their O&M abilities, this visit aimed at developing local capacity for making Esilanke pilot project financially sustainable. It was here again very encouraging to hear that the school staff together with Esilanke parents had agreed to charge a KSh 10/pupil/month fee for maintaining the power system. Furthermore mobile battery charging has been initiated as income generation activity.



Figure 6.8 Professor Kenneth Gitonga reporting fresh news about the energy situation on the school information board

The next step will be training school staff to wind turbine maintenance. This step should be carried out by BHEL team.

One year after installation in February 2008 the capacity of Esilanke Primary School to manage themselves the project will be assessed.

6.3. Installed system

6.3.1. The KenTec 1000 wind turbine

The installed wind turbine is FD3.2-1000 wind turbine, from Qingdao Anhua New Energy Development Co. Ltd. The power curve is presented below.

It is a three bladed turbine. The rated power is 1000W occurring at 8.5 m/s. Maximum power is 1500W at 15 m/s. Starting wind speed is 3.5 m/s.

Blades are made of reinforced fibre-glass and each one weighs 3.45kg. The blade has a maximum thickness of about 18%. Rotor diameter is 3.2m.

Hub height is 7m. Total weight is 220kW. Power is produced by a three phase Permanent Magnet Generator. Power control is ensured by yawing thanks to the offset tail fin.

| | | | | | | | | |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Radius [m] | 0.2 | 0.4 | 0.6 | 0.8 | 1 | 1.2 | 1.4 | 1.6 |
| Chord [mm] | 210 | 190 | 170 | 145 | 121 | 96 | 68 | 40 |
| Twist angle [°] | 20 | 12 | 10 | 8 | 6 | 3.5 | 2 | 0 |

Table 6.5 Blade geometry of the 1.5kW Qingdao turbine

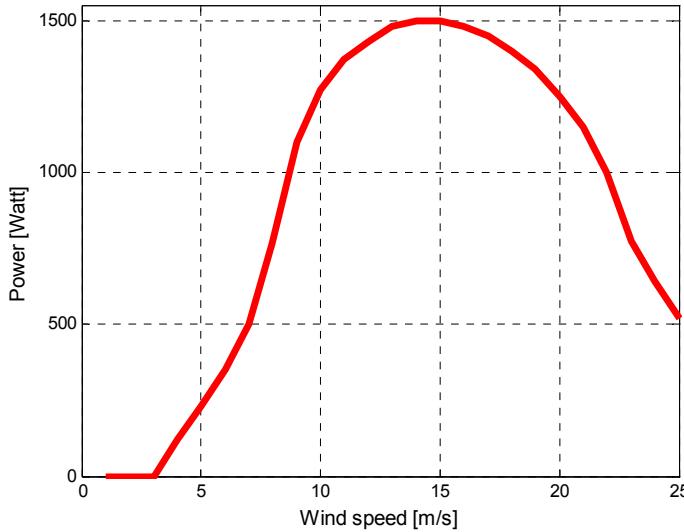


Figure 6.9 Power curve of the 1.5kW Qingdao turbine



Figure 6.10 1.5kW Qingdao turbine blade

6.3.2. Power control system and storage

Battery: 24 pieces of 2V GFX-200 Batteries (200Ah), Qingdao Anhua New Energy Development Co. Ltd

Control system: DC48V 1000VA 50HZ Controller and Inverter and DC48V/AC220V 1KW 50HZ sine wave inverter, Qingdao Anhua New Energy Development Co. Ltd



Figure 6.11 Batteries, charge controller and inverter

6.3.3. Appliances

Original setup

| | Installed appliances | Remark |
|---------------------|--|--|
| 6 classrooms | 3 36W fluorescent lights, 2 plugs | 1 light removed in each room to prevent from overloading |
| Community hall | 2 36W fluorescent lights, plugs | Switcher in classroom 7 on top position (2m high) to prevent children access |
| Office block | 2 36W fluorescent lights, 2 plugs | |
| Headmistress office | 1 36W fluorescent lights, 2 plugs, computer, printer | |
| Battery room | 1 36W fluorescent lights | |
| Teacher houses | 1 36W fluorescent lights, plugs | |
| Outside lighting | 3 18W fluorescent lights | |

Table 6.6 Original appliance setup

New setup

All lights were Philips TL-D 36W or 18W. Even though fluorescent lights were used, they were consuming so much power that it caused much inconvenience for the end-users. Therefore in August 2007, 13 of them were removed with energy saving lights (Philips Genie 11W).

Different lighting configurations have been installed in classrooms so that the school can easily adapt their power consumption to the available energy: 2 classrooms have very good lighting conditions with 1 TL-D 36W and 1 Genie-11W, 1 classroom has good lighting conditions with 3 Genie-11W, 3 classrooms have moderate lighting but extremely-low-energy consumption conditions with 2 Genie-11W. This last configuration is aimed at being used during lull periods when battery state-of-charge is low.

The lights of the office and headmistress rooms have been replaced as well.

6.4. Performance

6.4.1. Simulation of the expected energy production

Simulation inputs and parameters

- ρ_{air} : 0.973 kg/m³
- Altitude : 2025 m asl
- Wind data input: KenTec simulation (Monthly mean wind speed, Aug 2002-July 2006)
- Turbulence model: Kaimal Spectrum

| | | Annual | December | September | May | July | July 2006 |
|-----------------|-----|--------|----------|-----------|------|------|-----------|
| Mean wind speed | m/s | 6.78 | 8.8 | 6.1 | 4.8 | 4.1 | 3.3 |
| Mean DEO | kWh | 10.70 | 17.10 | 7.02 | 4.01 | 2.76 | 1.35 |

Table 6.6 Simulated mean wind speed and daily energy output

The seasonal variation of the wind climate induces strong variation of wind turbine power output. From January to April and from September to December, daily energy production is high or very high. During the low wind season (May to August), some power supply issues are expectable since in July 2006 was only 1.35 kWh/day and for the last four years, while over the 4 years of measurement the July's average Daily Energy Output (DEO) is 2.76 kWh.

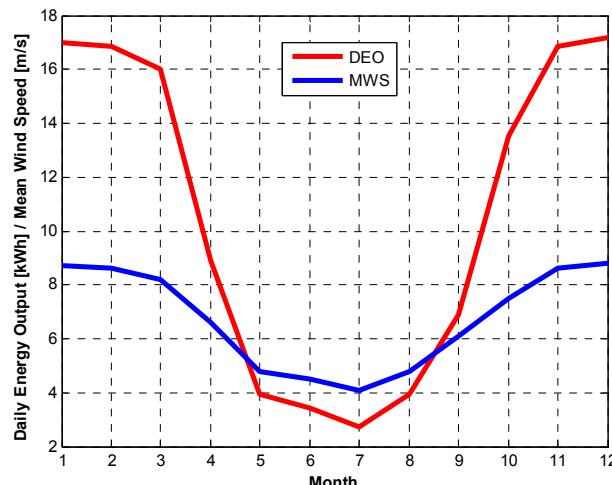


Figure 6.12 Mean Wind Speed and Daily Energy Output along the year

6.4.2. Energy consumption

Replacing 36W fluorescent lights with 11W energy-saving ones have considerably improved the situation: the energy consumption has been decreased by 67 to 85% in the classrooms and the office block.

As presented in 6.3.3, the new lighting strategy has enhanced flexibility. With three different lighting configurations for the classrooms (excellent-level lighting/moderate energy consumption, good-level lighting/low energy consumption, moderate-level lighting/extremely low energy consumption), the school can adjust their energy consumption to the available power while ensuring everyday morning/evening class.

A typical week of morning/evening classes (3 classes lighted for 4hours/day) is now consuming as low as 1.3 kWh/week, with the extremely low energy consumption configuration. In normal configuration, it reaches 2.6 kWh/week.

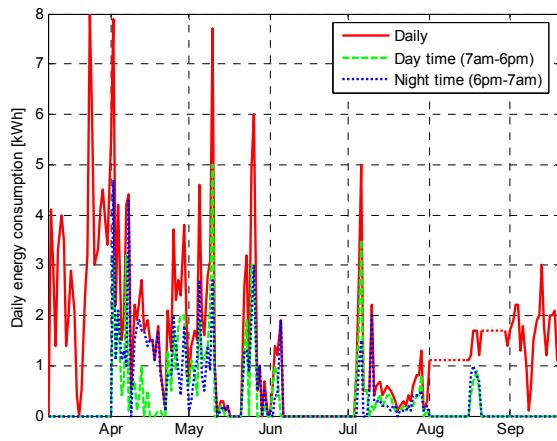


Figure 6.13 Daily energy consumption at Esilanke school

| Minimum | Maximum | Mean (1) | Mean (2) | Std (2) |
|---------|---------|----------|----------|---------|
| 0.10 | 8.00 | 1.47 | 1.81 | 1.51 |

1: over all period – 2: over days of energy consumed; values in kWh

Table 6.7 General statistics about daily energy consumption

In 2007 the low wind period (June-July) had some severe consequence on power availability since for about 3 weeks power was not available. This situation can be attributed to exceptionally low wind resource, inappropriate light settings (too high energy consumption) and underperforming wind turbine.

It is interesting to realize that the last month (September 2007) has a much more constant daily consumption than the two first months, traducing the fact that school has passed the period of system discovery and enters a time when they are now able to manage their energy consumption.

In September 2007, daily energy consumption gets stabilised between 1 and 2 kWh/day.

4.4.3. Technical sustainability

Based on the five first month consumption, the wind turbine is expected to produce, theoretically, enough energy for covering the school's energy needs on a daily basis for the whole year.

In reality some events can mitigate this very positive situation. Indeed the school claimed that they were not able to use the appliances in May and June 2007.

One clear reason was the inappropriate lights installed in March 2007 that were consuming too much energy. The new setup enables flexible energy consumption management so that energy consumption has

been minimized in some classrooms for the long-duration lull periods while other rooms benefit better lighting conditions but higher energy consumption, the latter being preferred for moderate to high wind periods.

Another reason that explains the impossibility to use the appliances in May-June 2007 could be the underperforming wind turbine. Indeed at the August's visit, it turned to be that the turbine at some difficulty to yaw. Two main hypotheses are: need for yaw bearing greasing (unexpected) and power cable blockage in the tower (likely). With the coming high wind season, this issue will affect power availability moderately but the next maintenance visit will focus on solving this issue together with school training for maintenance. Since August 2007, the school has reported that winds are sufficiently high now and all their energy needs are covered (including the new mobile battery charging activity).

To conclude, the turbine is producing much more energy than school needs during the high wind period (January to April and September to December). During those periods it could be advantageous to investigate how to take the most advantage of the extra energy produced. Water pumping could be an option.

During the low wind period (May-August), power production should produce enough power for covering all the school's energy needs. However, exceptional long lull periods would affect power availability and it is likely that the school might suffer power shortage for a few days to a few weeks during those four months.

It is therefore a key that power performance is maximum during low wind periods. The implemented training plan aims at ensuring local maintenance and energy consumption management. After 5 months, school's progresses are very promising even though complementary training is necessary especially for improving school's maintenance skills.

6.5. Financial viability

6.5.1. Project cost

| Activity | Subactivity | US \$ on 26-03-2007 2007 | | % | % |
|---|------------------------|-----------------------------|-------|------|------|
| Purchase of Power Supply System | WT+CC+Bat+Inv | 4260 | 5940 | 32% | 23% |
| | Local purchase | 1680 | | | 9% |
| Purchase of appliances | | 2479 | 2479 | 13% | 13% |
| Project identification | | 647 | 647 | 4% | 4% |
| Engineering study | Transport | 172 | 1572 | 9% | 1% |
| | Man Labour | 310 | | | 2% |
| | Engineering | 1090 | | | 6% |
| System delivery, Room cabling & Turbine foundation | Transport | 688 | 1756 | 10% | 4% |
| | Man Labour | 836 | | | 5% |
| | Supervision | 232 | | | 1% |
| Turbine erection and installation completion | Transport | 359 | 5422 | 29% | 2% |
| | PSS Man Labour | 609 | | | 3% |
| | Electrification Labour | 812 | | | 4% |
| | Supervision | 3120 | | | 17% |
| | Report | 522 | | | 3% |
| Maintenance visit | Transport | 202 | 637 | 3% | 1% |
| | Man Labour | 203 | | | 1% |
| | Supervision | 232 | | | 1% |
| | | TOTAL | 18453 | 100% | 100% |

Table 6.8 Esilanke project detailed costs

| Project activity | US \$ | % |
|--|-------|------|
| Purchase of Power Supply System | 5940 | 32% |
| Purchase of appliances | 2479 | 13% |
| Transport | 1219 | 7% |
| Installation -Man Labour | 2567 | 14% |
| Engineering | 5611 | 30% |
| Maintenance visit | 637 | 3% |
| Total | 18453 | 100% |

Table 6.9 Esilanke project activity costs

As any pilot projects, the costs of Esilanke wind electrification are high. The unawareness of wind solutions in rural Kenya explains those high costs.

There is obviously no wind system supplier nor expertise in the nearest town (Kajiado, 15km away). Therefore any engineering and workforce was supplied by Bobs Harries Engineering Ltd which has to travel about 150 km to reach Esilanke community from the company location in Thika.

Cumulated to the absence of local supply chain, the distance has also increased the engineering costs.

6.5.2 Willingness to pay

Maintaining school's wind power system

Pupil's parents have shown a remarkable willingness to get involved in financing the viability of the project.

To the question, "who should finance the maintenance?" 93% have answered Esilanke Community and 68% have answered the parents. Still 61% expect the donor to contribute to the O&M costs. The Government and the Ministry of Education are only reported by respectively 14% and 18% of Esilanke families. 14% would like maintenance to be free, 18% the school staff to pay for it, 25% the company installing the system and 11% the system manufacturer.

The community has also agreed to charge KSh 10/pupil/month (USD 0.15) for maintaining the system. The goal is to raise KSh 2000/month (USD 29.8). The survey has shown that 25% of the families are ready to pay this amount 36% more, 21% would prefer to pay KSh5/month/pupil.

The level of organisation and the commitment of Esilanke community to is probably one reason of this high willingness to pay. Furthermore, the concept of maintaining installation and paying for services has been introduced with the previous water supply project relying on a diesel generator. At the water point, customers pay KSh 5/20L (USD 0.075), farmers are charged KSh 5/month/head and every family pay Sh10/pupil/term for school water supply.

6.5.3. Prospects for income generating activities

Potential IGAs

Promoting income generation activities is a key method for reaching financial viability, especially in the case of high front cost project where the investment needs to become profitable with the development of new economic activities.

In Esilanke community most families have mobile phone: 37% have 1 mobile phone, 30% 2 mobile phones, 22% have 3 mobile phones and 11% have more than 3 mobile phones.

Charging mobile phone battery is a complicated job. It is available in a village's shop but it costs KSh 30/charging (USD 0.45) due to diesel-based power generation. It costs KSh 20/charging (USD 0.30) in shops located in the neighbour city centres but it requires going there.

The proposal for starting battery mobile charging at Esilanke school has been very well welcomed. Community has agreed on a fee of KSh 20/charging (USD 0.30). The survey has shown that 70% of the families are ready to pay this fee, 17% would prefer pay less, 13% are ready to pay more.

Four weeks after service opening, 30 customers have come to the school to charge their mobile battery. These KSh 600 (USD 8.94) are already enough to pay for the next O&M cost about distilled water required by the battery bank.

Similarly, it is possible to rent the community hall and enjoy the power system for KSh 100/h (USD 1.49/h). In August 2007, the organisation of a wedding in the community hall generated KSh 200 for 2h renting (USD 2.98).

A further perspective could be to use the extra wind power produced to pump water. Indeed as presented in next section, the current diesel pump generates high O&M costs. Wind power would minimize them. Savings could be used for new investment. This option is detailed further in the following section.

4.5.4. Financial and cost-benefit analysis of wind-based decentralised electrification projects

This analysis aims at improving the general knowledge about financing and potential induced benefits of wind-based decentralised electrification. Inputs are based on Esilanke case. The simulation for using extra wind power produced for water supply can not be directly applied to Esilanke project. Further investigations on pump suitability, power cabling and costing would be required.

Background

Financial analysis is based on the calculation of the annualised cost, net present value and internal rate of return. The cost-benefit analysis is always more difficult to effectuate since it needs to evaluate external effects.

About lighting, when switching from the polluting kerosene to electric energy, one clear positive impact affects health. Moreover lighting for morning/evening classes, access to computer, video... improve education conditions and better school results might be expected. Electricity for the teacher accommodation building is a factor of teacher stability. All those aspects are difficult to quantify, but are real in the case of Esilanke school.

Since it was out of the scope of this study to quantify all those external benefits, the study has only focussed on the cost saving external effects as kerosene for school lighting.

Due to input lack, the potential negative effect on the village mobile battery charging service business has also been neglected.

To carry out the financial and cost-benefit analysis, five scenarios were built.

- Scenario 0: as the project is financially perceived by Esilanke community: the equipment is donated and installation was funded, the community should pay for O&M.
- Scenario 1: as the project financing has really been, including the amount for equipment purchase, engineering and installation.

Scenario 2, 3 and 3bis envisage how would be the economic and social benefits of a more elaborated wind energy situation in Kenya; where there is local expertise for system installation and maintenance, and where projects take advantage of community's service needs to generate incomes.

- Scenario 2: engineering, installation and O&M are partially available locally.
- Scenario 3: engineering, installation and O&M are fully available locally, water supply is connected to power generation on moderate level.

- Scenario 3bis: engineering, installation and O&M are fully available locally, water supply is connected to power generation on high level.

For scenarios 0 and 1, inputs are real data from Esilanke case, for the other scenarios inputs anticipate cost reduction thanks to local servicing.

Income generation activities are based on current Esilanke values: morning/evening class fee: KSh 2000/month (8 months/year) (USD 30.0), renting PSS: KSh 100/h (USD 1.5), mobile charging: KSh 20/charging (USD 0.30), diesel cost saving due to wind powered water pumping according to 20 L diesel = 12000 L water, at the rate of KSh 70/L diesel (USD 1.04).

The amount of clients/PSS renting correspond to the current situation (scenario 0) and are extrapolated for the other scenarios.

Reduced cost of kerosene is calculated from the former kerosene need at school: average of 0.75L kerosene/day at KSh 50/L kerosene (40 weeks a year) (USD 0.75).

Replacing batteries and/or inverter occurs at year 5 (scenarios 0 and 1) and at year 10 (scenarios 3 and 3bis). Scenario 2 does not require batteries or inverter changing.

Batteries costs correspond to refilling the batteries with distilled water 2.5 times/year at KSh 600 each time. For scenario 0 and 1, 50% extra cost has been added due to school moderate knowledge about battery maintenance.

Wind powered water pumping represent about 19% (scenario 3) and 28 (scenario 3bis) of the yearly amount of pumped water. During the dry season, the 12000 L of water pumped from 50m deep correspond to a 1.65kWh hydraulic energy; there is therefore much wind electric energy non-used at the school that could feed the electric pump, even with very low pump efficiency. During the high wind months of the dry season, theoretically 100% of the pump energy could come from wind electricity. In July, where the situation would be the most critical, this ratio would fall down below 25% for 50% efficient pumping) and possibly to 0% if wind resource is very poor as in July 2006.

19% and 28% yearly water amount pumped thanks to wind power are therefore very consistent with wind turbine production and pump energy consumption.

When water supply is considered, an extra investment cost of USD 1500 has been added to count for power cabling, pump purchase/adjustment etc.

Summary table

| | | Scenario 0 | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 3bis |
|---|--------------------------|---------------|---------------|---------------|---------------|------------------|
| Discount rate = 10% | 1USD = 67.05 KSH | 10 | 10 | 15 | 15 | 15 |
| Investment (Wind Power System - Pumping Adjustment) | | | | | | |
| Engineering support base | | WPS | WPS | WPS | WPS + PA | WPS + PA |
| O&M support base | | Nbi | Nbi | Nbi/local | local | local |
| Revenue | IGA: mobile charging | clients/w | Nbi | Nbi/local | local | local |
| | IGA: renting PSS | /month | 7 | 10 | 20 | 30 |
| | Water supply | L/year | 1 | 1 | 1 | 2 |
| External effect | Reduced cost of diesel | L/year | 0 | 0 | 0 | 600000 |
| | Reduced cost of kerosene | L/month | 0 | 0 | 0 | 900000 |
| | | 150 | 150 | 150 | 150 | 150 |
| Investment | Power System Supply | USD | 0 | 5940 | 5940 | 5940 |
| | Pumping Adjustment | USD | 0 | 0 | 0 | 1500 |
| | Engineering | USD | 0 | 5600 | 250 | 250 |
| | Installation | USD | 0 | 3800 | 1500 | 750 |
| | Replacing batteries | USD | 1500 | 1500 | 0 | 3000 |
| | Replacing inverter | USD | 0 | 0 | 0 | 1100 |
| O&M | Maintenance visit | USD/year | 0 | 0 | 50 | 50 |
| | 5-year revision | 5 | 405 | 405 | 150 | 150 |
| | 5-year revision | 10 | 0 | 0 | 0 | 300 |
| | Batteries | USD/year | 37.5 | 37.5 | 25 | 25 |
| Revenue | Morning-evening fees | USD/year | 239 | 239 | 239 | 239 |
| | IGA: mobile charging | USD/year | 109 | 155 | 310 | 465 |
| | IGA: renting PSS | USD/year | 36 | 36 | 36 | 72 |
| | IGA: water supply | USD/year | 0 | 0 | 0 | 1044 |
| | Total | USD/year | 383 | 430 | 585 | 1820 |
| External effects | Reduced cost of kerosene | USD/year | 112 | 112 | 112 | 112 |
| Annualised Costs | All system | USD | 484 | 2981 | 1402 | 1874 |
| | Power system only | USD | 484 | 2981 | 1402 | 1676 |
| NPV | Externalities included | USD | 1980 | -13074 | -3964 | 3890 |
| | Externalities excluded | USD | 1293 | -13761 | -4652 | 7861 |
| IRR | Externalities included | % | / | / | / | 3040 |
| | Externalities excluded | % | / | / | / | 7010 |
| | | | | | 18.31% | 25.77% |
| | | | | | 16.61% | 24.23% |
| Cost of electricity | mean DEO : 1.5 kWh/day | USD/kWh | 0.88 | 5.44 | 2.56 | 3.06 |
| | mean DEO : 2 kWh/day | USD/kWh | 0.66 | 4.08 | 1.92 | 2.30 |
| | mean DEO : 5 kWh/day | USD/kWh | 0.27 | 1.63 | 0.77 | 0.92 |
| | mean DEO : 10 kWh/day | USD/kWh | 0.13 | 0.82 | 0.38 | 0.46 |

Table 6.10 Financing analysis of different wind-based rural electrification scenarios

Analysis

A very important point is to notice that the Income Generating Activities (IGA) set up at Esilanke Primary School should generate enough incomes for covering all the O&M costs for the current project (scenario 0). Indeed revenue and external saving are higher than annualised costs. The NPV is positive with and without externalities. Whatever the energy consumption, cost of electricity is low for the community; this is because the community has not had to pay for the investment.

Scenario 3bis cumulates all assets for financially feasible and profitable project: revenue is higher than annualised costs (even excluding externalities), NPV is largely positive and IRR is much above the discount rate. In Scenario 3, externalities are needed to boost revenue and generate higher annual incomes than annualised costs.

Scenario 1 and 2 are neither financially feasible (annualised costs exceed annual revenue, even including externalities) nor profitable (NPV is negative and IRR never above discount rate). They suffer from high O&M costs due to absence /low level of local skills and insufficient income generation.

After key output comments, it is interesting to compare them in order to extract some key lessons.

First the importance of Income Generating Activities is much enhanced. From scenario 0 to 2, IGAs remain low. Developing a unique service business activity (mobile battery charging) does not generate enough income. From project 2 to 3 and 3bis, adding water supply has dramatically improved the profit even though scenarios 3 and 3bis imply higher upfront costs due to pumping system investment.

Incorporate several IGAs matching community service needs is therefore a key aspect of the financing strategy. Scenarios 3 and 3bis propose a complementary financing strategy where social commitment (morning/evening class fee) is supplemented with individual initiatives and business development (mobile charging, water supply) on crucial community needs. Generating incomes at those two level, community and individual, has the main advantages to reinforce project acceptance and community management while enabling any individual or family to feel and enjoy the benefits directly.

Second the upfront costs remain a huge issue. Investing USD 8500 in a power system is not affordable for most rural communities of Kenya. While it has just been demonstrated that wind-based decentralised project can be much profitable, there is the need to work with financing institutions to facilitate wind system investments.

Third, the analysis of the cost of electricity (COE) illustrates their relativity. In scenario 0, the cost of electricity comprises almost solely maintenance activities. When taking as much as possible advantage of the produced power, COE is only USD 0.13/kWh (DEO=10kWh). Excluding battery replacement at year 5, COE would drop down to USD 0.07/kWh for the best case.

There is however a large margin between current energy consumption (1.5-2kWh/day) and the optimal one (10kWh/day). If today's COE is high, it also means that there is much advantage to develop new IGAs since it would not only generate supplementary incomes but also decrease the COE.

Comparing COE level to energy production and IGA benefit potentiality clearly shows that focusing on this COE level might lead to misunderstanding the advantages of wind power project where there is much opportunity to connect electricity access with easy-to-develop IGAs.

Last, local skills and end-user's management capacity is a decisive conditions of sustainability. It has a clear impact on improving the financial viability of wind-based project. From scenario 1 (real case, pilot project) to scenario 3bis, engineering and installation costs are divided by 9.5, and simulation have used consistent inputs. It is likely that those costs could even be decreased.

To conclude coherent approach are required to make Swal Wind Turbines affordable, financially feasible and profitable investments for the poor communities. The socio-economic environment is key input;

enhancing IGAs and local management are decisive aspects. Provided all those conditions are met, wind-based decentralised electrification project can be highly economically and socially beneficial.

6.6. Conclusion on the expansion of wind-based electrification pilot projects in rural Kenya

Thanks to this pilot project, it can be stated that small wind turbines are technically suitable for decentralised electrification in Kenya. Major points of concerns are: assessing the wind resource prior to project development, providing robust power generation and supply equipment, training the community for local operation and maintenance, sensitizing and training the end-users to power system and energy consumption management.

Regarding costs, the upfront investment is a barrier to the large dissemination of small wind turbines in Kenya. However given the current high energy expenses in remote areas, the power needs for improving education and living standards, the induced socio-economic benefits and the will of rural families to access electricity, small wind turbines are a promising option for community-based electrification.

Esilanke project has enhanced the high cost of energy for rural families. Therefore it is not surprising that most of them are ready to pay for accessing electricity and modern energy services. This willingness to pay is a very good basis for developing more widely electricity access within Esilanke community, and further in any windy area of Kenya: in the Northern districts, along the coast, on the Rift Valley highlands.

It is now necessary to act towards the development of a suitable local expertise network, regulatory framework and promotion of wind energy solutions.

Provided suitable local expertise and wind resource knowledge, project costs will necessarily decrease and wind decentralised electrification will become a very attractive option in any windy remote area thanks to its inherent assets: production of large amount of power, capability of mini-grid power supply, and enhancement of productive uses of electricity.

Developing these suitable local conditions is therefore a prerequisite for a sustainable growth of the small wind energy system market in Kenya.

Chapter 7: Manufacturing and selling SWT in Kenya

7.1. The Kenyan SWES technology

7.1.1. The Kijito windpumps

The Kijito windpumps have been manufactured by the Kenyan company Bobs Harries Engineering Ltd since 1979. About 400 items have been installed worldwide, mainly in Kenya, Tanzania, Uganda Somaliland and Sudan. BHEL windpumping is a 30employee company.

Technical focus

| | | |
|---------------------------|--------------------------|--|
| Rotor | Diameter [m] | 3.7 to 7.9 |
| | Number of blades | 16 to 24 |
| | Material | Steel |
| | Airfoil | Flat plate with camber and rod on suction side |
| | Chord variation | constant |
| | Typical twist angles [°] | 50 (root) to 25 (tip) |
| Tower | Type | Lattice |
| | Height [m] | 10-13 |
| Operating characteristics | U_S [m/s] | 2.5 |
| | U_r [m/s] | 7 |
| | U_{max} [m/s] | 40 |
| | Max. rot. speed [rpm] | 90 |
| | Control | Yaw and passive pitch |

Table 7.1 Main technical characteristics of the Kijito windpumps



Figure 7.1 Kijito windpump being maintained by BHEL team

| MODEL | 16ft (4.9m) | | |
|------------|-------------|-----|--------|
| Wind (m/s) | light | med | strong |
| Head (m) | 2-3 | 3-4 | 4-5 |
| 10 | 21 | 71 | 150 |
| 20 | 10 | 35 | 75 |
| 40 | 5 | 18 | 37 |
| 60 | 4 | 14 | 28 |
| 80 | 3 | 9 | 19 |
| 100 | | 7 | 16 |

Table 7.2 Kijito pumping performance in cum/day

Performance simulation

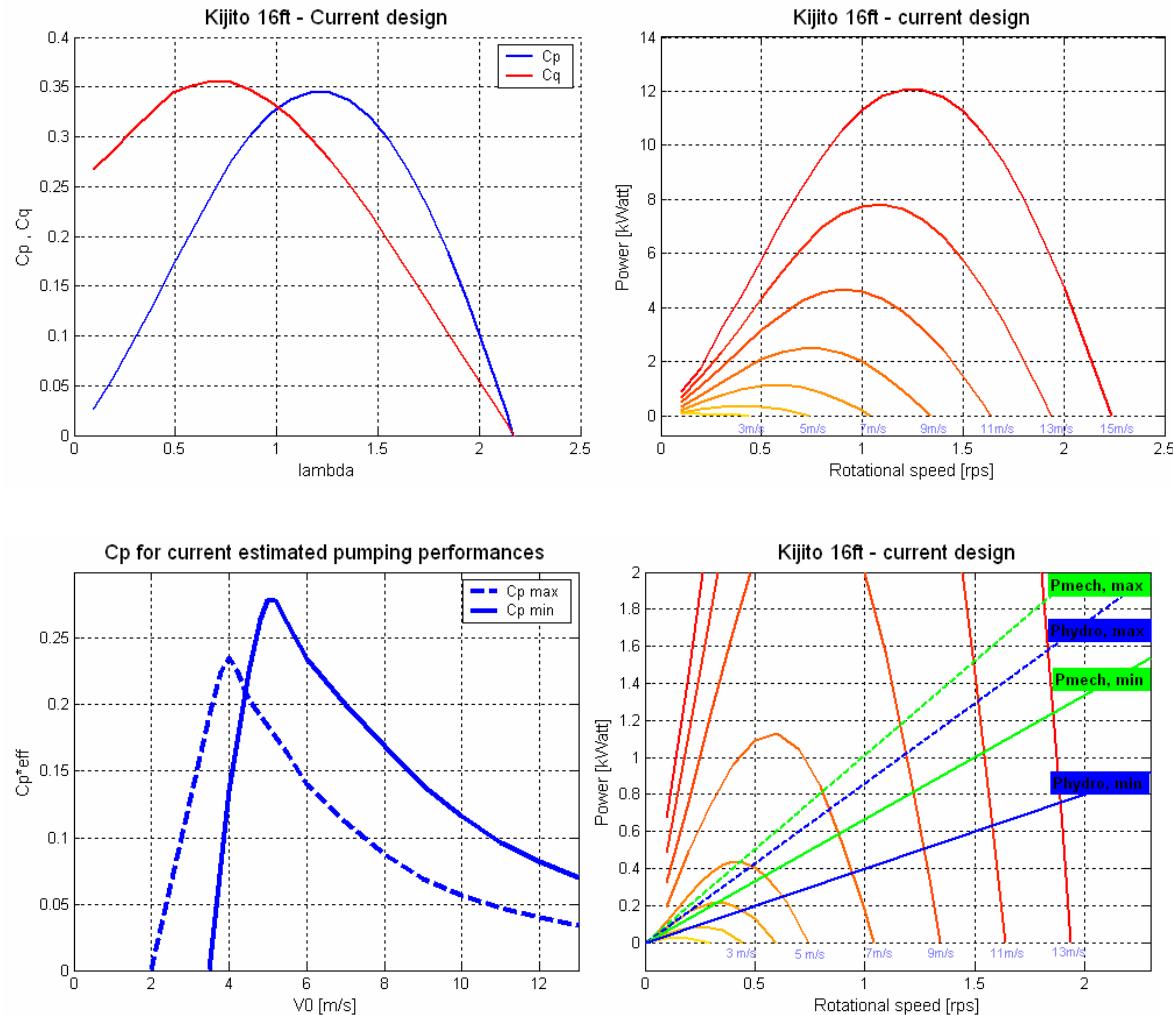


Figure 7.2 Simulation of 16ft Kijito windpump performances with the BEM code

Calculation of P_{hydro} and P_{mech} are evaluated through two hypotheses (maximum, minimum) based on outputs from original design and expected highest efficiency for low wind speeds (designed wind speed V_d around 3-5 m/s).

Outputs from original design are provided by the Kijito Information Booklet and correspond to theoretical values calculated 20 years ago: 21 cum (cube meters) at 2-3 m/s and 150 cum at 4-5 m/s (10-m head). To this vague information, it is necessary to add the number of hours of useful wind (assumption of 24 h a day) and the system efficiency (the assumed value takes into account both mechanical and pump efficiencies).

Then the maximum output estimation is based on the following assumptions:

- water yields of 21 cum at 2 m/s and 151 cum at 4 m/s,
- 24 hours of useful wind a day,
- 10m-head,
- system efficiency of 85%.

The minimum output estimation is based on the following assumptions:

- water yields of 21 cum at 3 m/s and 151 cum at 5 m/s,
- 24 hours of useful wind a day,
- 10m-head,
- system efficiency of 60%.

For the maximum output estimation, V_d should be 4 m/s corresponding to $C_{P,max} = 0.23$. For the minimum output estimation, V_d should be 5 m/s corresponding to $C_{P,max} = 0.28$.

These assumptions lead to a designed wind speed V_d which are in the range of coherent values for this kind of windmill. Corresponding rotational speeds are also coherent values.

Analysis

Kijito windpumps have been designed for mechanical water pumping in low wind speed areas. Therefore it is not surprising to observe interesting performance around 3-6 m/s. The multi-bladed design aims at generating important torque at starting; this is due to pumping requirement.

This high number of blades yields slow rotation. Therefore a gear system is required for power generation adaptation, unless the number of blades is reduced.

With higher rotation speed, the mechanical characteristics of blades might become an issue. Given the low amount of wind energy extractable for the lowest wind speed (< 5 m/s), it is not demonstrated that it is economically suitable to develop large multi-bladed rotor designed for power generation while 2-3 bladed rotor would induce much lower manufacturing cost and much better efficiency (as analysed in Chapter 11).

A Kijito 16ft windpump costs about US\$ 7000, pumping system and adjustment for 66m deep well would add about US\$ 5000 extra, transportation (100km round trip) and 14 work days for installation would cost about US\$ 4000.

To conclude, Kijitos windpumps are proven technology with some of the oldest installed 20 years ago and still operating. With such high water yield, products are very well adapted for farmers and community's water needs. With a more elaborated commercial strategy targeting more regular and higher orders, Kijito competitiveness could be substantially improved. Indeed today's prices are competitive to other water pumping system but the high investment costs, as for any wind energy system, remain a huge obstacle for poor communities.



Figure 7.3 Kijito water supply projects

7.2.2. The WindCruiser wind turbines

Craftskills Enterprises has been manufacturing small wind turbines since 1998. All items are made locally: blade, tower, generator, charge controller. They have sold about 50 SWTs in Kenya and a few in neighbour countries.

Technical focus

| | | |
|---------------------------|--------------------------|-----------------------|
| Rotor | Diameter [m] | Unknown |
| | Number of blades | 3 |
| | Material | GRP |
| | Airfoil | NACA4412 |
| | Design tip speed ratio | 6 |
| | Chord variation | Unknown |
| | Typical twist angles [°] | Unknown |
| Tower | Type | Lattice/Tubular |
| | Height [m] | 12 to 36 |
| | U_s [m/s] | 2.5 |
| | U_r [m/s] | 7 |
| Operating characteristics | U_{max} [m/s] | 40 |
| | Max. rot. speed [rpm] | Unknown |
| | Generator | PMG |
| | Power | 12V to 400V |
| | Control | Yaw and passive pitch |

Table 7.3 Main characteristics of Crafskills Windcruiser aerogenerator

Performance

Very few information is available about Craftskills wind turbine performance. Due to very low equipment for manufacturing, the reliability of the turbines is an issue.

The measurement undertaken by Mr. Simon NGuyo, Chairman, let expect that the rotation speeds of the 1200W Windcruiser vary from 150 to 450 rpm while delivering 50 to 1200 Watts. For the 3500W Windcruiser, rotations speeds would vary from 150 to 200 rpm while delivering 1000 to 3500 Watts.

Such low rotation speed and high power output for the 350W Windcruiser is uncommon for small wind turbine connected to direct driven generator. It could mean that the generator is much oversized for the rotor size, or that the rotor is much inefficient.

The provided performance for the 1200W Windcruiser looks particularly interesting. The simulation of the theoretical performance of NACA airfoils for SWT connected to PMG is provided in Chapter 11.

Analysis

Windcruiser turbine prices are quite low. The CS15TDR (1200W rated power) only costs US\$ 1650 (turbine, 10m tubular tilt tower charge controller). 30% should be added for commissioning and installation. The CS35TDR (3500W) costs US\$ 6464 (turbine, 20m lattice tower, charge controller). Those prices are very competitive with other small wind turbine manufacturers. However their low manufacturing infrastructure is an important drawback since quality and reliability is affected by this unfavourable environment.

Craftskills skills and expertise is unique in Kenya. However better equipment and more accurate design and power system choices are two requirements for improving product quality and enlarge commercial prospects.

Given the benefits yielded by Small Wind Turbines for rural development, this experience for the development of locally-made low cost power system should therefore be more supported.



Figure 7.4 Craftskills wind-based decentralised generation projects

7.2. The SWES market in Kenya

7.2.1. Background

Wind energy has a long history in Kenya and East Africa and has been used for more than 25 years. In Kenya, two industries are specialized in manufacturing small wind energy systems: BHEL has been manufacturing the Kijito windpumps since 1979 and Craftskills Enterprises the Wind Cruiser aero generators since 1998. The current wind energy data estimates that 25% of Kenya is compatible with current wind energy technology.

The wind energy market is evolving from pre-commercial to pioneer development stage and to date about 400 windpumps and small aerogenerators have been installed in Kenya. Private and public sector activities include:

- Importation of small wind turbines from the US by Renewable Energy System distributors
- Kenyan consulting companies providing wind energy expertise
- University research centres involved in improving the knowledge of the Kenya wind resource and the applicability of the systems made in Kenya,
- NGOs using wind energy systems in their projects
- Local utility companies Kengen and KPLC operating wind turbines.
- Financing of pilot wind rural electrification projects by international co-operation institutions.

The small-size wind energy systems, ranging from 1 to 20 kW, constitute solutions particularly adapted to the electricity and water supply of isolated settlements or towns, health centres, schools, industries, commercial centres... located in rural areas. While contributing to rural development, using wind energy systems made in East Africa stimulates also the industrialization of the region.

7.2.2. Market prospects

Wind power generation and windpumping for community development

Due to low electrification rate in Kenya and dry climate pattern in many areas, wind energy is a very relevant option to enhance electricity and water supply of any remote areas endowed with sufficient wind resource. 3 m/s and above average wind speed areas are adapted to windpumping, wind power

generation requires 5 m/s average wind speed and above. In any windy areas, even the ones which are “relatively” close to the grid, wind rural electrification can be a cost effective solution.

Therefore, the North of the country (Marsabit and Turkana districts), the edge of the Rift Valley and the coast are three priority areas. Small wind turbines (1-20kW) are ideal sizes to build community development plans around wind rural electrification and water supply projects like power kiosks, integrated energy service centre, school, health centre, farming and industry electrification and water supply.

Wind power for private business

Complementary to the electricity supply of rural communities, small wind turbines could also interest rural businesses like the tourist camp and lodges, large farmers and rural industries. This supplementary potential customer target is an important lever for wind energy sector growth since they have much higher and more regular income and are therefore more secured customers for the small wind industry manufacturers.

7.2.3. Limitations to market expansion

Several limitations exist to Small Wind Energy System (SWES) market expansion.

For many years the knowledge about Kenyan wind resource was very low due to few reliable measurements. The recent wind campaign by the Ministry of Energy in about 30 sites of Kenya is an encouraging progress. Furthermore the development of wind park projects also contributes to knowledge improvement. About 10 wind park projects are ongoing in Kenya and for 4 of them wind data have been collected for 5 years.

Obviously poverty, especially in rural Kenya (80% of rural household earn less than US\$ 2/day/capita), can constitute a limiting factor. At least it requires taking this parameter into account when targeting rural Kenya as key market for SWES. As demonstrated with Esilanke case study, rural context is relatively favourable for SWES since current energy costs are high and therefore communities are willing to invest in power systems.

The low awareness of wind energy technology in Kenya is an important issue since neither decision makers (policy makers, energy institutions, funding institutions, cooperation and development bodies), nor population are aware of the presence of local-made SWES. However offensive marketing and lobbying campaigns are necessary to change the present situation.

7.3. Conditions for a viable development of SWES manufacturing activities in Kenya

6.3.1. Reducing manufacturing costs

Esilanke case study does not bring only valuable information about the suitability of using small wind turbines for decentralised electrification in Kenya; it also enables to test a 1kW China-imported wind turbine and power system. Indeed in the range of small wind turbines, Chinese companies are becoming serious competitors. The cost of the system: US\$ 4260, including wind turbine, power control system and battery bank, is dramatically low. However it underlines that manufacturing low cost small wind turbines is possible.

Kijito windpumps are obviously much more expensive. It is wrong to believe that windpumps can not be affected by Chinese product competition. Indeed if importing windpumps from China is an unrealistic hypothesis due to large volume required by windpumps and therefore high shipping costs, small wind turbines coupled with electric pump could be serious competitors.

Regarding Craftskills, even though costs are close to Chinese products, quality and reliability are not as advanced. Here is the weak point of Windcruiser turbines.

To remain competitive, it is a key for both BHEL and Craftskills to reduce their product price and/or improve the quality.

In Africa's context, decreasing prices is not only a matter of Chinese competition; it is first driven by the will to supply the poor with low-cost high performance systems. Furthermore on a purely business strategy, accessing this market is a key segment since it cumulates large number of potential clients and high development impact.

Reducing manufacturing costs is a necessity to improve Kenyan SWES competitiveness. It should also be accompanied with other strategic activities: product performance and quality certification, investment in R&D, promotion and lobbying.

7.3.2. Guaranteeing performance and system quality

Performance and system quality is even more important in Africa for two reasons.

First, most of SWES operates in remote areas where technical support is not always easy to access. Therefore systems must be very robust and preferably simple or based on well-proven technology so that maintenance can be minimized.

Second, no development project can be built if system performance is low. Indeed economic stakeholders need reliable power to develop their business activities and launch new investments.

Preferring cost decrease to quality is finally a risky and likely counter-productive method. Propagation of end-user dissatisfaction would be an important drawback while SWES promotion campaigns are ongoing.

Guaranteeing performance and quality would be a major asset for the Kenyan wind industry. Collaborating with Kenyan research university sector to assess Kenyan-made SWES performance and quality would be an interesting option. It would first reduce costs notably while benefiting the wind energy R&D thanks to researchers and students involvement. Obviously partnering with international wind energy public research/private stakeholders would bring some expertise that might be lacking in Kenya.

7.3.3. Promoting wind energy solutions in Kenya and lobbying

The low awareness of the advantages and potentialities of SWES is incontestable in Kenya. Therefore promoting wind energy solutions and lobbying are key activities. Those activities should act at three levels.

It is first urgent to have a suitable legal and regulatory framework that promote local manufacturing of wind energy systems, facilitate R&D public-private partnership, and develop standards. Furthermore the national strategy on rural electrification and water supply should also take advantage of wind energy options.

The customer base should be enlarged. Indeed very few rural Kenyans are aware about wind solutions. Those promotion campaigns should target rural communities but also rural Small and Medium Enterprises. The latter are a strategic segment in the development stage of SWES market.

To facilitate investment, financing institutions should be sensitized to the benefit of SWES for rural economic growth. Developing financing facilities is indeed required for making SWES investment affordable for poor rural communities.

7.3.4. The importance of developing key-partnerships

The three activities mentioned above for developing wind energy in Kenya: improving Kenyan SWES competitiveness, performance and quality certification and promoting wind energy advantages and systems, can not be carried out only by the Kenyan wind industry. Key partnerships are necessary.

Partnership with R&D stakeholders (Kenyan university research sector and/or international wind energy research bodies) is a strong way to improve system performance and quality. Not only public-private partnerships are encouraged but public-public research collaboration projects would be highly valuable for

wind energy development in Kenya since it would significantly contribute to the development of local expertise.

Industrial partnership could also be built with developed country wind turbine manufacturers. Those partnerships would bring mutual benefits since the developed country wind turbine manufacturer would access a new market with large growth prospects while the Kenyan SWES manufacturer would be able to improve its competitiveness by acquiring new skills, expertise and knowledge and increasing its business activity.

To organize the maturation of SWES market and set up business development strategies, the support of cooperation / industrial development institutions or consultancy companies would enable the Kenyan SWES manufacturers to access capacities that are currently lacking.

The involvement of financing institutions will be at a point required for developing SWES market for the poor. To secure financing, some programme should be built between the Kenyan wind industry, those financing institutions and customer/community associations.

Chapter 8: Conclusion on SWT suitability for decentralised electrification in rural Kenya

8.1. Great prospects but obstacles to overcome

This study has tried to evaluate the sustainability of SWT for decentralised electrification in rural Kenya according to the following criteria:

- Kenya's wind resource
- Economic / financial suitability of wind-based projects and linkage potential with rural development
- Social acceptance and interest from end-users
- Technical skills and expertise present in Kenya

Esilanke pilot project has been a key source of information. The collaboration with BHEL and the contribution from Craftskills have enabled to build a more comprehensive analysis.

From this analysis, guidelines and implementation strategy is proposed in the next section.

Regarding Kenyan wind resource, in several areas of Kenya wind climate is suitable for a large development of wind energy in Kenya. Along the coast, on the highlands of central Kenya, in the Northern areas, winds are sufficiently strong for developing pertinent wind energy projects. The seasonal wind regimes must always be studied with care since seasonal wind climate variations have much impact on the technical choices and economics of wind energy projects.

Going beyond lighting to power productive activities is the great philosophy of projects using small wind turbines. From a technical point of view, their various sizes (from 500W to 20kW) and technology options (battery charging, hybrid wind-diesel, mini grid, water pumping) are key assets when considering rural service needs for boosting economic growth.

Esilanke pilot project has shown that demand for electricity access is high. The current cost of energy paid by rural dwellers for inefficient and hazardous energy (kerosene, wood, charcoal, candles) constitutes an obstacle to development. Electricity could replace the lighting, entertainment and communication cost of energy, which cost an average of KSh 1526/month (USD 22.75) for Esilanke families.

The financial feasibility and profitability is much dependant on the capacity to develop Income Generating Activities. Provided IGAs are incorporated, small wind turbine projects can become much lucrative for communities. Enhancing multi-sector productive uses is a key measure to ensure financial viability

The main issue is however the high upfront costs that need to be overcome with suitable financing schemes and facilities.

Esilanke project has also shown the high degree of interest from end-users and their capabilities to get appropriate the project on a very quick time-basis. This is a very interesting feature and a decisive condition for large dissemination of wind energy project within rural communities.

The presence of Kenyan-based wind energy system manufacturers is a formidable opportunity to link rural development and industrial development in a joint global strategy. The long wind energy history of Kenya and the expertise already present in Kenya is a strong factor of success.

However those skills and expertise are concentrated in Nairobi area. To become technically sustainable, developing wind energy in Kenya must target the dissemination of a supply chain in all areas endowed with good wind potential. The presence of those local skills is an essential step towards the reduction of wind energy project costs. Indeed installation and maintenance managed by local enterprise would improve financial and technical sustainability while this local network would contribute to wind energy promotion.

The performance, quality and competitiveness of Kenyan-made wind energy systems can still be much improved. To succeed, partnerships with Kenyan and international R&D bodies would enable product maturation and the emergence of a denser network of wind energy expertise in Kenya. Kenyan wind energy companies should also see much advantage in developing closer relationship with European, American, Australian or Asian wind industry stakeholders.

To conclude, there are still some efforts to do in order to reinforce the sustainability of SWT for decentralised electrification in rural Kenya. This sustainability will proceed from a joint action promoting the development of a local network of expertise, the technical improvement of Kenyan-made product and a more elaborated business strategy of Kenya wind industry stakeholders including partnership with Kenyan and international public R&D bodies and industries.

8.2. Proposed guidelines and implementation strategy for developing wind-based decentralised electrification in rural Kenya

Guidelines

This part is inspired by the concept paper “Developing Wind Energy in Kenya” written by the Kenyan companies: Bobs Harries Engineering Ltd, CraftsSkills Enterprise and Energy for Sustainable Development with the support of Baptiste Berges. The complete document is provided in Appendix IV.

“While the prospects for rural water supply and decentralised electrification projects based on SWES are large in Kenya, it is still very difficult to realize such projects. Indeed on top of suffering from wind data scarcity, development of small wind projects faces the barrier of technology unawareness in rural Kenya and the absence of a sufficiently developed supply chain for SWES country-wide.

The ultimate goal of this project is to support the growth of the Kenyan wind industry and enable the SWES market to reach sufficient state of commercialization in Kenya.

This project will be focused on four activities:

- Identifying the suitable areas with respect to wind resource, population density and local economy vibrancy; and developing a detailed wind atlas for those areas,
- Demonstrating the effectiveness of small wind energy projects and their impacts on rural development through implementation of pilot projects
- Creating awareness, marketing and setting up of SWES supply chain in target districts; enhancing local/regional capacity for installation, operation and maintenance of SWES
- Incorporating wind energy into the national and regional strategic plans for rural electrification and water supply

The project team will work closely with the relevant national authorities, local government and authorities, and District and Constituency Development Committees.

The output will be the implementation of 20 wind-based decentralised electrification and water pumping pilot projects executed to enhance productive uses of water and electricity and rural development.

This project will be a reference for developing wind energy in other Eastern African Countries”

Implementation strategy

The implementation strategy aims at building the conditions for a sustainable large dissemination of wind-based decentralised electrification and water pumping. It targets community development in rural Kenya and the industrial development of the Kenyan wind industry.

The implementation strategy can be broken down into the following activities:

1. Pre-feasibility studies

- a. Evaluate the wind regimes of Kenya from existing data and studies
- b. Incorporate data about wind resource, population density, economy vibrancy, electricity access, water needs and expected socio-economic benefits to identify the meaningful areas for small wind-based projects
- b. Set up a working group involving the Kenyan Wind Industry Committee together with the organisms in charge of water supply and rural electrification (MoWI, MoE, REA) in order to incorporate wind energy into the national strategic plans regarding rural electrification, water supply and industrialisation

1. Co-ordinating the development of wind energy in Kenya with the strategic plans of Government of Kenya

- a. Prepare an action plan to structure and strengthen the development of the Kenyan wind energy sector. Enhance link with Kenya industrial strategy.
- b. Promote State support of partnerships between the Kenyan wind industries and Research sector
- c. Promote the emergence of legal and regulatory framework favourable enabling a sustainable and profitable development of commercial SWES activities in Kenya
- d. Suggest target districts for the implementation of a coherent programme enhancing the socio-economic impacts of wind-based Rural Electrification and Water Supply

2. Feasibility studies

- a. Carry out complementary measurement campaigns in the target districts
- b. Realize the detailed wind atlas of the target districts
- c. Identify needs in details in the target districts
- d. Work with the local Government and Authorities, District and Constituency Development Committees to develop the Rural Electrification and Water Supply programme
- e. Identify partner communities to implement the pilot projects and get community buy-in
- f. Define the suitable technology for the given socio-economic situation of each pilot project
- g. Secure project financing
- h. Meet the legal requirements induced by the projects

3. Pilot Project implementation and development

- a. Pilot project implementation
- b. Build capacity for local operation, maintenance and management

- c. Mobilizing and educating customers and end-users about energy efficiency and power consumption management

4. SWES market structuring

- a. Set up a supply chain in the target districts capable to undertake installation and post-installation activities
- b. Create SWES awareness among public thanks to a promotion campaign
- c. Promote SWES “*made in Kenya*” at a wind energy conference organized in Nairobi

5. Project follow up and impact assessment

- a. System monitoring
- b. Assess SWES technology acceptance and appropriation
- c. Assess the socio-economic impacts on a regular time basis

Development of small wind turbines for optimal power production and starting performance in Kenyan wind climates

Chapter 9 : Model validation

9.1. Methodology

Reference data and studies

The present project has used the research studies carried out within the wind energy group of the University of Newcastle to validate the computer model developed in this study. Therefore the results of the present project have been compared to measurements and simulations developed by the wind energy group of the University of Newcastle.

Indeed the wind energy group of the University of Newcastle has been involved in developing small wind turbines for more than 10 years. They have designed several small wind turbines focussing on optimizing starting and power production performance.

Furthermore, similarly to the present project, they consider operating conditions in demanding context (remote areas, developing countries situations) and low/medium wind climates as main parameters governing SWT design. They therefore also aim at designing robust, low cost and high performance small wind turbines.

They have notably designed 600W and 5kW wind turbines. On top of the abovementioned considerations, the 600W turbine has much operating characteristics similar to the constraints of the present study: same power range, self starting and tail furling control mechanism.

This project uses the design of their 600W wind turbine for model validation. This turbine is hereinafter referred as Newcastle 600W.

The wind energy group of the University of Newcastle has produced many papers detailing the design, operating characteristics and performance. The main studies used as reference for this project are the wind energy book by Professor David Wood [6] and the PhD thesis of Andrew Wright [8]. Both studies detail design characteristics, present measurements of power production and starting behaviours and assess simulation models.

The Newcastle 600W wind turbine

General description

The original turbine was the 400W Australian Wind Power (AWP) turbine. Blades and generator were redesigned [24]. The new rated power was 600W occurring at 10 m/s.

The original design had a 5° pitch to increase clearance between the blade tips and the tower. The new blade design was based on the SD 7062 airfoil. The root section is rectangular.

The generator is the one presented in the Inputs part and referred as Newcastle PMG 600W. Safety and power control was governed by the horizontal tail furling system. A minimum rotating speed of 268 rpm is required for generating power. The cogging torque is 0.36 Nm.

Main features

The main Newcastle 600W features are summed up in the following table.

| | | |
|---------------------------|-----------------------|-----------------------|
| Rotor | Diameter [m] | 1.94 |
| | Number of blades | 3 |
| | Material | Pine wood |
| | Airfoil | SD 7062 |
| | Chord variation | 0.13 to 0.04 |
| | Twist angles [°] | 13 to 2 |
| Tower | Type | Lattice |
| | Height [m] | / |
| Operating characteristics | U_s [m/s] | 3 |
| | U_r [m/s] | 10 |
| | U_{max} [m/s] | 40 |
| | Max. rot. speed [rpm] | 1070 |
| | Generator | Newcastle PMG 600W |
| | Control | Yaw and passive pitch |

Table 9.1 Main features of Newcastle 600W wind turbine

The blade root lengths were set to 9.64cm long by 1.51cm thick after calculation from the inputs provided by [6].

| | Cross-sectional area AB [m^2] | Second moment of area about x-axis I_x [m^4] | Second moment of area about y-axis I_y [m^4] | Blade second moment of inertia J_B about the turbine axis [kgm^2] |
|---------------|-------------------------------------|--|--|---|
| Inputs | 0.00146 | 2.79e-8 | 1.199e-6 | 0.0633 |
| Re-calculated | 0.00146 | 2.77e-8 | 1.127e-6 | 0.0609 |

Table 9.2 Computed and measured Moments of inertia and area

The total measured rotor moment of inertia J_R about the turbine axis (blade and hub) was 0.43 kgm^2 . The rotor moment of inertia is used for evaluating starting performance.

Since complete hub design is out of the scope of this study, an evaluation of the rotor moment of inertia is needed. Assuming the same ratio between the blade and rotor second moments of inertia as for Newcastle 600W turbine, the rotor moment of inertia was set as:

$$J_R = 7 \times J_B = 8 \times J_{BnoRoot}$$

where $J_{BnoRoot}$ refers to the calculation without considering the root section.

Evaluated designs

During his PhD investigations, Andrew Wright evaluated the behaviour of several SWT configurations. The four following configurations are considered for comparison to the present work.

Configuration (a): 5°-pitch, no yaw offset

Configuration (b): 5°-preconed, no yaw offset

Configuration (c): no pitch, yaw offset

Configuration (d): no pitch, no yaw offset

Though no yaw control offset was engineered for configuration (a) and (b), measurements revealed that a slight offset angle still occurs. This yaw behaviour was inputted in the calculation for model validation. From the yaw angle measurements for configuration (c), a yaw behaviour model is built. This yaw behaviour is inputted later in the optimization step in order to consider this effect in performance simulation for the designed turbines. All yaw behaviours and model are presented in table 9.3.

Configuration (d) corresponds to measurements for the twin tail wing in Wright's PhD thesis. The twin tail fin enabled to reduce yaw oscillations with wind direction changes and provided therefore more accurate results.

Blade design

Blade chord and twist distributions are presented below from fitting equations provided by Wright [8].

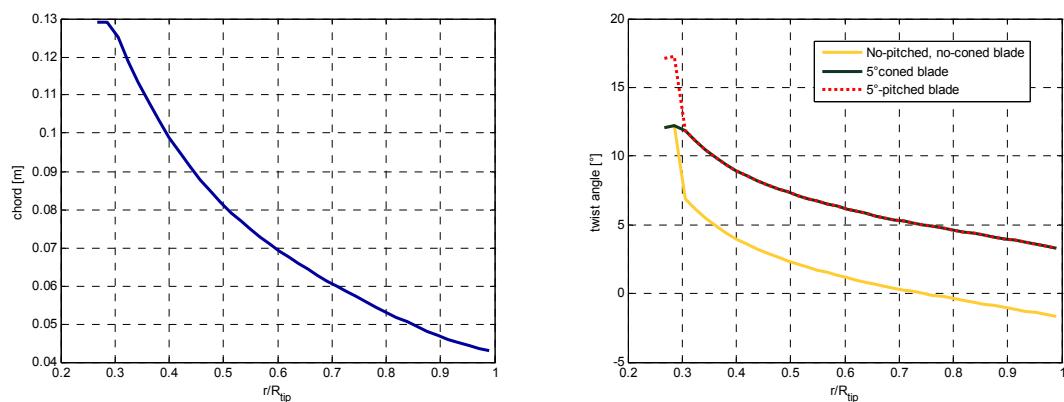


Figure 9.1 Chord and twist distributions for the Newcastle 600W blades

Yaw behaviour

| U [m/s] | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---------------------|---|---|---|-----|-----|-----|-----|-----|-----|-----|
| (a) - Yaw angle (°) | 3 | 3 | 3 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 |
| (b) - Yaw angle (°) | 2 | 2 | 2 | 2 | 4 | 4 | 4 | 4 | 4 | 4 |

| U [m/s] | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|-------------------------------|------|------|------|------|------|----|----|----|------|----|----|----|----|------|
| (c) - Real yaw behaviour (°) | 20.5 | 20.5 | 16.5 | 17.5 | 18.5 | 20 | 22 | 23 | 24 | 25 | 26 | 26 | 27 | 29 |
| (c) - Yaw behaviour model (°) | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 22.5 | 24 | 26 | 28 | 30 | 31.5 |

Table 9.3 Yaw behaviour

9.2. Power production performance

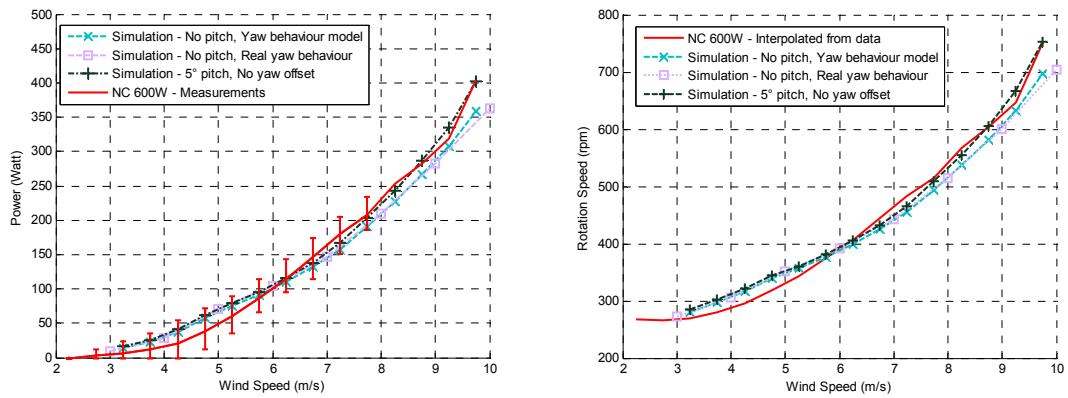


Figure 9.2 Simulated and measured/interpolated power and rotation speed for Newcastle 600W turbine

The simulations for power production performance give very good agreement with the measurements. For the power curve, all curves fits within the error boundaries. After 8 m/s, error boundaries are not plotted anymore due to too little measurement information. The agreement with measurement is also quite remarkable for the rotation speed curve.

5°-pitched blade rotors provide the best fitting (only 5°-pitch simulation is shown on the above graph because results are so close that they can not be distinguished).

For the rotation speed curve of the twin tail fin (no pitch, no yaw offset), measurement and simulation fit also extremely well up to 11 m/s. The lower agreement beyond 11 m/s can be explained by two reasons: on one hand few measurements were recorded for the higher wind speeds, and on the other hand information the generator behaviour was unavailable above 1070 rpm. Therefore at 15.75 m/s, generator behaviour was approximate to meet the expected power output and rotation speed. From this result, simulated rotation speeds were linearly interpolated between 10.75 m/s and 15.75 m/s.

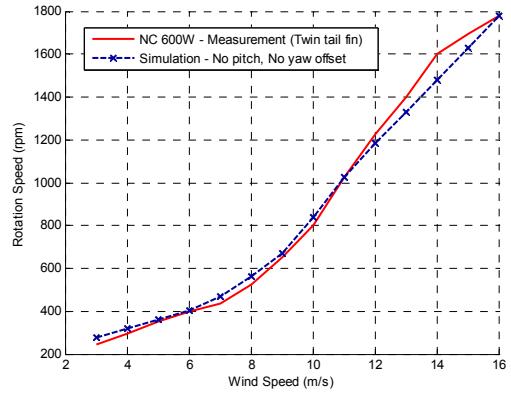


Figure 9.3 Rotation speed comparison with Wright's Thesis for the Newcastle 600W wind turbine

9.3. Starting performance

As presented in 1.4.2, four estimate of lift and drag coefficients are used for simulating starting behaviour:

- Estimate (a): interpolation for infinite AR ,
- Estimate (b): interpolation for finite $AR = 9$,
- Estimate (c): generic flat plate equations,
- Estimate (d): Ostowari ($AR = 9$) and (c).

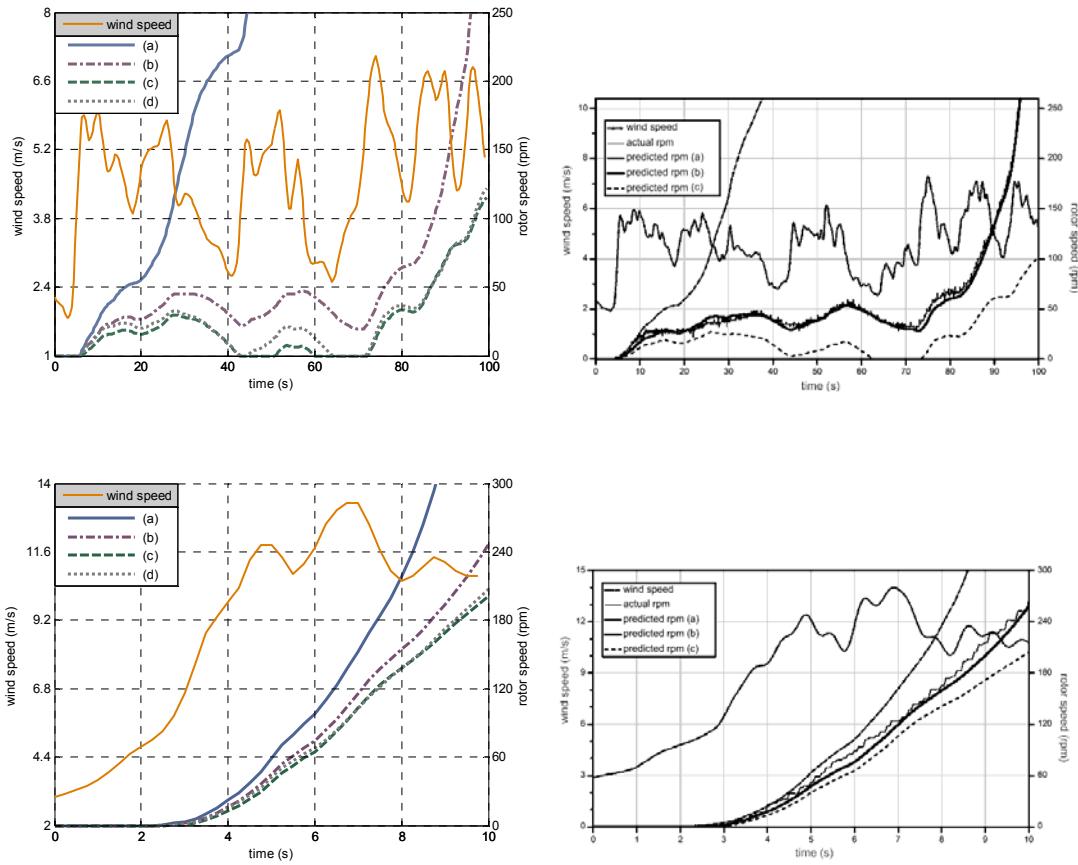


Figure 9.4 Comparison of starting performance with Wright's PhD thesis

For the starting sequences as well, agreement between simulations and Wright's research outputs are very good. Unfortunately, both results can not be compared on the same graph due to no access to the real wind speed time series used by Wright. Therefore some similar time series had to be built. Considering the inerrant approximate similarity between both wind speed time series, fitting is very good.

Best fitting is provided by C_L - C_D estimate (b). Estimate (c) and (d) undervalue the rotation speed while estimate (a) overvalues the rotation speed.

Further analysis of starting behaviour is provided in Chapter 10.

Chapter 10: Performance of the NC 600W wind turbine

The Newcastle 600W wind turbine provides the opportunity to analyse a turbine that has been designed for optimal power production and starting performance. Therefore it is a very interesting case study to understand more in details why such a turbine design is able to reach those apparently antagonist objectives.

Power production and starting performances of the NC 600W wind turbine has already been introduced in the previous chapter. This chapter focuses on analysing the power production and starting performance and connecting those performances to the design choices.

10.1. Power production performance

Details for design 4 (5° twist, no yaw offset)

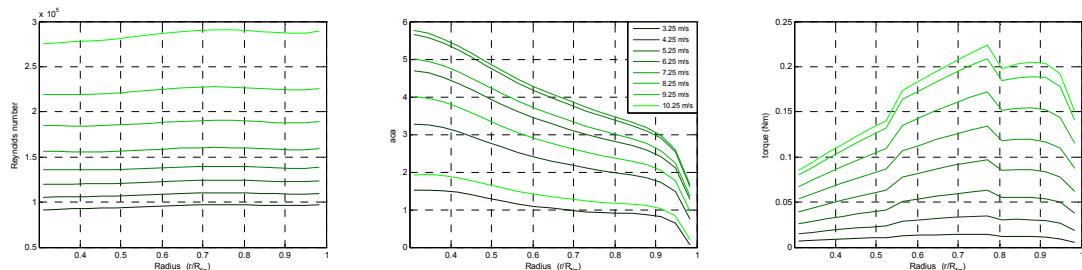


Figure 10.1 Aerodynamic characteristics during power production operation for the NC 600W turbine

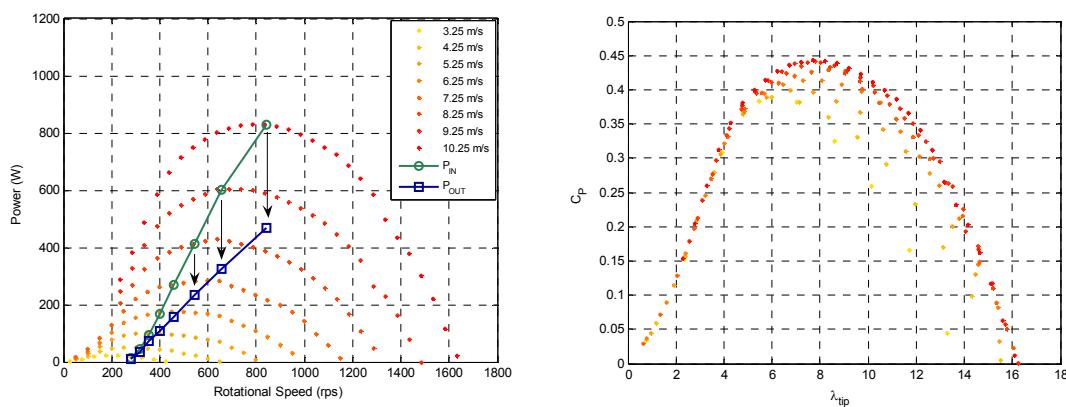


Figure 10.2 Power production performance for the NC 600W turbine

Performance comparison for design 1, 3, 4 and 5

Details about designs are provided on figure 9.1 and in appendix V.

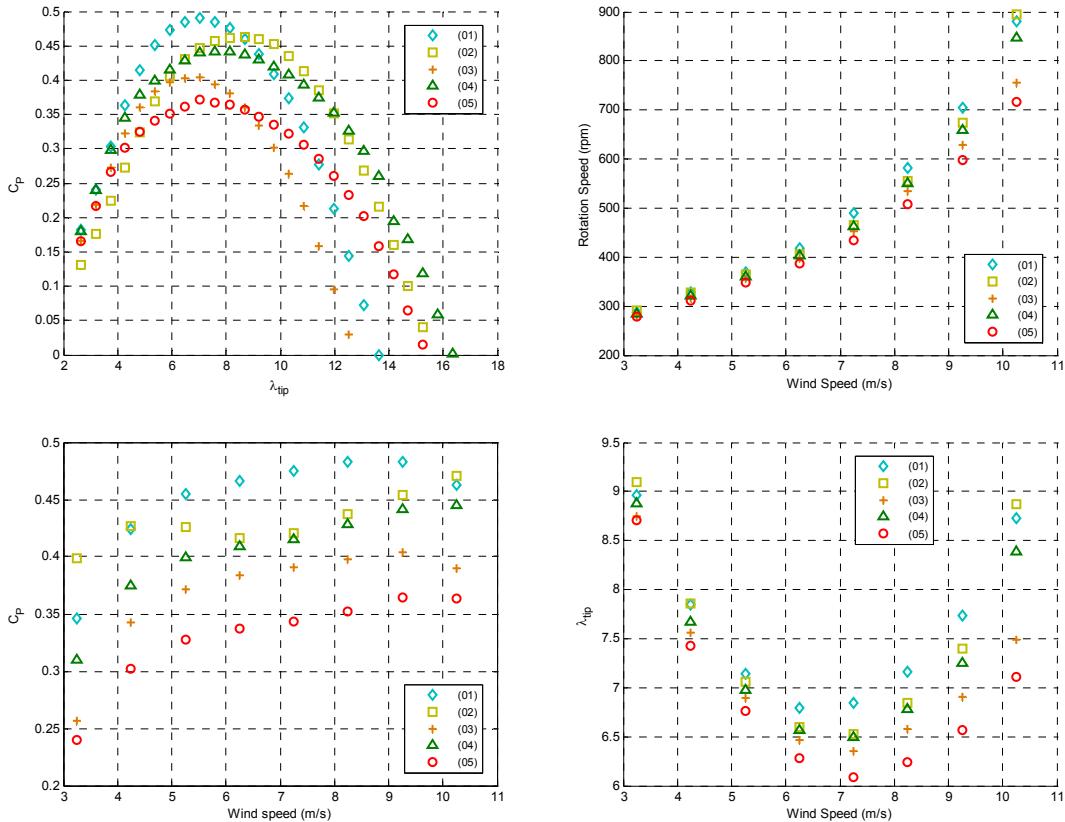


Figure 10.3 Power production operating characteristics for the NC 600W turbine

During operation, typical Reynolds numbers vary from 1 to 3.10^5 . This variation enhances the better strategy of using C_L - C_D for different Re and interpolation process as it is done in this study. It is interesting to note that Re is almost constant along the blade. This is due to chord reduction compensating the effective wind speed increase with radius.

In theory, blade design enables to keep the angle of attack close to its optimal value all along the blade. For the original Newcastle 600W, it can be seen that the value at the root is about 3° higher than at the tip. It is due to optimizing root design for starting performance purposes.

Torque logically increases both with the radius and the wind speed. The local increase $0.55 < r/R_{tip} < 0.8$ results from the large twist angle at the root which generates large tangential force at root with negative gradient towards the tip. This effect is specific to this blade design and does not occur for blades solely designed for power performance optimization.

Figure 10.3 shows excellent rotor performance since $C_{P,MAX}$ is about 0.5 for the case without pitched blades and operating with no yaw offset (design 1). For design (1) $C_{P,MAX}$ occurs at $\lambda = 7$. C_P increases also with the wind speed for design 1 and reaches its maximum value at 8.8 m/s.

Pitching and yawing effects are important and reduce power production by 10 to 30%. Furthermore inherent PMG losses affect notably power outputs as shown on figure 10.2. Another consequence of pitching and yawing is the reduced operating rotation speed and therefore operating λ as shown on figure 10.3.

10.2 Starting performance

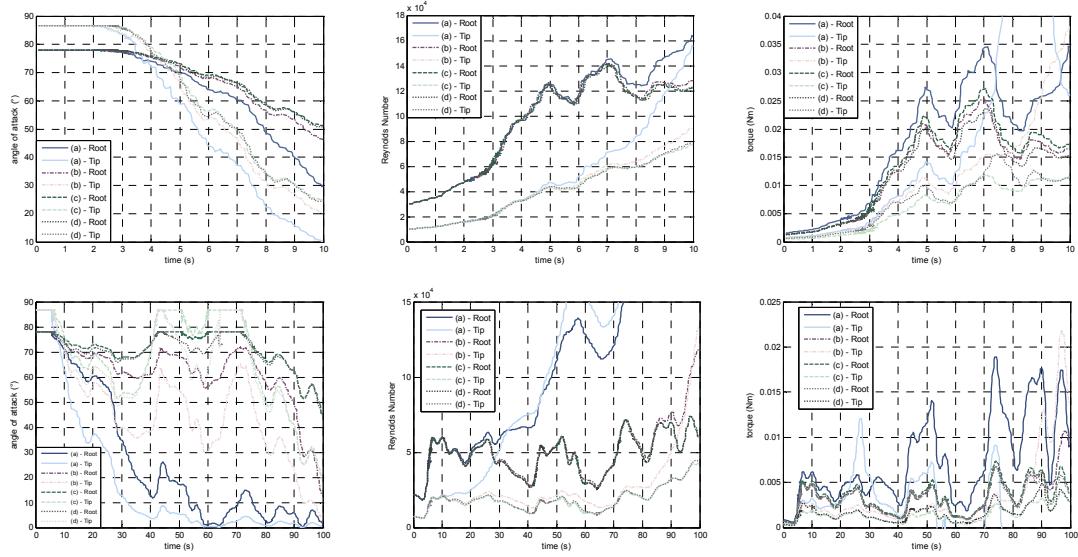


Figure 10.4 Aerodynamic characteristics during starting for the NC 600W turbine

The analysis of the high wind start sequence is very helpful for understanding starting behaviour of small wind turbines. The starting sequences and estimates (a), (b), (c) and (d) correspond to those presented in Chapter 9.

The first point to realise is the high angles of attack induced with starting. They are about 90° when the blade is stationary. Once rotation starts, due to twisted blade and low rotation speeds, the angle of attack is lower at the root for the very first seconds of the starting sequence. While for power production root performance has minor influence, at the 8th second, torques at root and tip have about equal values (estimate b). At that time, rotation speed varies from 100 to 160 rpm, i.e. about one half of the required rotation speed for producing power (268 rpm). At the 10th second, while power production is about to start, torque at root is still 44% of the tip torque value.

The same comments can be done for the low wind starting sequence.

Therefore root design is of major importance to improve self-starting performance of small wind turbines.

Another important aspect is the low Reynolds numbers occurring during starting sequences. At root, they do not exceed $2 \cdot 10^4$ when the blade just starts rotating and remains low all along the starting sequence. At the 10th second, Reynolds number at root is about $9 \cdot 10^4$, at tip it reaches about $16 \cdot 10^4$.

Estimating lift and drag coefficients at high angle of attacks and low Reynolds numbers is the main difficulty for simulating starting behaviour of self-starting SWTs. As presented in 1.4.2, four estimates are used and no one provides perfect results.

It appears that the *AR* effect must be taken into account when inputting measured C_L and C_D as shown by the very poor results provided by estimate (a). Then due to the close behaviour of any airfoils with flat plate for high angles of attack, using generic flat plate equations (estimate c) is tempting. However the simulation shows that those equations, which overweight drag at high α , generate lower rotation speeds than measurement values. Estimate (b) provides very good fitting. However the method used by Wright requires some accurate knowledge of the stall point to use the Viterna equations and furthermore some weighting between measurements and calculated C_L and C_D is implemented to fit the starting behaviour. It is therefore difficult to use this method when data are lacking or on the design step when no blade have been built yet.

To try to overcome the lack of replicability of estimate (b), a fourth estimate was developed. By using the Ostowari NACA4418 for $AR = 9$ at high α ($>60^\circ$), flat plate equations for $\alpha < 30^\circ$, and interpolating

between, some better results would be expected. But this is not the case. Even with good lift and drag fitting for high α , the inaccuracy for $20^\circ < \alpha < 60^\circ$ yields much lower rotation speeds than measurements. The absence of better results when using estimate (d) highlights the key-importance of accurate estimation of C_L and C_D for $20^\circ < \alpha < 60^\circ$. Indeed it is at those angles of attacks that the blade starts accelerating much. Between the 5th and 10th second, the angle of attack at tip varies from 65° to 20° (High wind sequence, estimate b); meanwhile torque at tip is multiplied by about 4. For estimate (c) and (d), torque at tip is almost stable along this period and much lower than the root value!

This importance of accurate C_L and C_D for $20^\circ < \alpha < 60^\circ$ is particularly obvious on the low wind speed starting sequence graph. At the 20th second, estimate (b), (c) and (d) provides close simulation results. At that time $\alpha = 57^\circ$ (b), $\alpha = 65^\circ$ (d), $\alpha = 69^\circ$ (c). Between the 20th and the 70th second, wind speed is oscillating between 2.4 and 5.5 m/s. While simulation (b) keeps some rotation speed yielding α varying between 30° and 65° , from $t = 30$ s simulation (c) and (d) starts decelerating and at $t = 42$ s, the rotor stops rotating. Even though the angle of attack for simulation (c) and (d) is around $50-55^\circ$ at the 30th second, drag/lift ratio is not high enough to make the rotor keep rotating.

A third point to note is the duration of a starting sequence. For high wind speed values, this is a little issue. But for low wind periods, the starting period can exceed a minute and requires sufficiently high wind speeds for such duration. Indeed even though the cut-in wind speed is about 2-3 m/s, the starting wind speed is often much higher (about 5-6 m/s). The low wind speed sequence shows that for the considered small wind turbine, three wind speed peaks above 6.6 m/s in 30 seconds are needed to generate sufficient torque and acceleration to start power production.

10.3. Conclusion on Newcastle 600W wind turbine performance

The 600W wind turbine designed at Newcastle University in Australia has very good power production and starting performance. From the theory for optimizing blade geometry for power production, chord has been enlarged to generate more torque.

In low wind sequence, generated torque is high enough to enable the turbine to start power production after an idling period of about 1min. In high wind, rotor acceleration is quick and power production starts after less than 20 seconds. The designed geometry provides excellent starting performance.

Regarding power production, the modified geometry has narrowed the λ corresponding to peak C_P and shifted it to lower values. $C_{P,MAX}$ (0.492) occurs at $\lambda = 7$. The most interesting point is that C_P has actually been increased thanks to those larger chord values. Pitching and yawing reduce those ideal values but are still at high level. Solidity has also increased with the chord but maximum value (0.23 at root radius) remains at acceptable level.

Observing operating characteristics shows that $C_{P,MAX}$ is reached at 8.8 m/s. C_P increases also continuously with the wind speed. Furthermore λ values are all around peak C_P : from 4 m/s, C_P is above 0.42. Operating characteristics are therefore close to optimum point for all wind speeds between 4 and 10 m/s. They denote very good complementarities between rotor design and generator characteristics.

To conclude Newcastle 600W wind turbine demonstrates that it is possible to design a small wind turbine with high power production and starting performance.

| | Airfoil | R_{tip} [m] | B | λ_d | V_d [m/s] | P_d [W] | Blade design | Pitch / Twist [°] | Yaw offset [°] | Generator | Daily Energy Output [Wh] | |
|---|------------|------------------|---|-------------|----------------|--------------|-----------------|----------------------|-------------------|-----------|-----------------------------|--------------|
| | | | | | | | | | | | Low wind | High wind |
| 1 | SD 7062 | 0.97 | 3 | 7 | 9 | 300 | NC | 0 | 0 | NC 600W | 1680 | 3692 |
| 2 | | | | | | | Theory | | | | 1567 | 3412 |
| 3 | | | | | | | NC | 5 | Model | | 1420 | 3127 |
| 4 | | | | | | | | | 0 | | 1509 | 3327 |
| 5 | | | | | | | | | Model | | 1281 | 2828 |

Table 10.1 Details of design 1-5

Though rated at only 300W (with peak power production at 600W), this turbine can provide about between 1281 and 1680 Wh/day in low wind regime (MWS = 3.5 m/s), corresponding to 64 to 84% of the energy needs of rural Kenyan school (2 kWh/day). In high wind regime, the turbine produces more than school energy needs. Even though using two NC 600W turbines would be an option to meet rural Kenya school energy needs, a better option would be to enlarge the turbine itself.

The next chapter will study in details the different effects induced with design criteria choices. It will notably enhance design suitability for meeting energy needs of a rural Kenyan school in low/moderate wind regimes.

Chapter 11: Analysis of design choice effects on SWT performance

Based on the background from the previous chapter, this part is focussing on analysing the consequences of design choices on small wind turbine performances.

For power performance evaluation, C_P curve is the first criterion used. Operating characteristics (rotation speed, λ) are also studied in order to evaluate rotor adequacy with generator characteristics. In order to assess design suitability for supplying a rural Kenyan school with electricity, the daily energy consumption is computed for the two 1min time series representing Kenyan high and low climates (4.3.2).

Concerning starting performance, the starting wind speed is computed and starting sequences are simulated for each design. In order to have comparable results, the generic flap plate equations (estimate c) are always used for calculating C_L and C_D during the starting period.

Some information about material economy is also provided. The reference is the NC 600W blade. Calculated blade mass excludes root part and mounting system. First radius for aerodynamic and mass calculations is 0.25m for all designs. For the NC 600W blade, total blade mass is 0.4 kg [6]. Mass computation gives: 0.215 kg (for the aerodynamic sections, radius = 0.25 to 0.97m), 0.120 kg for the rectangular root part; therefore 0.065 kg can be attributed to further mounting metallic equipment, which is a realistic value.

11.1. Considered designs

The design criteria, blade geometry and generator choices for the tested designs are presented in next table.

| | Airfoil | R _{tip} [m] | B | λ_d | V _d [m/s] | P _d [W] | Blade design | Pitch [°] | Yaw offset [°] | Generator | | | | | |
|----|---------|----------------------|---|-------------|----------------------|--------------------|--------------|-----------|----------------|-----------|--|--|--|--|--|
| 1 | SD 7062 | 0.97 | 3 | 7 | 9 | 300 | NC | 0 | 0 | NC 600W | | | | | |
| 2 | | | | | | | Theory | | | | | | | | |
| 3 | | | | 9 | 7 | | NC | | Model | | | | | | |
| 4 | | | | | | | | | | | | | | | |
| 5 | | | | 6 | 11 | | Theory | | 5 | | | | | | |
| 6 | | | | | | | | | | | | | | | |
| 7 | | | | 1.05 | 7 | | NC | | | | | | | | |
| 8 | | | | | | | | | | | | | | | |
| 9 | | | | 0.97 | 9 | | NC | | | WM 850W | | | | | |
| 10 | | | | | | | | | | | | | | | |
| 11 | | | | 1.5 | 7.5 | | NC | | | | | | | | |
| 12 | | | | | | | | | | | | | | | |
| 13 | | | | 1.6 | 7.85 | | Theory | | | | | | | | |
| 14 | | | | | | | | | | | | | | | |
| 15 | | | | 1.7 | 2 | 10.5 | 9 | 0 | | | | | | | |
| 16 | | | | 1.2 | 6 | 4.8 | 11 | | | | | | | | |
| 17 | | | | 1.2 | 6 | 4.25 | 9 | 600 | | | | | | | |
| | Airfoil | R _{tip} [m] | B | | V _d | P _d [W] | Blade design | Pitch [°] | Yaw | Generator | | | | | |

| | | | | λ_d | [m/s] | | | | offset [°] | |
|----|------------------------|-------|---|-------------|-------|-----|--------|---|------------|---------|
| 18 | SG 6043 | 0.97 | 3 | 7 | 9 | | Theory | 0 | | NC 600W |
| 19 | | 1.335 | | | | | | 5 | | |
| 20 | SG 6041 | 0.97 | 3 | 7 | 9 | 300 | Theory | 0 | | |
| 21 | | | | | | | | 5 | | |
| 22 | SG6040 | 0.97 | 3 | 7 | 9 | | Theory | 0 | | |
| 23 | | | | | | | | 5 | | |
| 24 | NACA 4412 | 0.97 | 3 | 7 | 9 | 300 | Theory | 0 | | |
| 25 | | | | | | | | 5 | | |
| 26 | Flat plate with camber | | 3 | 7 | 9 | | NC | 0 | | |
| 27 | | | | | | | | 5 | | |
| 28 | | | | | | | | | | |

Table 11.1 Details of tested designs

11.2. The effect of pitching

| | Design | 1 | 4 |
|-------------------------------------|-----------------------------------|----------|-----------|
| Power production (between 3-10 m/s) | C_p, MAX | 0.483 | 0.445 |
| | DEO low wind (% school need) | 84 | 75 |
| | DEO high wind (% school need) | 185 | 166 |
| Starting | U_s [m/s] | 13.4 | 6.0 |
| | Rot. Speed at sequence end [rpm] | Low wind | High wind |
| Material economy | Root-tip blade mass (% reference) | 100 | 100 |

Table 11.2 Effect of pitching summary

Design (1) has no pitched blades while design (4) blades are 5°-pitched.

Effect of pitching can be viewed on graphs 10.1 to 10.4. Pitching affects power production performances and energy production negatively but improves starting performance. Indeed it can be viewed on figure 10.3 that C_p has decreased by 0.1 to 0.13 for the considered wind speed range and daily energy output drops by 5.4 to 13%. However while design (1) has very poor starting performance, design (5) shows excellent rotation speeds at the end of the starting sequences.

11.3. The effect of yawing power regulation

| | Design | 4 | 5 |
|--|-----------------------------------|-----------|-------|
| Power production (between 3-10 m/s) | C_p, MAX | 0.445 | 0.364 |
| | DEO low wind (% school need) | 84 | 64 |
| | DEO high wind (% school need) | 185 | 141 |
| Starting | $U_s [\text{m/s}]$ | 6.0 | 6.0 |
| | Rot. Speed at sequence end [rpm] | Low wind | 125 |
| | | High wind | 204 |
| Material economy | Root-tip blade mass (% reference) | 100 | 100 |

Table 11.3 Effect of yawing power regulation summary

It is not surprising that yawing has major negative consequences on both power production and starting performance. Design (4) has no yaw offset while design (5) has a 20° yaw offset; both are 5°-pitched.

For the considered yaw offset, C_p drop between design (4) and (5) amounts to 0.05 to 0.08 from 3 to 10 m/s wind speed. Energy losses are very important and reach 24%. Starting performances are poorer but wind turbine still starts rotating even though the 20° yaw offset yields 6% reduction of the effective wind speed.

Following figures provides clear viewing of yaw offset effects on starting and power production performance of SWTs.

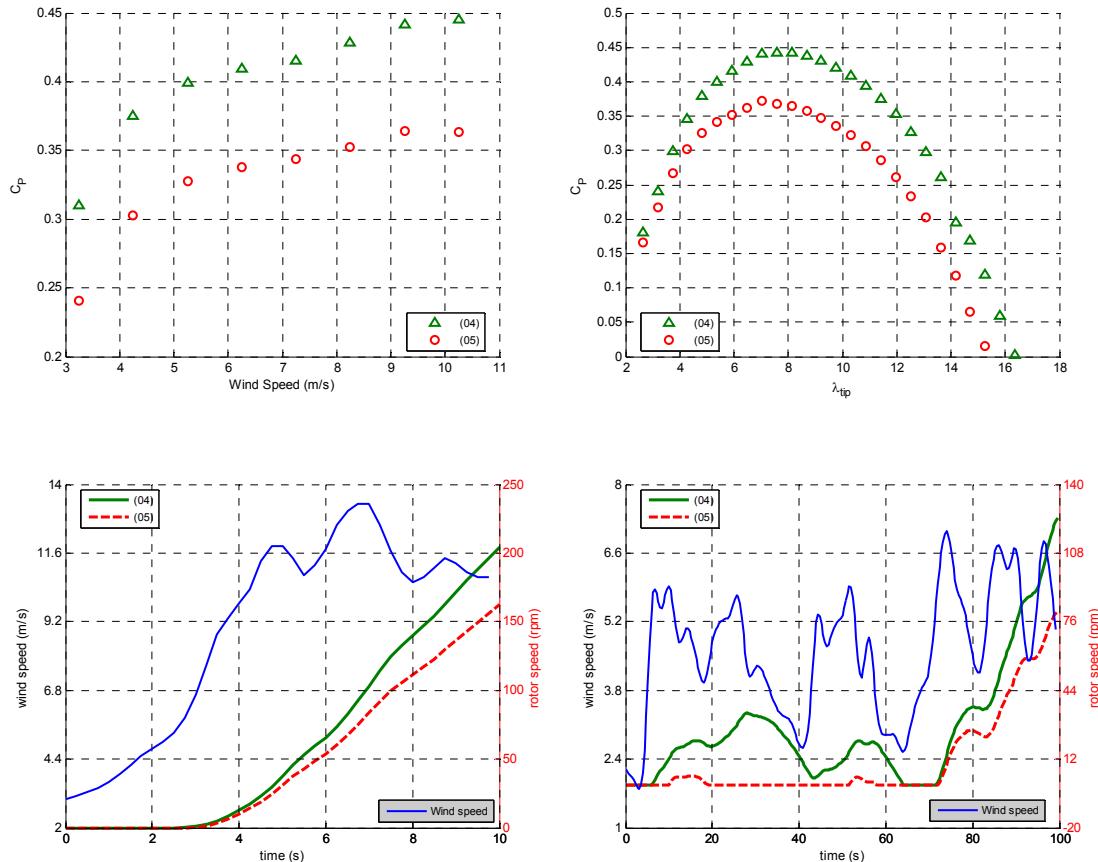


Figure 11.1 Yawing power regulation effects on power production and starting performance

11.4. The effect of changing the number of blades

| | Design | 13 | 14 | 15 | 16 | 17 |
|---|-------------------------------------|-----------|-------|-------|-------|-------|
| Power production (between 3-10 m/s) | C_p, MAX | 0.329 | 0.266 | 0.326 | 0.337 | 0.396 |
| | DEO low wind (% school need) | 162 | 135 | 106 | 109 | 128 |
| | DEO high wind (% school need) | 358 | 291 | 238 | 249 | 283 |
| Starting | U_s [m/s] | 3.2 | 4.4 | 3.12 | 2.67 | 3.42 |
| | Rot. Speed at sequence end [rpm] | Low wind | 52 | 19 | 369 | 327 |
| | | High wind | 103 | 33 | 201 | 177 |
| Material economy | Root-tip blade mass (% reference) | 151 | 140 | 88 | 130 | 130 |

Table 11.4 Effect of number of blades summary

Design (13) is a three bladed turbine, design (14) a two bladed turbine; design (15), (16) and (17) are 6 blades turbines. While λ_d is 4.8 for (15), it is 4.25 for (16) and (17). There is 0-pitching on design (17) blades while all other designs have pitched blades

Blade number should not have much influence on power production performance as long as the rotor design criteria match generator characteristics. As presented in 1.3.2, there is very little loss due to rotation for tip speed ratio above 6 compared to Glauert limit. The considered generator for design (13) to (17) is the Windmission PMG 850. This PMG operates at moderate rotation speeds: at 850W design power, the rotation speed is 430 rpm. Therefore keeping this ω_d implies targeting higher V_d . That is the main reason why the 2-bladed design (14) has lower power production performance for the considered wind regimes. Figure 11.3 shows clearly that design (14) does operate much below the optimum point between 3 and 10 m/s. Operating λ for design (14) comprises between 5.5 and 9, which are low value for 2-bladed turbines. 6-bladed designs (15-16-17) operate at λ comprised between 3.5 and 6.5 while 3-bladed designs (13-14) operate also at λ between 5.5 and 9. Those tip speed ratio ranges correspond exactly to peak C_p for the 6-bladed designs while it occurs a bit before the optimum point ($\lambda = 9$) for design (13) and much before for design (14) ($\lambda = 12.5$).

Increasing the number of blades does not affect either the theoretical optimum performance but move the optimum point towards lower λ_d . Low operating λ is therefore an advantage for the considered wind regimes and logically operating C_p are much higher for 6-blades wind turbines in low wind regimes. This is enhanced by the moderate rotating speed characteristics of the generator and the choice not to include a gear system between the rotor and the generator. The lower daily energy output for 6-bladed designs can be imputed to BEM convergence failure for wind speeds below 3.75 m/s. The only drawback of high blade number is the narrow λ range C_p is close to the optimum, and to some extend lower C_p .

Starting performance are also much improved with higher blade number. Indeed the generated torque is proportional to the blade number. Therefore it is easier to overcome the resisting torque with 6 rather than 3 blades. Furthermore, blade design optimization for power production, as presented in 1.3, will generate larger twist angles at root when increasing blade number (Appendix V). This yields high values for the chord-pitch integral close to the root which is an indication of good design for starting performance. Figure 11.2 shows that the 6bladed designs have much higher values for the chord-pitch integral.

With 6 blades, it is even not necessary anymore to pitch the blades for improving starting performance. Comparing design (17) and (13) shows that high blade number much improves starting in low wind regime while in high wind regime performance are similar.

It is a noticeable point that starting performance of designs (15), (16) and (17) are very good in low wind regime. Optimizing power production blade performance for 6-bladed turbines yields large chord length at the root, and therefore very high solidity. Those solidity values (above 0.5) can actually become a drawback for starting by attenuating the aerodynamic performance of the blades. No information is

available on this issue and measurement would be required to clarify its impact on starting of high blade number SWTs.

Concerning manufacturing economy, more numerous blades usually means higher rotor manufacturing cost. However material need is about the same between designs (13) and (15) since blade number is multiplied by 2 while single blade mass is divided by 1.7. Indeed to have sufficient power production while targeting similar V_d , it was required to reduce the rotor diameter.

Figure 11.2 Effects of the number of blades on the pitch-chord integral

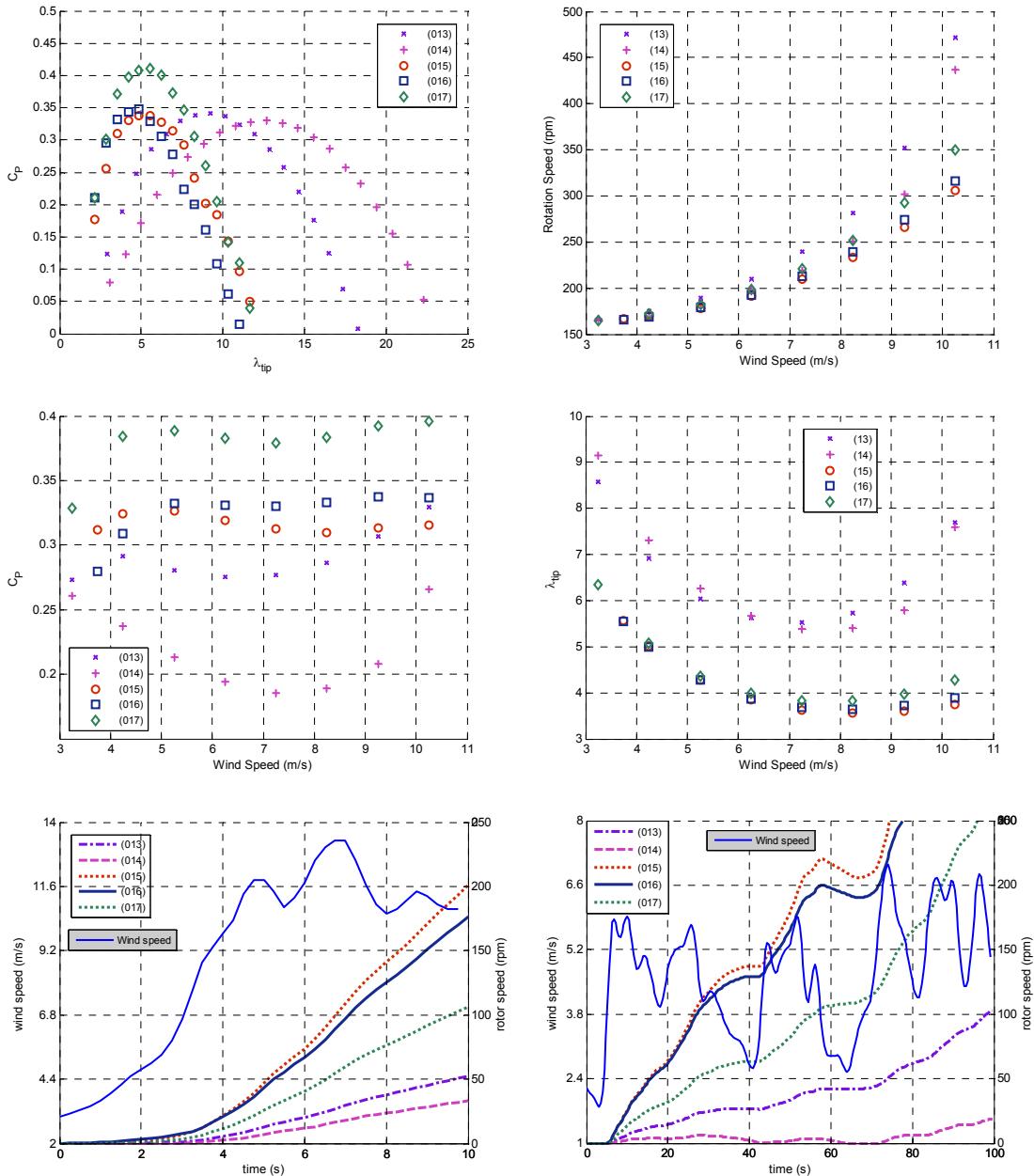


Figure 11.3 Effects of the number of blades on power production and starting performance

11.5. The effect of changing the airfoil

| | Design | 6 | 19 | 22 | 24 | 26 | 28 |
|---|-------------------------------------|-------|-------|-------|-------|-------|-------|
| Power production (between 3-10 m/s) | $C_{P,\text{MAX}}$ | 0.303 | 0.314 | 0.274 | 0.300 | 0.305 | 0.168 |
| | DEO low wind (% school need) | 58 | 57 | 49 | 52 | 57 | 33 |
| | DEO high wind (% school need) | 125 | 126 | 112 | 119 | 127 | 77 |
| Starting | U_S [m/s] | 6.9 | 7.8 | 4.1 | 7.8 | 5.3 | 6.4 |
| | Rot. Speed at sequence end [rpm] | 32 | 0 | 457 | 0 | 426 | 33 |
| Material economy | Root-tip blade mass (% reference) | 51 | 35 | 126 | 60 | 84 | 933 |

Table 11.5 Effect of changing the airfoil summary

All designs are based on theoretical optimum chord-twist distributions for power performance at $V_d = 9$ and $\lambda_d = 7$.

Apart from designs (22), (24) and (28), corresponding respectively to airfoil SG 6041, SG 6040 and flat plate with camber, the three other designs have very close energy production performance (design 6: SD7062, design 19: SG6043, design 26: NACA4412). However energy production is dependant to the considered wind climate. More accurate analysis is therefore necessary to classify them according to power production performance.

The C_P vs. λ_d curve clearly demonstrates that design (6), (19) and (24) have the highest power performance and corresponding λ range. SD7062 and SG6043 are known for their good performance at low Re and SG 6040 is a root airfoil, which is therefore also designed for low Re . The SG6041 (design 22), which is designed for $Re = 5e5$ has much poorer performance since given the wind turbine design criteria it never operates at its optimal point. The NACA 4412 (design 26) power performance is moderate with about 10% loss compared to SG6043.

The flat plate with camber airfoil (design 28) is very poor but the considered blade geometry is not the optimum one for this kind of airfoil which is more adapted for multi blade turbines (above 8 blades).

SG6041 (design 22) shows notably better starting performance but this only due to larger values for chord and twist distribution. Therefore design 22 mass is very high!

Same comments are also right for design (26). In high wind sequence, design 6, 19, 22 and 26 have good or very good starting performance. It is clear that given the design methodology (based on theoretical optimum for power performance), non-adapted designs to starting are likely. Therefore it is not surprising to observe that designs with low chord-twist integral (design 19, 22, 24, 28) have poor starting performance in low wind regime.

One would notice the very low relative mass of design (19). Design (28) has huge mass because of steel material.

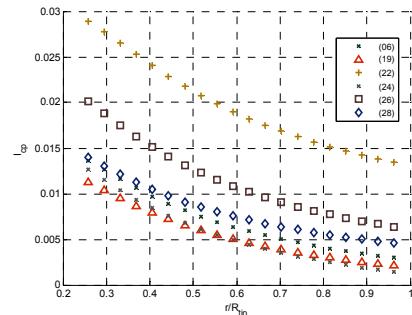


Figure 11.4 Effects of changing the airfoil on the pitch-chord integral

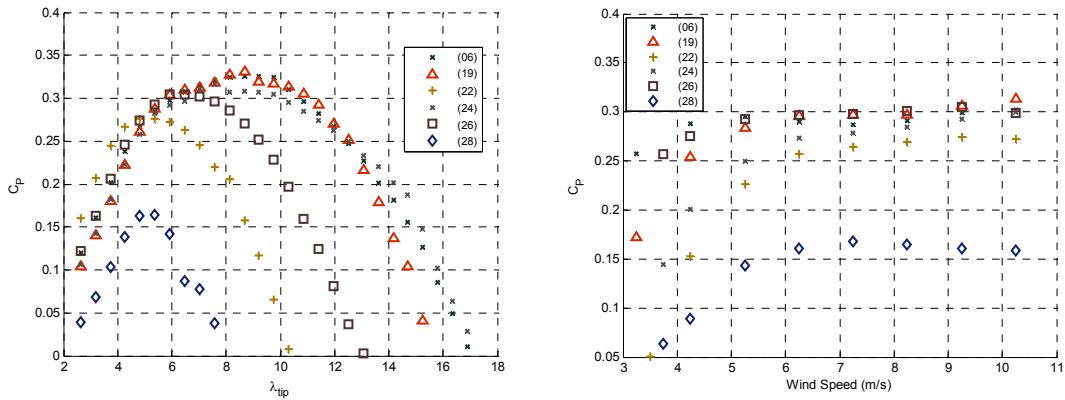


Figure 11.5 Effects of changing the airfoil on power production performance

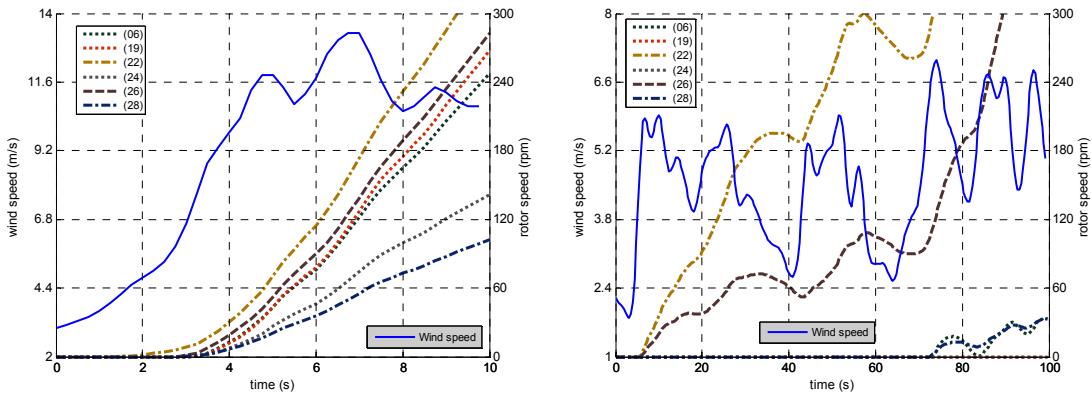


Figure 11.6 Effects of changing the airfoil on starting performance

11.6. The effect of increasing blade length

| | Design | | 5 | 9 | 12 | 13 | 19 | 20 |
|---|-------------------------------------|-----------|-------|-------|-------|-------|-------|-------|
| Power production (between 3-10 m/s) | C_p , MAX | | 0.364 | 0.372 | 0.308 | 0.329 | 0.314 | 0.329 |
| | DEO low wind (% school need) | | 64 | 73 | 141 | 162 | 57 | 88 |
| | DEO high wind (% school need) | | 141 | 163 | 309 | 358 | 126 | 210 |
| Starting | U_s [m/s] | | 6.0 | 5.6 | 3.5 | 3.2 | 7.8 | 3.3 |
| | Rot. Speed at sequence end [rpm] | Low wind | 81 | 69 | 119 | 88 | 0 | 317 |
| Material economy | | High wind | 162 | 129 | 63 | 173 | 268 | 115 |
| Root-tip blade mass (% reference) | | 100 | 96 | 148 | 151 | 35 | 100 | |

Table 11.6 Effect of increasing blade length summary

Increasing blade length enables to catch more power. Indeed wind power caught by the rotor varies with the square of rotor radius length. Therefore it is not surprising to observe higher energy production for design (9), (5) and (20) compared to respectively (5), (12) and (19). 8.2%, 6.7% and 37.6% blade length increases (from respectively (5) to (9), (12) to (13) and (19) to (20)) yields energy production increase of respectively 16%, 17% and 60%. It is an interesting feature when wind energy is lacking (during the low

wind season for example). Design (20) enables almost to meet electricity needs for a Kenyan rural school, even in low wind climate and with such a low rated generator (300W).

We can however observe that energy increase is about proportional to R_{tip} for the two former cases but not anymore for the latter. This is due to modification of operating points. Design (5) operates at tip speed ratios comprised between 6 and 9. Increasing blade length has yielded a modification of the operating points and design (9) operates at λ between 7 and 10. It can be viewed on the C_P vs. λ curve that design (9) really operates on the peak part of the curve where power efficiency is the highest while design (5) operates slightly before the peak. Therefore design (9) is more power efficient than design (5) from an aerodynamic point of view. The same comments are valid for design (12) and (13) but the effect is lower. For designs (19) and (20), the reverse effect occurs. While design (19) was operating on the peak part of the C_P curve, design (20) operates just after the peak. On an aerodynamic point of view, design (20) is less efficient; this is one reason why the energy increase is lower than the R_{tip} increase could let expect. The second reason comes from generator efficiency. While design (19) operates at moderate rotation speeds (300-650 rpm), design 20 rotation speed are as high as 950 rpm at 10.25 m/s. At those speeds, generator energy losses are higher and therefore the wind turbine becomes less efficient on a global energy conversion point of view.

Increasing R_{tip} makes the wind turbine operate at higher λ ; this can have a positive or negative impact depending on the original design. For designs (12) and (13) that are built from the same blade design methodology, effect is lower while it is higher between design (5) and (9); since design (5) was improved for starting performance, it has lost a bit of its power performance capacity. Increasing much R_{tip} as for design (20) can be an interesting method for securing power production in low wind climate. The only constraint is the connected blade cost increase since more material is needed. One would notice that even though blade (20) requires about 3 times more material than design (19), it does not require more material than design (5).

Concerning starting performance, increasing blade length has no positive effect for small blade length increase. It can even have some minor indirect negative effect if the new chord-twist distribution generates lower torque at the root sections. However design (20) shows excellent starting performance in low wind regime but moderate performance in high wind regime.

Design (20) is therefore very adapted to low wind climate. Increasing R_{tip} is a potential solution to improve starting performance that should be incorporated in the global power production/ starting performance optimization strategy.

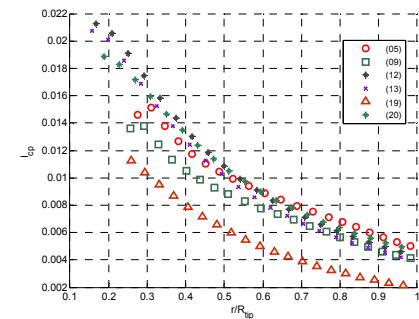


Figure 11.7 Effects of increasing blade length on the chord-pitch integral

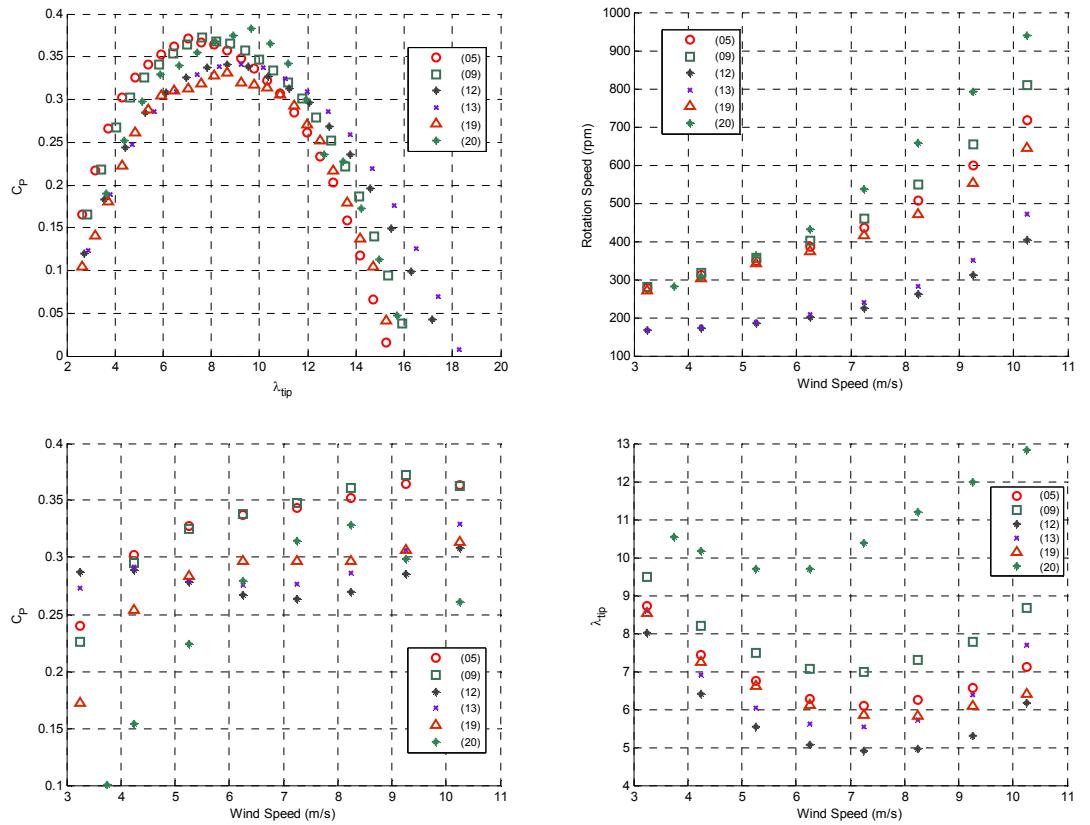


Figure 11.8 Effects of increasing blade length on power production performance

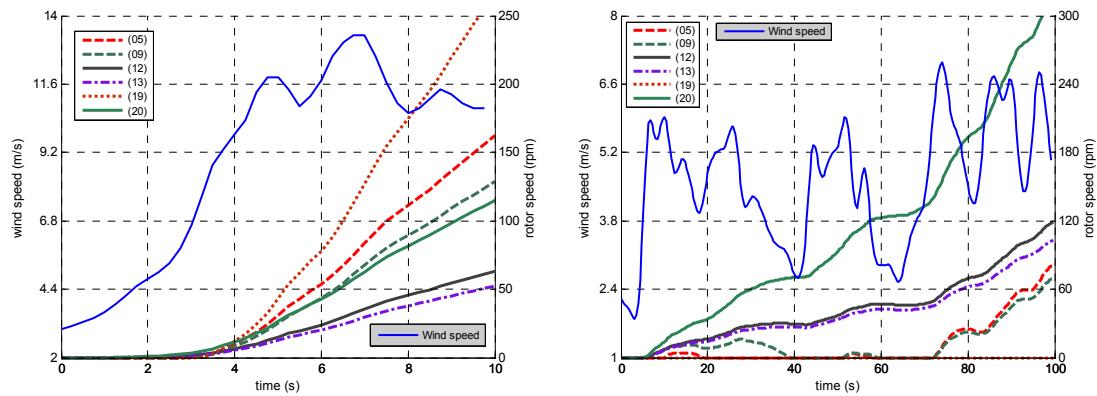


Figure 11.9 Effects of increasing blade length on starting performance

11.7. The effect of changing the generator

| | Design | 5 | 10 |
|--|-----------------------------------|-----------|---------|
| Power production (between 3-10 m/s) | C_p, MAX | 0.364 | 0.224 |
| | DEO low wind (% school need) | 64 | 41 |
| | DEO high wind (% school need) | 141 | 92 |
| Starting | $U_s [\text{m/s}]$ | | 6.0 7.7 |
| | Rot. Speed at sequence end [rpm] | Low wind | 81 0 |
| | | High wind | 162 133 |
| Material economy | Root-tip blade mass (% reference) | 100 | 100 |

Table 11.7 Effect of changing the generator summary

Blades for design (5) and (10) are identical but the rotor is connected to the NC PMG 600W for design (5) while design (10) rotor is connected to Windmission PMG 850W. WM PMG 850W is also suitable for being rated at 600W.

Comparing performance for designs (5) and (10) clearly shows that changing generator implies re-designing the blade. Furthermore operating characteristics for design (10) show very low λ (2-4) while design (5) operates at λ comprised between 6 and 9. Those low λ yields low C_p .

Given respective generator characteristics and assuming no gear system, it is more interesting to use the NC PMG 600W at higher rotation speeds than the WM 850W. This implies whether using blades designed for higher λ_d or targeting lower wind speed. The latter case might require reducing blade length for optimal performance at the given V_d . In the present case, blades for design (5) and (10) are identical. It means that they were designed for the same V_d and λ_d and considering connection to the NC PMG 600W. Therefore when connecting to a generator with different characteristics, power production performances are lower.

Regarding starting performance, the cogging torque of NC PMG 600W is 0.36 Nm while the WM 850W cogging torque is 0.6 Nm. Therefore starting performances are lower for the latter. It is even critical for low wind sequence since the non-adapted blades do not generate enough torque and rotor remains stationary.

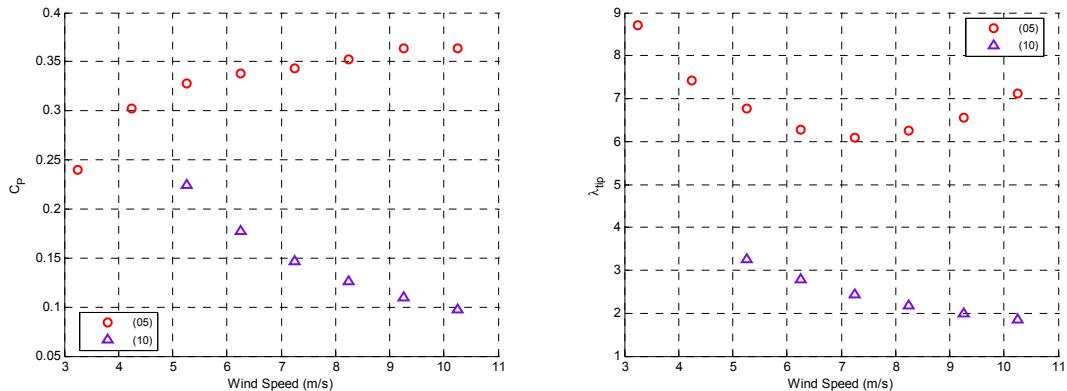


Figure 11.10 Effects of changing the generator on power production and starting performance

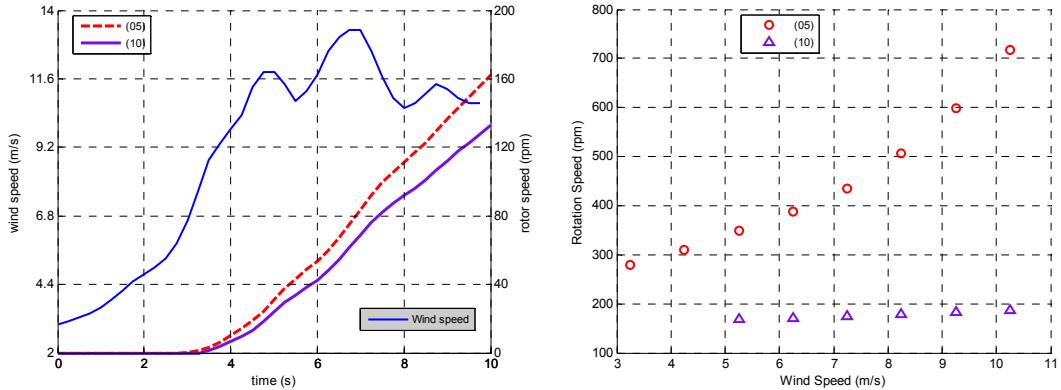


Figure 11.10 Effects of changing the generator on power production and starting performance (cont)

11.8. The effect of blade design method

Design (1) is based on Newcastle blade polynomial fitting while design (2) is generated from theoretical equations for power production optimum.

| | Design | 1 | 2 |
|---|-------------------------------------|-----------|-------|
| Power production (between 3-10 m/s) | C_p, MAX | 0.483 | 0.470 |
| | DEO low wind (% school need) | 84 | 78 |
| | DEO high wind (% school need) | 185 | 171 |
| Starting | U_s [m/s] | 13.4 | 14.2 |
| | Rot. Speed at sequence end [rpm] | Low wind | 81 |
| | | High wind | 29 |
| Material economy | Root-tip blade mass (% reference) | 100 | 51 |

Table 11.8 Effect of blade design method summary

Appendix V provides detailed twist and chord distributions. Power production performances are detailed on figure 10.3. One would notice the close twist distribution but higher chord lengths for design (1). Newcastle 600W blade is indeed 3cm larger than theory at root and 1cm at tip. This yields higher solidity which amounts to 0.23 at root. Design (1) maximum solidity is 0.19.

The optimum aerodynamic properties of design (2) are visible on figure 11.11. Indeed the angle of attack is almost constant along the blade length for every wind speed. At designed wind speed (9 m/s), it is even constant along the blade apart from the tip region and correspond to the maximum C_L/C_D ratio (figure 4.6). The optimum angle of attack is about 7.2° . It means that for every blade stations, the turbine operates at optimum C_L/C_D ratio. Operating Re are also more narrowed and comprised between $0.65 \cdot 10^5$ and $2.2 \cdot 10^5$. Torque distribution along the blade is smooth.

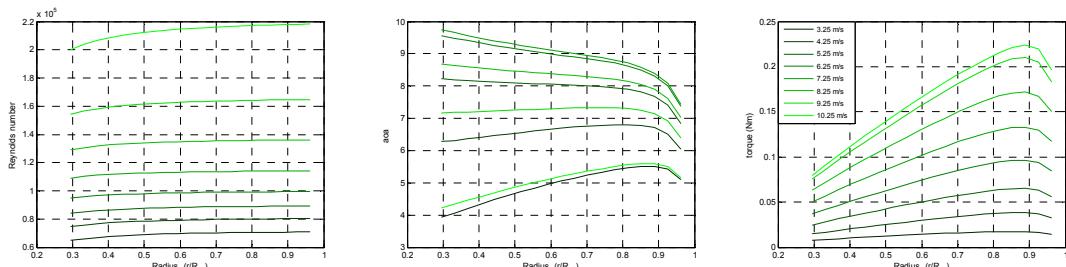


Figure 11.11 Aerodynamic characteristics during power production operation for design (2)

Regarding operating parameters, at V_d (9 m/s), the rotation speed is 644 rpm while the design value was 623 rpm and the tip speed ratio is 7.26 while $\lambda_d = 7$. It is due to the fact that actually

However it is striking to realise that C_p is higher for design (1). The larger chord enables to extract more power. Design (1) is therefore very well optimized for power production as well since operating λ matches the peak C_p . The λ range corresponding to peak C_p is however a bit narrow for design (1). When including yaw offset power regulation, the effective wind speed is reduced and the turbine operates at higher λ . That is the reason why design (9) has better power performance than design (5) which uses the same blade as (1) but pitched and operates with yaw offset. Increasing blade length for design (9) has moved the operating tip speed ratios towards optimum values.

The larger chord generates more torque and starting performance are also better for design (1). The higher values for the chord-pitch integral traduce the better starting performance for design (1). It also enhanced that blade optimization for starting sequence is a different job than optimizing for power production performance. Design (1) and the derived version (5) show that it is possible to conciliate high power production performance and high starting performance.

But this larger chord generates blade mass increase. Design (2) blade mass is only 51% of design (1). Design (20), which is based on the theoretical optimum power performance equations, has targeted blade length increase to reach the same mass as the reference. Comparing design (20) and (5) shows that actually increasing blade length is also an interesting strategy for blade optimization for dual power production and starting performance. Design (20) generates much more power than design (5) while starting performance in low wind sequence is also better.

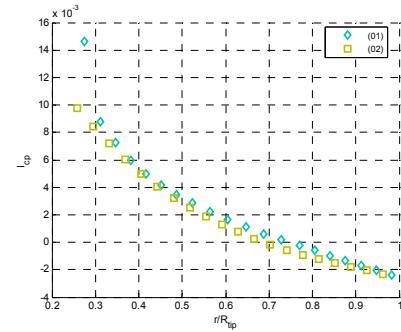


Figure 11.12 Effects of the blade design method on the chord-pitch integral

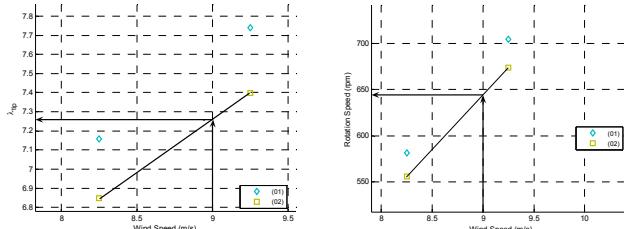


Figure 11.13 Comparison of design criteria with simulation outputs for design (2)

11.9. The effect of changing the design criteria

| | Design | | 6 | 7 | 8 |
|--|-----------------------------------|-----------|-------|-------|-------|
| Power production (between 3-10 m/s) | C_p, MAX | | 0.303 | 0.286 | 0.327 |
| | DEO low wind (% school need) | | 58 | 50 | 59 |
| | DEO high wind (% school need) | | 125 | 104 | 130 |
| Starting | U_s [m/s] | | 6.9 | 11.3 | 4.85 |
| | Rot. Speed at sequence end [rpm] | Low wind | 33 | 0 | 467 |
| | | High wind | 248 | 114 | 258 |
| Material economy | Root-tip blade mass (% reference) | | 51 | 19 | 108 |

Table 11.10 Effect of changing the design criteria summary

Design (6), (7) and (8) are produced from the theoretical equations for optimum power production for respectively $\lambda_d = 7, 9$ and 6. All designs target $P_d = 300W = 300W$. Blade length is the same and set to 0.97m. V_d are therefore respectively 9 m/s (design 6), 7 m/s (design 7) and 11 m/s (design 8).

One could be surprised by the higher energy production for design (6) and (8) which have higher V_d . Indeed design (7) operates below C_P peak due to too low operating $\lambda = 5\text{-}9$ while $\lambda_{opt} = 11$. Designs (6) and (8) operate closer to λ_{opt} .

Therefore selecting design criteria should really consider generator characteristics and interaction with rotor characteristics as a critical issue. The key step is to check that the power available at V_d is bigger than the input power required by the generator at ω_d . For the present case, designs (7) and (8) were built for $\omega_d = 65 \text{ rad/s}$ (623 rpm) corresponding to $P_{gen,out} = 300\text{W}$ and $P_{gen,in} = 550\text{W}$. At 7 m/s with $C_P = 0.4$, the maximum power that can be extracted for the given rotor radius is : 240W, at 9 m/s it reaches 509W and at 11 m/s 929W. Therefore the generator for design (6) and (7) will operate below the design point since not enough wind power will be provided by the rotor. Design (8) will operate above the design power since the latter was much below the Betz limit at V_d . Obvious evidence that design (7) does not fit generator characteristics is that actually C_P decreases when wind speed increases.

When increasing λ_d , the right strategy is to increase rotor radius rather than decreasing V_d . It enables to catch more power and therefore operates at the optimum point. It can be an interesting economic strategy for power production as described previously with design (14) (2 blades, $\lambda_d = 10.5$, $V_d = 9$ m/s).

Low λ_d is also an advantage for starting performance since during the idling period λ varies from 0 to a value close to λ_d . It explains why blade geometry for design (8) has much better starting performance than design (6) and why design (7) stays stationary all along the low wind starting sequence. Design (8) has indeed much larger chord and twist values as its chord-pitch integral.

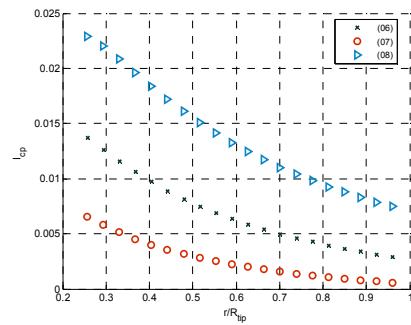


Figure 11.14 Effects of the changing the design criteria on the chord-pitch integral

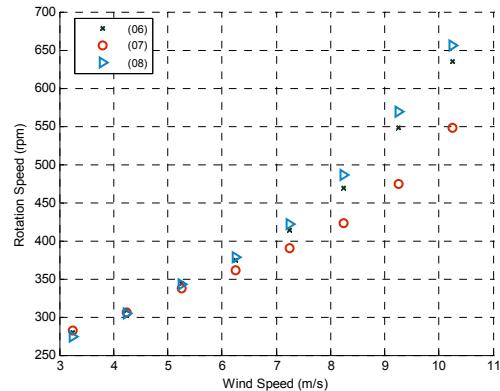
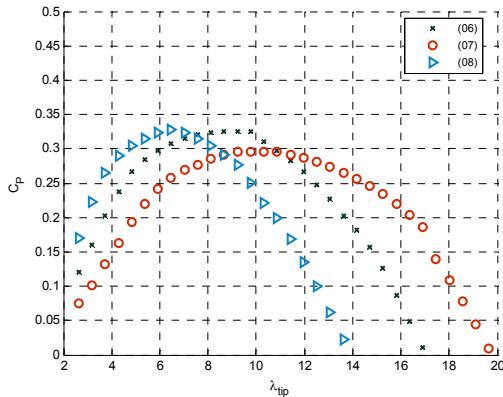


Figure 11.15 Effects of changing the design criteria on power production and starting performance

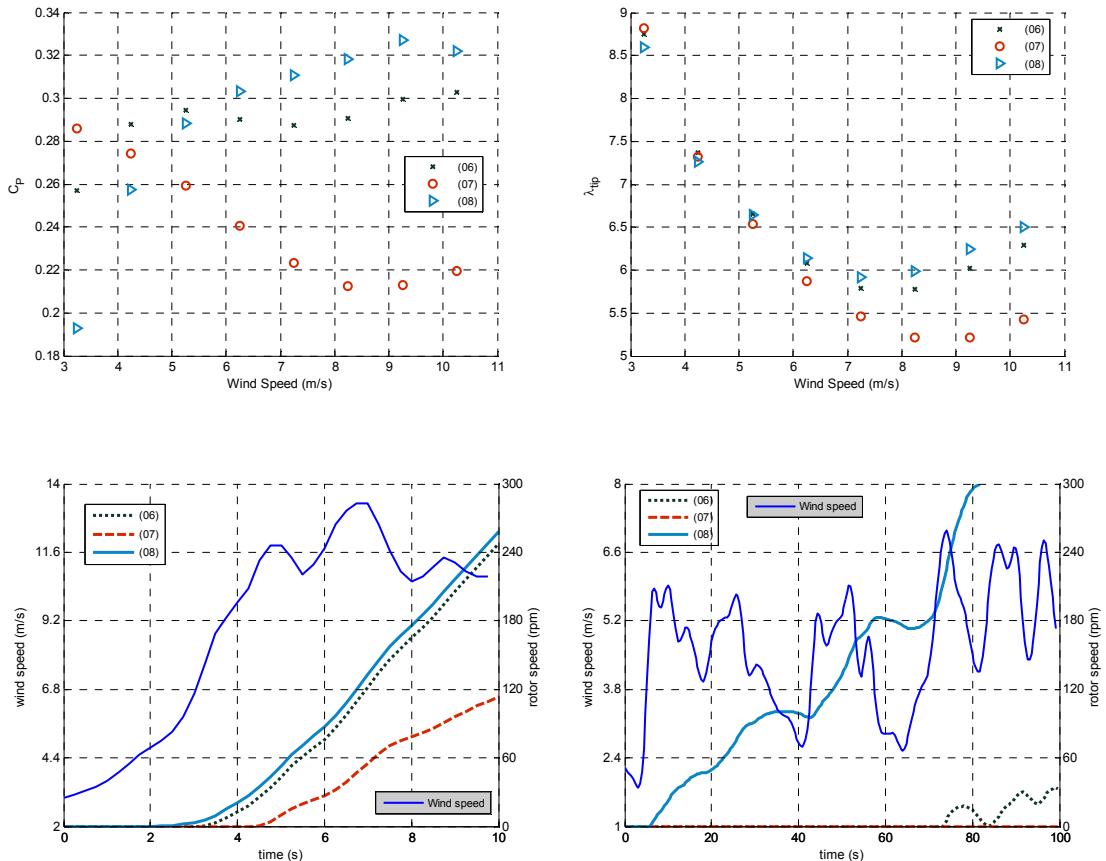


Figure 11.15 Effects of changing the design criteria on power production and starting performance (cont)

11.10. Design suitability for electricity provision in rural Kenya

All designs using the Newcastle 600W generator have not met the requirement of supplying 2kWh/day in low wind climate. Designs 11 to 17 using the Windmission 850W generator have successfully met the requirement.

Given that the Newcastle 600W has been rated to 300W (at 9 m/s), power production performance of design 1 to 4, 9, 18 and 20 are very interesting. Those very small wind generator designs are indeed capable to meet already 70% of Kenyan school energy needs in low wind season, while it produces much more than needed during the high wind season. In the same condition, inputting the power curve of the 1.5 kW Qindgdao wind turbine into the low wind time series would yield an daily energy output of 5065 Wh/day and in the high wind time series an DEO of 11248 Wh/day. At 9 m/s the Qindgdao wind turbine produces 1100 W and its C_P is 0.32. Design (5) C_P is 0.37 at 9 m/s. From a power production point of view, the wind turbine installed in Esilanke has good power performance, but its design is not as efficient as Newcastle's design.

Designs (9) and (20) where R_{tip} has been increased (and therefore blades are oversized for the considered generator) shows energy output very close to 2 kWh/day.

Using a higher rate generator, as the WM PMG 850W, enables to meet the rural Kenyan school energy need in low wind climate.

It is therefore clear that small wind turbines are very interesting options for rural electrification in Kenya. Provided suitable generator rating, they meet the basic energy need for rural school, even in low wind period. It is also very interesting to note that very small wind turbines ($P_r = 300W$) are close to this objective. If such a turbine would be too small for developing income generating activities with school electrification projects, they could be an economically attractive option for rural households.

Chapter 12: Proposed guidelines for designing and manufacturing small wind turbines adapted to operation in Kenyan wind climates

12.1. Key points about SWT design

Pitching the blades

- Concerning starting performance, pitching the blades is a helpful option for turbine with low blade number (below 3). 2- and 3-bladed wind turbines designed for sole optimal power production performance have poor starting performance. Pitching the blades enables to decrease the angle of attack during the idling period when rotation speed is low; therefore the lower angle of attack gets closer to the optimum C_L/C_D point and more torque is created.
- The disadvantage of pitching is that it applies on the whole blade length and at any wind speed. Therefore it also affects power production situation.
- From a blade designed for optimal power production, 5°-pitching will reduce energy production by about 10%. This is due to the reduction of the angle of attack which goes below the optimum C_L/C_D point.

Yawing power regulation

- Depending on whether yawing power regulation is cumulated with pitching, 20°-yaw offset generates 0.05 to 0.08 C_P decrease. In low and medium wind regime (as presented here with the Kenyan wind speed time series), energy production will decrease by 20 to 25%.
- Starting performance are also affected by yawing offset since the incoming wind velocity decreases with $\cos(\gamma)$ and consequently the generated torque is much affected.
- For micro wind turbines yawing power regulation is the most realistic way for ensuring safe power production. Therefore it is advisable to integrate this parameter early in the design process.
- Increasing R_{tip} is one solution to counteract the negative effect of yaw offset.

Blade number

- In theory blade number affects power performance little provided the λ_d is sufficiently high ($>5-6$). However given the target low and moderate wind resource and the constraint of direct driven generator, this theoretical fact should be mitigated.
- Concerning starting, since rotor torque is proportional to blade number, the higher blade number, the higher torque, and the easier to overcome the generator-drive train resistive torque.
- 2-bladed SWTs have optimal performance at high tip speed ratios (above 10). Given generator rotation speed characteristics, such λ might be difficult to achieve at low wind speeds unless increasing blade length dramatically. Regarding starting, 2-bladed turbines have the poorest performance unless blade design is much modified from the original optimum design for power production. The economic advantage is the reduced blade manufacturing cost.

- 3-bladed turbines appear to be an interesting compromise between the economic advantage of low blade number and high starting and power production performance for the considered wind climate condition and direct-driven generator constraint. Indeed λ_{opt} is about 7 and meets very well PMG rotation speed at the target moderate wind speeds. Therefore as Newcastle 600W turbine example shows, 3-bladed SWT can operate very close to the Betz limit as early as 4 m/s. Starting performances are also very good for 3-bladed turbine provided some design optimization is effectuated. Chord increase is an interesting strategy that enables to keep C_P high while increasing the generated torque notably. Pitching, or at least higher twist at root sections, is needed to accelerate starting.
- 6-bladed turbines operate at low λ (around 4). It is an interesting feature for low wind climate. To get optimal power production performance, those turbines also require connection to low/moderate speed generators unless R_{tip} is reduced. Some PMGs are suitable for that requirement. Their main advantage is about starting. Indeed 6-bladed turbines generate enough torque so that pitching is not necessary anymore (and therefore power production is improved). They have excellent starting performance in low wind starting sequences due to high chord and twist values. However it also implies high solidity at root which could actually become a handicap for starting due to aerodynamic performance reduction. Very little information is available about this issue. Another handicap of high bladed turbines concerns the economic viability of SWTs inducing high material cost due to many blades to manufacture for a single item.
- Generator characteristics and wind regime target plays a key role to determine the suitable number of blades.

Airfoil

- The choice of the airfoil is very important for power production and starting performance, but also because it will directly affect the mass of the blade.
- SD7062, SG 6043 and SG 6040 have the highest power production performance: with no pitch nor yaw offset $C_{P,MAX}$ is above 0.49. Furthermore given the induced operating Re (0.5 to 3.10^5), those airfoils are very suitable. NACA 4412 shows a $C_{P,MAX}$ 10% below SG 6043. SG 6041, designed for $Re = 5.10^5$, has moderate power performance due to too low operating λ . Logically flat plate with camber has the poorest power production performances: $C_{P,MAX}$ reaches 0.35 with no pitch nor yaw offset, i.e. 30% less than modern airfoil designed for low Re .
- SG 6043 has the big advantage to produce much lighter blades designed for optimal power production performance: 30% lighter than SD 7062 and 42% than SG 6043. It should be highlighted that SG 6043 is thick airfoil designed for root sections; therefore it is not surprising that mass increases.
- Given that all the designs originated from theory for optimal power production, the ones with larger chords present the best starting performances (NACA 4412 and SG 6041). However remembering the low mass of SD7062, SG 6043 and SG 6040, optimization for starting (by increasing slightly chord lengths and twist at root) would much improve their starting performance while keeping power performance very high for a minimum mass. Such methodology was developed with success at Newcastle University with the SD 7062 for the NC 600W wind turbine.

Blade length

- Increasing blade length enables to catch more power; since the turbine is connected to a PMG, it will work at higher rotation speed and therefore at higher λ .
- The effect on power production performance is ambivalent. This operating λ increase might yield operation beyond the C_P point, and therefore lower operating C_P . But on an energy production perspective, the impact will be positive since more wind power is caught. It simply means that the wind/electricity energy conversion is qualitatively less efficient but quantitatively higher.

- Lower energy conversion efficiency is enhanced by the risk to move to the very high speed part of the generator curve where energy losses are huge (above 40%).
- Therefore this energy conversion dissymmetry between efficiency and quantity will often yield lower energy output than R_{tip} increase could let expect.
- Concerning starting, increasing R_{tip} by a small amount (~10%) has no effect. Large increase (30%) induces much better starting performance, especially for low wind starting sequences. Indeed optimum design for power performance generates higher chord length when R_{tip} increases. Furthermore the radius of the first aerodynamic section can be closer to the hub in normalized length.
- The suitability of R_{tip} increasing option will much depend on the energy output gain vs. material cost increase.

Generator

- Permanent Magnet Generators have the interesting characteristics to be variable speed generators. This asset enables to design SWTs that operates at maximum C_P for a large wind speed range as shown with the Newcastle 600W turbine which operates at C_P above 0.4 from 4 m/s to 10 m/s (no pitch, no yaw offset).
- The direct drive constraint imposes that blade number and R_{tip} should be defined together with the generator.
- Targeting low wind/moderate climate can be a limiting factor if generator characteristics require oversized blades for catching enough wind power. Therefore the design wind speed V_d should also be associated with generator choice P_d determination.
- Energy conversion losses are particularly high for PMGs. Therefore oversizing rotors requires considering PMGs losses at high rotation speed.
- Cogging torque is a key parameter for starting. Provided modern PMGs and suitable rotor designs, SWTs have good starting performance with PMGs.

Blade design methodology

- Though power production and starting performance looks antagonist objectives, it is possible to design small wind turbines that met those two objectives.
- The theoretical equations for optimum power production provide a good first design. To improve starting performance, increasing chord length and keeping the same twist distribution is an interesting strategy. As shown with Newcastle 600W turbine, C_P is above 0.49 at λ_d .
- Whatever the strategy chosen (increasing R_{tip} , chord lengths or blade number), optimization for starting implies rotor mass increase.
- Considering yaw power regulation from the beginning of wind turbine design is an important matter for the optimization of power production operation. Indeed yaw offset reduces the effective incoming wind velocity and therefore SWTs operates at lower λ .

Design criteria

- The design tip speed ratio λ_d is the key parameter for designing blades. It is closely connected to the design wind speed V_d and the design rotation speed ω_d . Therefore determining the target wind climate and generator characteristics is required prior to calculate λ_d .
- An important calculation when selecting the right V_d , ω_d , P_d , R_{tip} combination is to check that enough wind power is available at the design wind speed to meet the input power required by the generator.

- With high λ_d (above 6), blade design will need to be altered from the geometry provided by the theoretical equations for optimum power production. Indeed this latter design has very poor starting performance when inputting high λ_d .
- Conversely low λ_d shows better starting performance because either larger chord is generated by the theoretical equations for optimum power production or because blade number becomes higher. Therefore those designs require less alteration from the theoretical geometry for optimal power production.
- When increasing/decreasing λ_d , the turbine designer should keep vigilant about the selected R_{tip} , ω_d combination. For example, decreasing λ_d in order to be more efficient in low/moderate wind regimes might induce reducing R_{tip} and ω_d quite importantly in order to operate at optimum aerodynamic characteristics. The necessity to have lower R_{tip} is enhanced by the minimum rotation speed (about 10 rad/s) required by PMGs to start power production. The resistive torque to overcome at starting will limit this R_{tip} diminution.

12.2. Proposed guidelines

12.2.1. Objectives to achieve

Objectives are threefold:

- meeting rural electricity needs so that productive uses of electricity can be enhanced by wind rural electrification project
- designing robust system that need little maintenance
- promoting local skills and equipment.

The first objective implies high performance in low/moderate wind regimes, excellent starting behaviour and high efficient blades. The second objective suggests that the right balance between advanced and simple equipment should be determined. It especially concerns how to regulate power production with respect of wind speed increase and therefore guarantee safety and long system lifetime. In remote areas detecting early disoperation is a key to prevent expensive maintenance job. Therefore simple remote control system could be an attractive option. The last objective is inherent to develop sustainable projects. It is indeed crucial that developing small wind energy in Kenya is accompanied by technology transfer and capacity building so that local stakeholders can ensure project sustainability themselves and make the market for small wind energy systems grow up.

12.2.2. Useful small wind turbine sizes for rural electrification in Kenya

Wind turbines from 300W to 20kW are all potentially interesting. Wind turbines rated below 500W should be dedicated quasi-exclusively to household electricity supply since such turbines would just produce enough power for the basic electric needs of rural institutions like school and therefore connecting productive uses of electricity would be limited. For households, 500W would be a big power amount and could allow a few households to access electricity. Small business shops could also be interested in such an energy amount as well. 500W to 2kW wind turbines would meet the electricity needs of institutions, small business shops and small settlements. From 2kW, projects promoting productive use of electricity can be developed. From 5kW stimulating rural economy is a realistic objective. Farming and agro-processing activities, small industries, service business can be modernised or developed. Beyond 5kW, developing mini grid or incorporating small wind turbines in existing isolated grids would become an option inducing

much environmental, social and economical benefits. It should especially focus the existing isolated grids relying on diesel generators.

12.2.3. Adapting Kenyan small wind energy system technology

Kijito windpumps are multi bladed machines (16 to 24 blades). Such a large blade number is not compatible with direct driven generator constraint. Indeed rotation speed does not exceed 60rpm in normal operating conditions. It would therefore require a gear system. There are two main options for adapting windpumps to power generation: whether developing dual windpump-power generation operation (in parallel or in series) or modifying the design to produce solely electricity.



Some windpump experiences in South Africa have shown that windpumping and power generation could be developed on the same machine. The Turbex Wind Turbine uses the rotary principle to pump water instead of the traditional reciprocating (up-and-down) pumping method. A PMG is installed at mid tower. Southern Cross has developed a windpump-mini-hydro power generation system for their windpumps installed on hilly places: the windpump pumps the water up to a reservoir on the top of a hill. The water can then run down and pass through a micro-turbine downhill. The water can then whether be tapped and used or is pumped back up to the reservoir again. On an efficiency point of view, it is not sure that dual systems in parallel lead to dual optimal operating. It would be very interesting to simulate the performance of those dual systems.

Kijito windpumps use the reciprocating system for pumping water. Therefore using the Turbex methodology would require redesigning the pumping system. Furthermore Turbex technology is patented. Southern Cross option is a much more feasible option. It only requires a micro hydro turbine and some control system to regulate water flow. It is also patented.

However as shown in this study flat plate with camber airfoil has low aerodynamic performance, about 30% below the modern airfoil designs for low Re . Developing dual windpump-power generation operation is interesting for Kenya since BHEL has already all the necessary engineering, manufacturing, operating skills and experience. The windpumping-power generation series option is the more realistic.

Figure 12.1 Turbex dual windpump/power generation technology

Regarding adapting the Kijito windpumps for sole power generation, there are a few major challenges that make this enterprise quite risky. Indeed mechanical constraint could not enable fast rotation speed. This point should be investigated in details to determine which rotation speed can be allowed for cambered steel plate. A gear system would probably be anyway necessary, except maybe if blade number is no larger than 8. The connected constraint is the cost of material with such a high blade number.

The accumulation of lower power production, much material required and bigger technical complexity make this option relatively disadvantageous even though investing costs would be minimized since equipment and skills are already available in Kenya. The competition with low cost, good performance 3-bladed Chinese items would be tough.

To conclude about adapting Kenyan small wind energy system technology, it would be advantageous for BHEL to provide power generation together with windpumping. The parallel operation option is the most technically realistic. From a market point of view, it has the advantage to provide two services in one system. Water is a key need in rural Africa. Global warming could make it worse. Therefore wind energy system package capable to secure water supply would have a key asset. The economy of this option should be more investigated.

12.2.4. Material selection, power equipment supply and local manufacturing

The Craftskills experience shows that manufacturing 3-bladed turbines using composite material and permanent magnet generators is a feasible option. BHEL experience that system reliability can be achieved provided suitable design.

Craftskills is suffering from their low manufacturing equipment. Their reliability of their wind turbines is an issue. Furthermore manufacturing PMGs and electronic control systems as few units is very costly. It is definitively very hard to compete with Chinese systems. Craftskills' experience regarding power generation is an asset.

The manufacturing equipment at BHEL workshop enables to do all steel job: manufacturing towers, nacelle casing and other steel parts. They also have a huge experience of wind energy projects in all East Africa. Therefore BHEL and Craftskills have quite remarkable complementary skills. There would be much mutual benefits to join more closely their effort for developing small wind energy system market in Kenya as the project of Kenyan Wind Industry Committee with the Kenyan Renewable Energy Association has initiated.

Modern blade design should be selected and SG series airfoils are the most suitable. The choice of the material will have much impact on manufacturing process and required investment to upgrade BHEL's workshop.

The first point to investigate is whether some suitable wood is available in Kenya. Craftskills started originally manufacturing wood blades but they used low quality wood and therefore it led to low blade quality and performance as rotor were unbalanced. Craftskills is using now fibreglass.

Using composite material would be an attractive solution. There are some companies in Nairobi specialized in composite material job who have long experience with composite material manufacturing. Therefore manufacturing blades with composite material could be whether done in BHEL's workshop or subcontracted if a company is interested in such a partnership. Equipment investment would be needed. In the case of subcontracting, investment could be limited to blade moulds while BHEL's option would imply some workshop upgrade. Working with composite material could be health harmful if no proper working conditions are guaranteed. Therefore this safe working condition issue should be considered in the investment.

12.2.6. Design criteria

As already presented there is much advantage to go to modern blade design. SG series airfoils provide very interesting characteristics for high power production and starting performances in low/moderate wind climates.

The number of blades should be 2, 3 or 6. Generator characteristics, target wind resource and manufacturing economy would define the most economic blade number.

Setting design wind speed V_d to 9 is very relevant for low/moderate wind climates. It means that at 9 m/s the turbine is the most power efficient (highest C_P). If other wind climates are also targeted (for example the high wind resource of Northern Kenya, Somaliland and Ethiopia), then it would be necessary to determine the right compromise.

Setting design wind speed λ_d to 7 is adequate for 3-bladed wind turbines; 6-bladed λ_d should be around 4 and 6-bladed λ_d around 11.

Direct driven generator is suitable below 2kW, further size should investigate induction generator. As consequence of generator size and characteristics, control regulation should be added for generator above 5kW; this would also facilitate connection with existing diesel generators. Indeed hybrid wind-diesel systems constitute a large market in Africa.

Yawing power regulation is required for small wind turbines.

12.2.7. Strategy recommendations

Enhancing market potential and manufacturing cost optimization when selection SWT sizes

In order to meet rural household, institutions and economic stakeholder market segments, it is proposed to focus on three ranges of small wind turbines: <500W, 1-2kW and about 5kW.

The lowest wind turbine would be rated below 500W and dedicated to households and small business shops. The second size should be ranged between 1 and 2kW and would target rural institutions, small farmers, industries and shop-power centres and micro-grid. The biggest one would be around 5kW and dedicated to mini-grid and hybrid wind-diesel applications. It would target especially high energy consumers of rural areas such as agro-processing industries, tourist business... If larger sizes are considered, it is likely that 20kW would be the lowest interesting size due to market potential and required synergies with 5kW turbines. Indeed 5 and 10kW would compete on the same mini-grid and small hybrid wind-diesel market segments while 20kW wind turbines enable to develop small wind farms of 100 to 200 kW at a lower cost.

Taking advantage of wind energy Kenyan skills and experience to build an ambitious project

The respective 30 year BHEL's experience in windpumping and 10 years CraftsSkills experience in small wind generators are great assets for developing a sustainable future for small wind energy systems in Kenya. Joining their effort would reinforce the technological strength and economic viability of such a project.

Kenyan research university sector and energy consultant should be associated to this project. Linking with public research is a key for the sustainability of Kenyan wind industry growth. The Kenyan universities have already got involved in wind energy projects and such public-private partnerships should be enhanced.

Developing partnerships abroad with experienced wind energy stakeholders

For the parts where local manufacturing is not the most economic option (generator, electronic control system), partnership with China's stakeholders would enable to develop cheaper and better quality systems. Furthermore partnership with a wind industry player from a developed country would be mutually beneficial since they would access a new large market while the Kenyan wind industry would get new capacities. It would clearly be a major step forward that would strengthen the technological sustainability of the project.

Regarding R&D, collaboration with experienced universities from developed countries would be the opportunity to enlarge wind energy expertise capacity building to other Kenyan energy stakeholders like Universities, energy consultants or NGOs.

Promoting wind energy solution in Kenya and developing supply chain

Promoting wind energy solution in a key of a sustainable market growth of small wind energy systems in Kenya.

Wind energy solutions are still widely unknown in rural Kenya. Policy makers, financing and co-operation institutions are also not really aware of the potential for wind rural electrification and windpumping potential in Africa. Lobbying should be accompanied with the improvement about wind resource knowledge in order to achieve promote the emergence of accurate and coherent renewable energy policy in rural areas.

Sustainability will mainly depend on the capacity to manage locally most of wind rural electrification project. Developing supply chain and expertise network in all target areas of Kenya would reduce project costs while reinforcing technical sustainability.

Project Evaluation

Chapter 13: Study limitations, lessons learned and future projects

13.1. Study limitations

Collecting data inputs has been the main issue for this project. This project has been developed with the Kenyan windpump manufacturer Bobs Harries Engineering Ltd. Therefore it did not aim at testing a small wind turbine at the Technical University of Denmark but try to collect as much data as possible in Kenya towards the large expansion of small wind turbine projects there.

Esilanke project has enabled to collect valuable information about the socio-economical, financial and technical viability of wind rural electrification projects. This project has been a very positive point of the whole Master Thesis project. The following points would enable a more comprehensive understanding of the interest for developing wind-based rural electrification in Kenya.

- This analysis is based on a single project and therefore it would be interesting to face the present conclusion with the evaluation of other wind-based rural electrification projects; many case study opportunities exist in Kenya.
- Regarding the answers to questionnaire, results are coherent with energy and socio-economic situation in rural Kenya. About financial situation of Esilanke communities, families reported difficulty to answer that point due to seasonal income variation. Its linkage with financing small wind turbine project should be studied more in details.
- Investigating the water situation in Esilanke community was done thanks to the information provided by Mr. Samuel Njanka who was in charge of collecting it. Therefore no verification has been undertaken. His information was coherent. However it would be interesting to assess families' water situation directly.
- The analysis provided in this study about water pumping and mobile battery charging income generating activities is the minimal linkage that could be developed between wind-based rural electrification and productive uses of electricity; according to local socio-economic situation there are many other opportunities in rural Kenya. Due to very poor economic situation, Esilanke community case was quite restricting on that aspect. Therefore further investigations should be carried out to identify all the potential for linking wind-based rural electrification and productive uses of electricity.

The lack of measurement concerning small wind turbine behaviour and performance has generated some issues to overcome. Fortunately much information was available from the research work that has been done for more than 10 years at Newcastle University in Australia to develop high performance SWTs. Those have been the inputs used to validate the present project simulations.

However the following issues must be considered when using the simulation results.

- Modelling starting performance requires information about C_L and C_D at very low Re ($1-5 \cdot 10^4$). Measurements at such low Re are very rare. The methodology used by Wright in his PhD thesis combines theory with adjusting and guess work for the considered blade and operating conditions.

It is therefore difficult to apply it to other airfoils without measurements. Therefore generic flat plate equations have been used to determine C_L and C_D during the starting sequences.

- It is difficult to find aerodynamic data for flat plate with camber. Two sources were found and both of them has yielded difficulty to simulate windpump performance with very high number of blades (rotation speed range where calculation is feasible is very narrow). However results are in accordance with windpump theoretical performance.
- Even though blade inertia was calculated accurately, the calculation of the total rotor inertia was extrapolated from the ratio blade inertia/rotor inertia for Newcastle 600W turbine. This ratio might change notably from turbine to turbine, especially when blade number changes.
- Yaw aerodynamic behaviour is complex. It was out of the scope of this study to model it. Furthermore 1-D BEM methodology is not suitable. Therefore the yaw offset (20°) reported for the Newcastle NC 600W wind turbine has been inputted. Using the same offset has facilitated comparison. However yaw behaviour is a key for power production (reduction) and safety of small wind turbines, therefore it would be interesting to improve the knowledge about this phenomenon.
- The effect of high solidity at root section might reduce the expected aerodynamic properties due to separation delay and lift and drag altering. Unfortunately Wood reports that there is no available information on finite solidity at high α .
- For comparison purposes, the same material as the Newcastle 600W blades were used (Pine wood). For the flat plate airfoils, steel has been inputted to get close to Kijito windpump blade design. However it is not sure that pine wood would be the best option in Kenya. Further investigation (Glass Reinforced Plastic) would be required. Blade mass and therefore material choice is indeed a key input for starting performance.
- Load computation is a key step for ensuring small wind turbine safety. The IEC 61400-2 standard provides some background about it. Calculations have been performed within the present study and met Newcastle's results. Unfortunately time has lacked to proceed calculation and analysis for the other designs presented in this study.

13.2. Lessons learned

Wind-based rural electrification in Kenya and beyond

- Using small wind turbines is a feasible option for rural electrification in Kenya. There are no technological barriers but local wind energy expertise and capacities should be strengthened. Small wind turbines fit rural energy needs from households to rural institutions and small industries; even large energy consumers like tourist business would benefit from this new decentralised power generation option.
- There are large market prospect in Kenya and beyond. Indeed suitable areas of Kenya for wind-based rural electrification projects are the North, the coast and the highlands. In Tanzania, Ethiopia, Somaliland, Eritrea, South Africa... prospects are also big.
- The involvement of Esilanke community to manage the project and make it sustainable has been very encouraging. There is a big local will to get involved, understand, participate in management and generate incomes from electricity supply. Their responsibility, demonstrated with community's willingness to pay and create the conditions of financial viability, has been remarkable. Their ability to technically manage the system has demonstrated the technical viability of small wind turbine electrification project in remote areas. Technical sustainability should however be reinforced with the development of SWT expertise network and supply chain throughout Kenya.
- From a rural development point of view, the main benefits are: improved studying, living and health standards, productive uses of electricity and new income potentialities. Furthermore wind-based electrification projects could impact positively water supply securing, security and communications and would reduce the polluting emissions due to current fossil energy-based lighting.

Kenyan wind industry growth

- The growth of Kenyan wind industry could bring some valuable benefits for Kenya's development. From an industrial point of view, Kenyan wind industry is a country's asset that should be promoted. By targeting the rural electrification market, the Kenyan wind industry and rural development process could enter a phase of growing synergies.
- However the situation should be improved before synergies occur between Kenyan wind industry growth and rural development. Indeed wind energy solutions are insufficiently known in rural Kenya, among policy makers, cooperation and financial institutions. The Kenyan wind industry needs also to get stronger by developing strategic partnerships in Kenya and beyond.
- The suitable technical options are dictated by commercial prospects and competition environment. 300W to 5kW wind turbines have big market prospects targeting individual customers, rural institutions, small business and industries, farming and tourist activities and village mini-grid. For such projects, configuration would be either wind battery charging or hybrid wind-diesel.
- Partnerships with China generator and electronic control system manufacturers would reduce manufacturing cost and improve SWT reliability. Partnership with a developed country's SWT manufacturer would be a complementary advantage.

SWT design

- High power production and starting performance in low/moderate wind regime is a key for technically sustainable systems.
- Altering the geometry from optimal design for power production to improve starting performance does not necessarily reduce power efficiency during operation: high power production and starting performance are not antagonist objectives.
- Increasing chord length distribution, R_{tip} or blade number are interesting strategies. Generator characteristics are key inputs. Pitching much improves starting performance but reduces wind energy extraction efficiency.
- Concerning the design of a modern small wind turbine, 2 to 6 bladed rotors would be the most adapted configuration for the target low/moderate wind climate. Manufacturing cost and generator choice would define the most suitable blade number.
- Even though yawing power regulation yields power production reduction, it is the most adapted option to secure high wind operation.
- Adapting Kenyan small wind energy systems is an interesting option if the designed product has some comparative assets with respect to competitors. Therefore dual water supply-power production with Kijito windpumps is an attractive challenge. Series configuration for water pumping and power production is the most feasible option. Adapting Kijito windpumps for sole power production induces more technical/economic constraints than benefits.

13.3. Future projects

Concerning wind energy development in Kenya, the future projects should enhance:

- Develop environment impact model of wind-based rural electrification.
- Set up strategic Kenyan wind industry development plan including accurate project economics estimate, supply chain and partnership in Kenya and beyond, and the identification of capacity building needs.
- Develop District wind maps for the target areas (Northern Kenya, highlands, coast)
- Promote wind energy solutions within the target areas and among policy makers, cooperation and financial institutions. It implies coherent national rural electrification policy, suitable legal and regulatory frameworks for decentralised electrification, support to Kenyan wind energy industry

and R&D, SWT standards and financing facilities available to rural individual customers and communities that wish to invest in SWTs.

Concerning research work for the development of SWTs adapted to operating in African wind climate, the following projects are suggested:

- Assess Kenyan small wind energy systems performances (field measurements, evaluation of dual windpumping-power generation suitability).
- Develop an SWT design optimization model.
- Develop maintenance strategies for SWTs operation in remote areas where technical expertise is lacking; this includes the study of potentiality for SWTs performance monitoring in order to detect early disoperation.

Regarding the development of a SWT design optimization tool model, some economy inputs and realistic load model are required. A constraint on minimum power production efficiency (C_P) should be applied. The optimization should target a specific energy output and minimum starting period in a given wind climate. The parameters to play with are B , R_{root} , R_{hub} , R_{tip} , chord and twist distribution, airfoils, material. The question of whether the optimization should occur for a specific generator should be investigated. The optimization should allow inputting several airfoils along the blade (one specially designed for the root and another one for the tip for example, and between interpolating). The codes developed in this project could be used as objective subroutine for the optimization process.

An optimization code has been built at the end of this present project with maximizing C_P and minimizing U_S as objectives. Only twist and chord distribution could be optimized. It has given some interesting results but time has lacked to go further.

Conclusion

This final project of wind energy Master's studies at the Technical University of Denmark has been carried out in partnership with the Kenyan windpump manufacturer Bobs Harries Engineering Ltd. The main objective was to analyse the suitability of small wind turbines for decentralised electrification project in rural Kenya. Field works in Kenya have focussed on collecting information and developing the suitable conditions for sustainable development of small wind energy activities. The periods in Denmark have focussed on the design of SWTs adapted to operating in Kenyan wind climate conditions.

The study of the pilot project carried out at Esilanke primary school by the B2B partnership between the Danish wind energy consultant KenTec and the Kenyan company Windgen has much contributed to clarify the technical sustainability, financial viability and socio-economic impacts of wind-based rural electrification projects.

It can now be stated that Small Wind Turbines are suitable technology for decentralised electrification in Kenya.

Esilanke case study has confirmed the extremely high cost of energy paid by Kenyan households. In this poor community located 1hour away from Nairobi, households pay in average KSh 3519/month. According to information reported by families, the energy expenditures represent in average 50% of households' monthly income. Those energy sources: kerosene lamps, charcoal, wood or cow dung for heating and cooking, dry cell batteries for radios, are inefficient and source of major indoor air pollution and health hazard. Fossil energy uses that could be substituted with wind electric energy represent 43% of the monthly energy expenditures. Therefore the installation of the 1.5kW Qingdao wind turbine has been much welcomed by the community. The installation occurred in March 2007 and project assessment occurred in August 2007. Five month after installation, the capabilities of school staff to manage the project and involvement of the community was remarkable. March's training had been very well assimilated by the school staff: Teacher Kenneth Gitonga, in charge of power supply management, has an accurate understanding of wind power generation operation, can identify each components and carries out everyday monitoring. All school staff is very well aware of the necessity to manage their energy consumption due to wind dependency constraint. The community has also decided to finance morning/evening classes with KSh 10/pupil/month. The collected amount is dedicated to system maintenance. Furthermore mobile battery charging is now available at the school for KSh 20. This income generating activity is a great success: the first month has enabled to collect more money than needed for next battery distilled water changing. The involvement of the Kenyan windpump manufacturer Bobs Harries Engineering Ltd for system installation and project follow-up has been a key for guaranteeing sustainability.

Regarding the economical and financial issues, Esilanke project was funded by the Danish International Development Agency, DANIDA. Therefore the community did not pay for the system and has only to cover the O&M costs. For a sustainable development of small wind turbine market in Kenya, it is a key that such projects are affordable even for poor rural communities. Based on Esilanke inputs, five scenarios were built. It turns to be that wind-based rural electrification projects become financially feasible when engineering, installation and O&M are fully available locally and projects take advantage of community's

service needs to generate incomes. Provided all those conditions are met, wind-based decentralised electrification project can be highly economically and socially beneficial. However the high investment cost required by 1.5kW wind turbines is the main issue for poor rural communities. While wind-based decentralised project can be much profitable, there is the need to work with financing institutions to facilitate wind system investments.

Regarding the design of small wind turbines adapted to operation in Kenyan wind climate, the main project conclusion is that high power production and starting performance can be met in low/moderate wind regime.

As guidelines, meeting rural electricity needs so that productive uses of electricity can be enhanced by wind rural electrification project, designing robust system that need little maintenance, promoting local skills and equipment should be the core ideas of any project for designing of small wind turbines adapted to operation in rural Africa.

Regarding designing strategy, from the optimal design for power production, some adjustments would be needed to improve starting performance. One important conclusion is that high power production and starting performances are not antagonist objectives: increasing chord length distribution, R_{tip} or blade number are interesting strategies to meet those both objectives. Adjusting root design is decisive. The project enhances that the generator choice is a key step in the SWT design process.

Furthermore three and six bladed rotors would be the most adapted configurations for the target low/moderate wind climate given the constraint of direct driven connection to permanent magnet generator. SG series airfoils provide very interesting characteristics for high power production and starting performances in low/moderate wind climates. Yawing is the best power regulation option for small wind turbines (<5kW) in order to ensure safe operation even though it yields up to 25% power production reduction.

About design parameters, setting design wind speed V_d to 9 is very relevant for low/moderate wind climates. Setting design wind speed λ_d to 7 is adequate for 3-bladed wind turbines; 6-bladed λ_d should be around 4.

A well-designed 300W wind turbine can already provide 60% of basic rural Kenyan school electricity needs (2kWh/day) in low wind climate, and up to 90% if the rotor is oversized for the given generator. In high wind climate, the wind turbine would produce much more than the basic needs. A small wind turbine rated at 600W at 9m/s provides 130% of rural Kenyan school electricity needs in low wind climate.

Finally to achieve a sustainable development of small wind energy in Kenya, the project enhances four points. First environment impact model of wind-based rural electrification should be developed in order to promote the usefulness of such solutions for counteracting global warming effect. Second, the Kenyan wind industry has to set up some strategic development plan, targeting especially the development of supply chain and partnership in Kenya and beyond, and the identification of capacity building needs. Third, regional wind maps for the target areas (Northern Kenya, highlands, the coast) are needed to facilitate local business development. Fourth, wind energy solutions should be promoted within the target areas and among policy makers, cooperation and financial institutions in order to reach a coherent growth of small wind energy with the National rural electrification and energy strategies.

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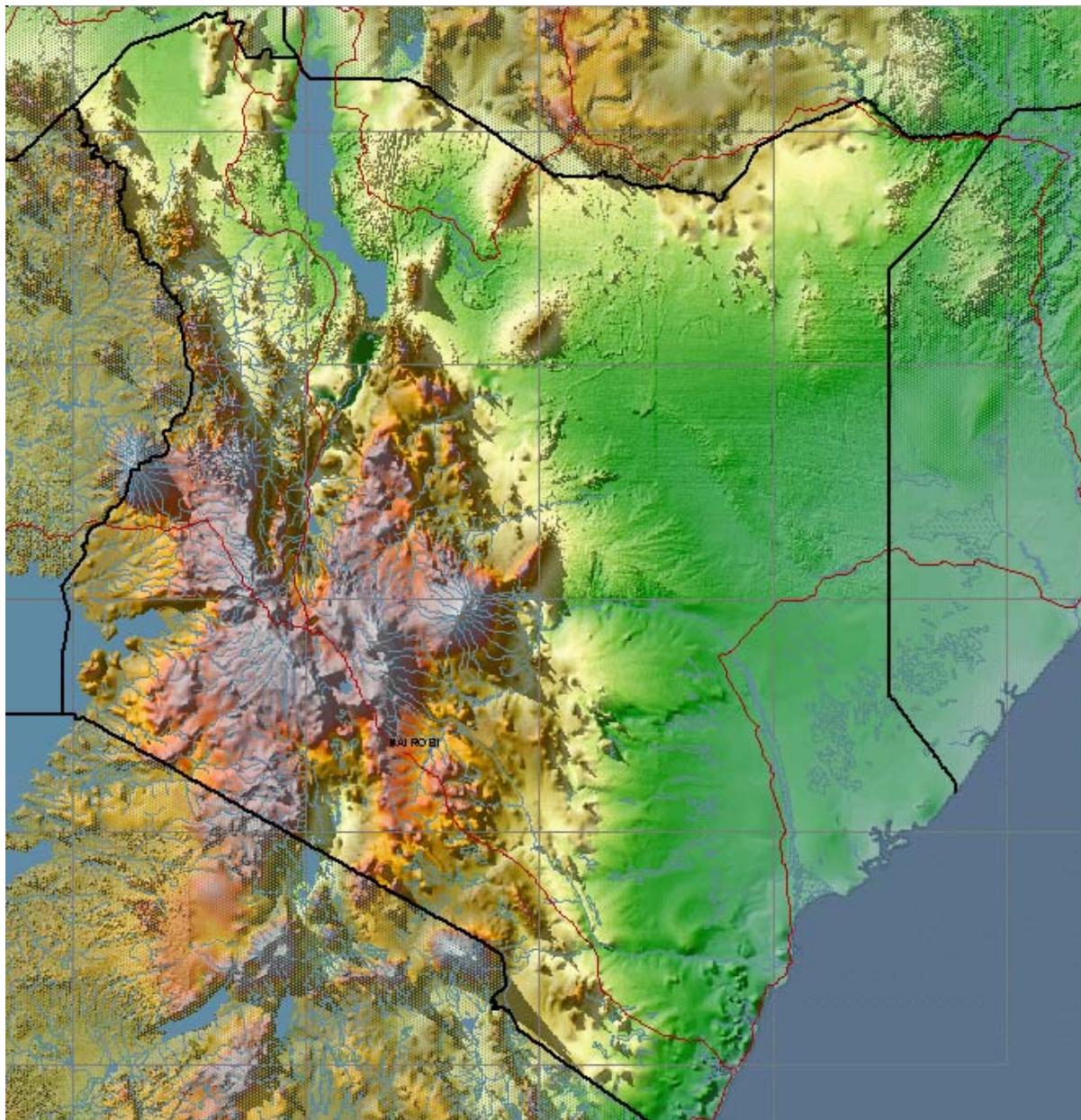
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Appendices

Appendix I: map of Kenya



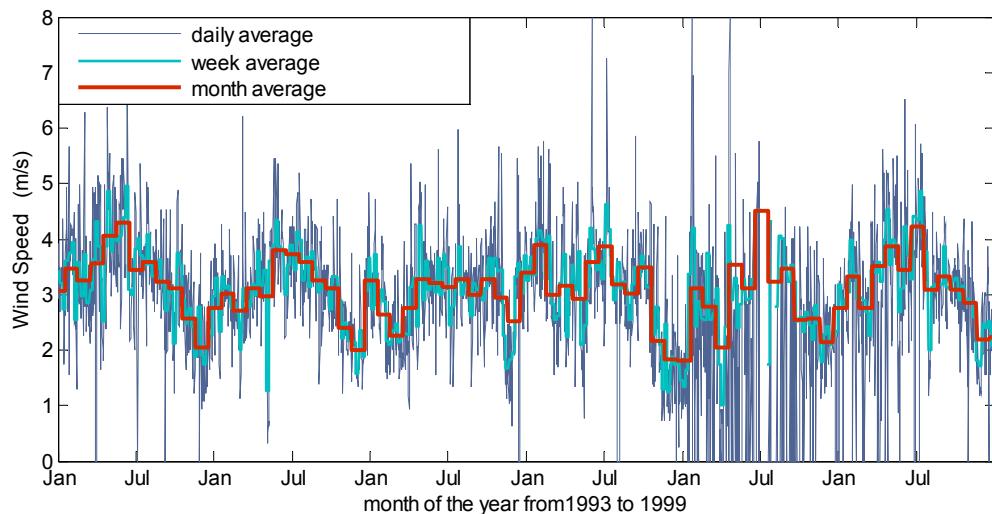
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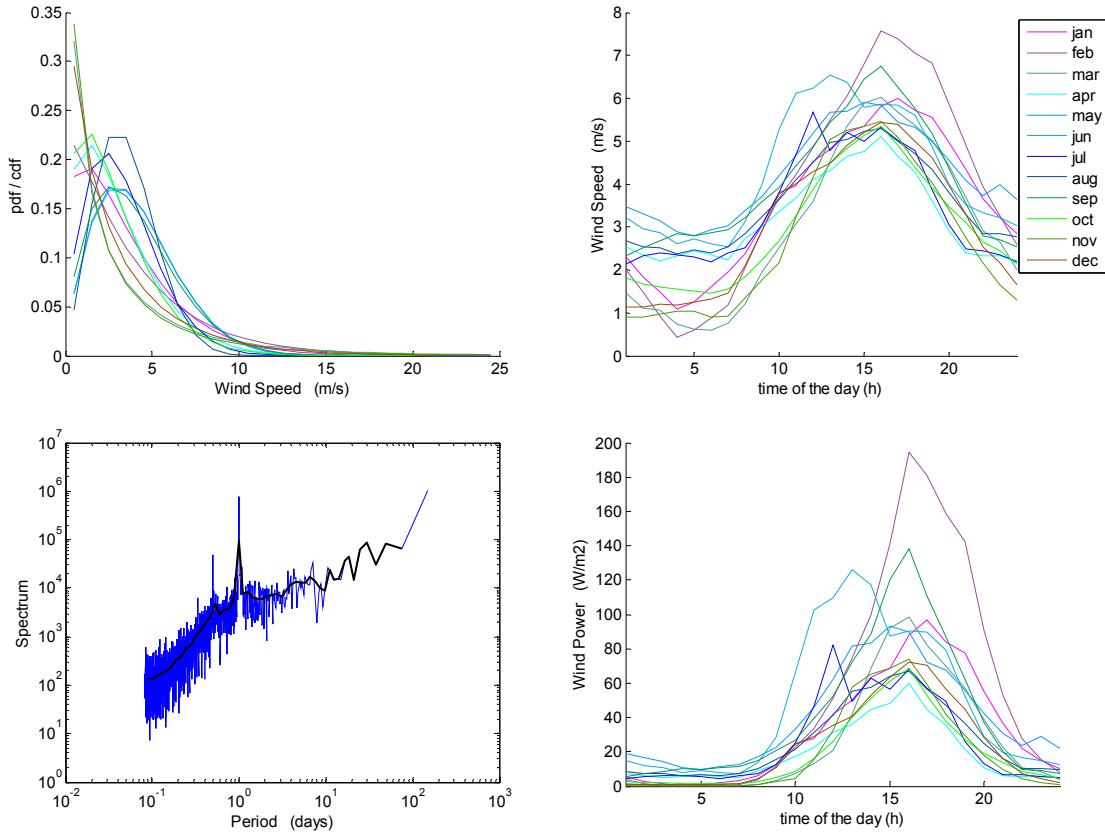
Appendix II: wind climates of Kenya

Some Kenyan wind climates and their characteristics

Wind climate along the coast (Mombasa data)

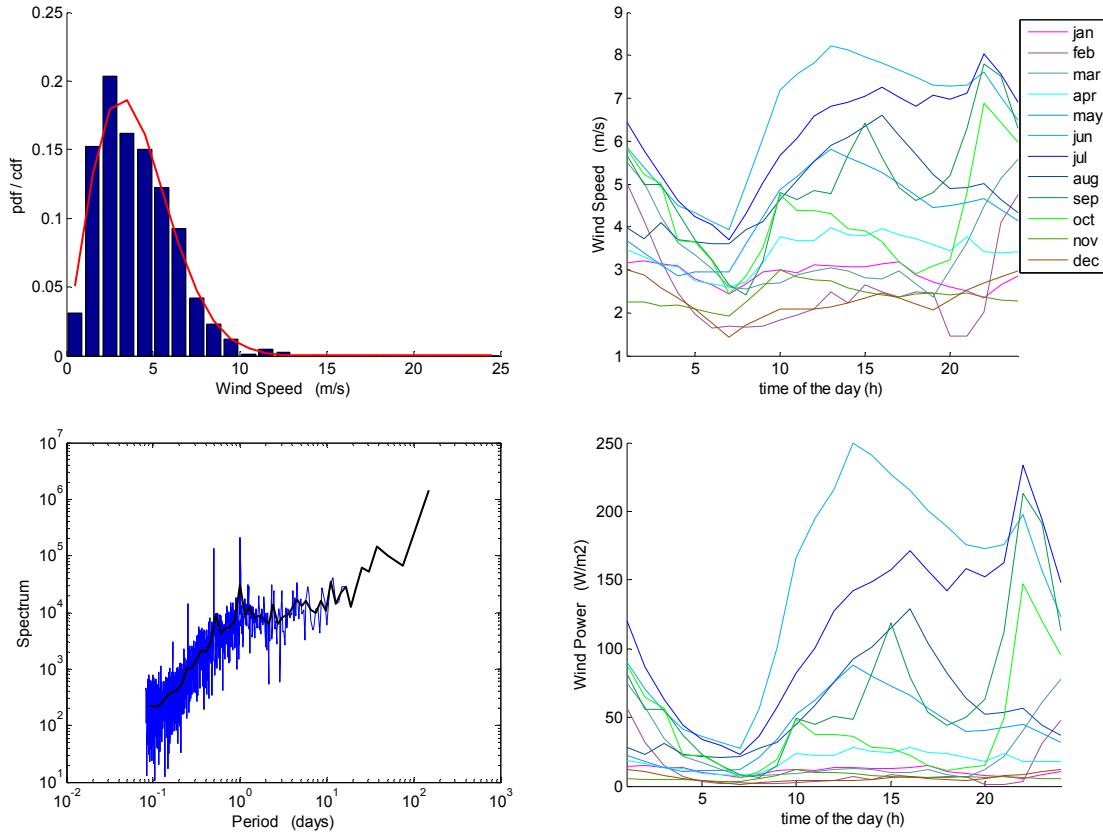
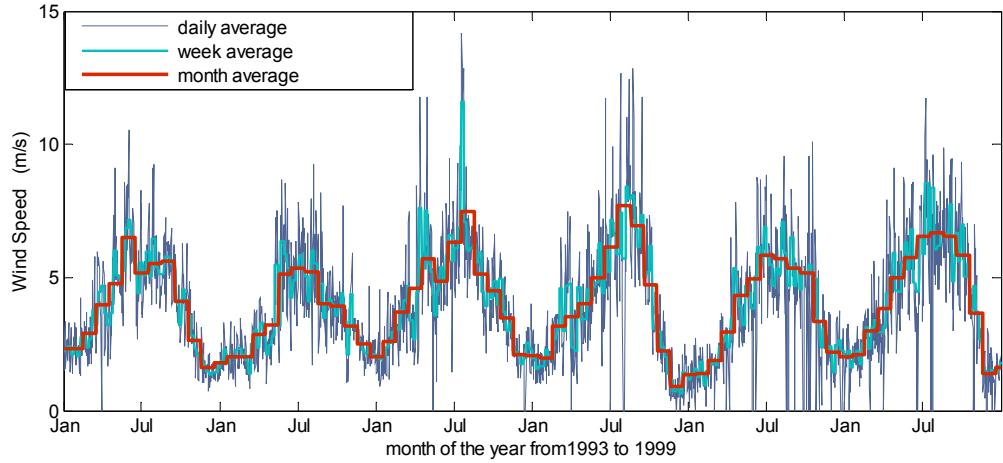
| | WIND SPEED (m/s) | | | | | | | ENERGY (W/m ²) | | | | | | |
|-----|------------------|------|------|------|------|------|--|----------------------------|--------|-------|-----|-------|------|--|
| | mean | std | max | min | A | k | | mean | std | max | min | A | k | |
| Jan | 3.61 | 2.17 | 9.7 | 0.02 | 3.80 | 1.25 | | 44.4 | 58.1 | 411 | 0 | 24.60 | 0.42 | |
| Feb | 3.87 | 2.7 | 11.3 | 0.02 | 3.93 | 1.05 | | 66.9 | 99.3 | 649 | 0 | 27.25 | 0.35 | |
| Mar | 3.01 | 2.31 | 9.3 | 0.02 | 2.65 | 0.73 | | 35.3 | 56.6 | 362 | 0 | 8.39 | 0.24 | |
| Apr | 3.20 | 1.86 | 12.9 | 0.02 | 3.40 | 1.34 | | 31.5 | 64.9 | 966 | 0 | 17.62 | 0.45 | |
| May | 4.23 | 2.13 | 12.6 | 0.02 | 4.65 | 1.80 | | 61.2 | 86.1 | 900 | 0 | 45.14 | 0.60 | |
| Jun | 4.26 | 2.19 | 11.3 | 0.02 | 4.69 | 1.80 | | 65.3 | 97.7 | 649 | 0 | 46.46 | 0.60 | |
| Jul | 3.43 | 1.91 | 26.7 | 0.02 | 3.78 | 1.71 | | 43.9 | 316.9 | 8565 | 0 | 24.26 | 0.57 | |
| Aug | 3.58 | 1.56 | 9.3 | 0.02 | 3.96 | 2.19 | | 32.7 | 40.4 | 362 | 0 | 27.90 | 0.73 | |
| Sep | 4.02 | 2.65 | 36.6 | 0.02 | 4.51 | 1.69 | | 116.5 | 1034.2 | 22063 | 0 | 41.25 | 0.56 | |
| Oct | 2.99 | 1.8 | 9.3 | 0.02 | 3.18 | 1.34 | | 26.0 | 40.0 | 362 | 0 | 14.54 | 0.45 | |
| Nov | 2.73 | 2.22 | 10.3 | 0.02 | 2.39 | 0.73 | | 29.4 | 51.4 | 492 | 0 | 6.12 | 0.24 | |
| Dec | 3.10 | 3.35 | 42.2 | 0.02 | 2.98 | 0.90 | | 154.3 | 1626.9 | 33818 | 0 | 11.88 | 0.30 | |





Inland wind climate (Garissa data, 200 kms from sea coast)

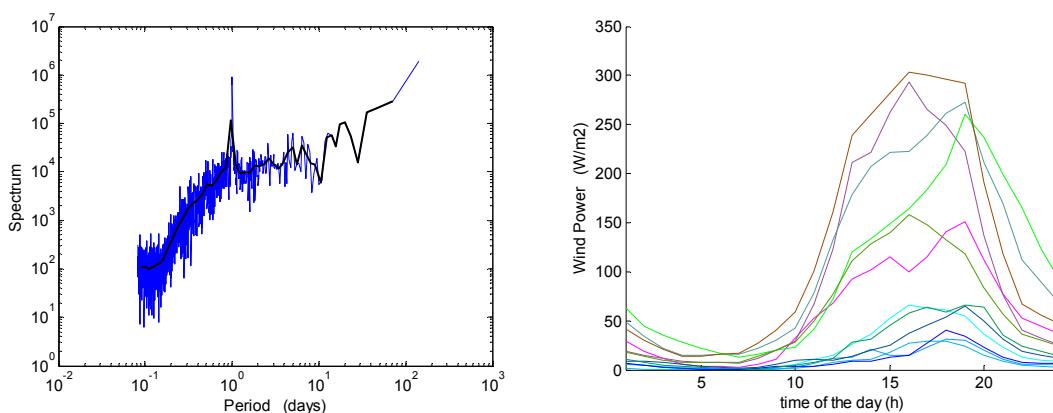
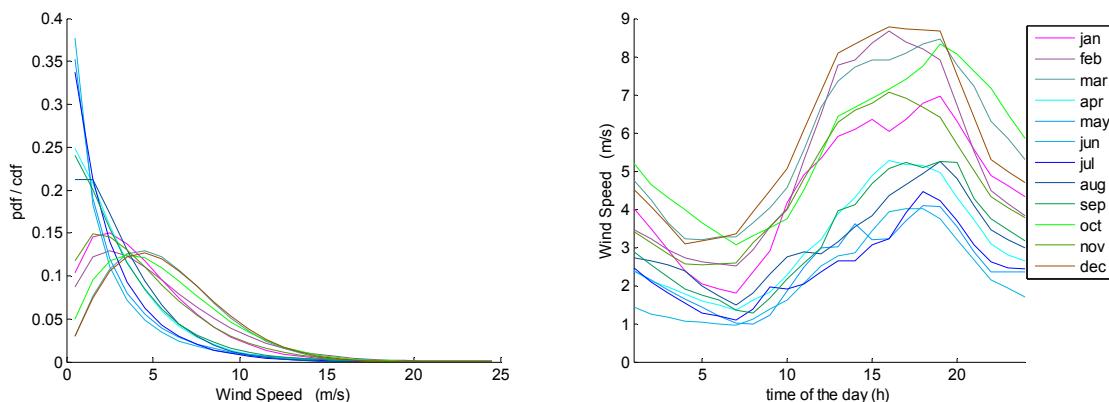
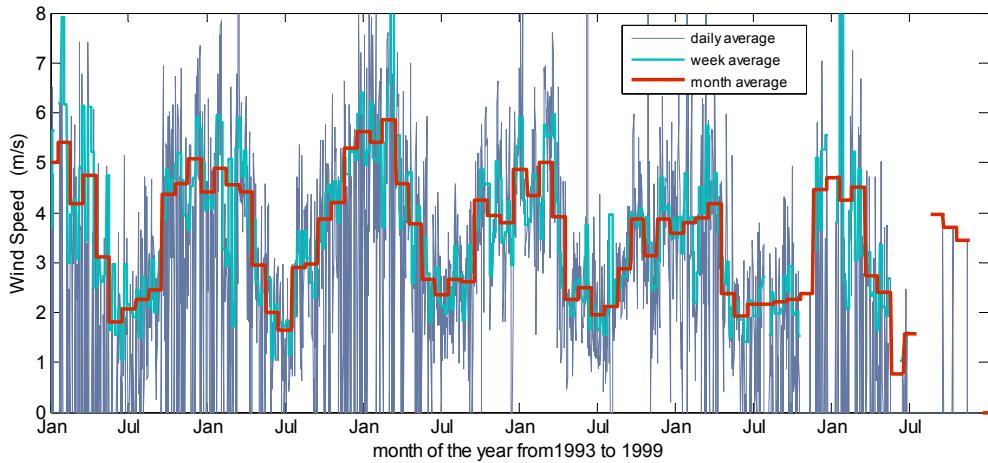
| WIND SPEED (m/s) | | | | | | | | | ENERGY (W/m²) | | | | | | | | | | | |
|------------------|------|------|------|------|------|------|--|-------|---------------|-------|-----|--------|------|--|------|-----|-----|-----|---|---|
| | mean | std | max | min | A | k | | mean | std | max | min | A | k | | mean | std | max | min | A | k |
| Jan | 2.89 | 1.97 | 12.4 | 0.02 | 3.09 | 1.32 | | 30.0 | 72.7 | 858 | 0 | 13.29 | 0.44 | | | | | | | |
| Feb | 2.51 | 2.08 | 14.4 | 0.02 | 2.51 | 1.00 | | 29.3 | 103.0 | 1344 | 0 | 7.10 | 0.33 | | | | | | | |
| Mar | 3.44 | 2.03 | 12.9 | 0.02 | 3.81 | 1.64 | | 41.4 | 82.4 | 966 | 0 | 24.81 | 0.55 | | | | | | | |
| Apr | 3.42 | 1.67 | 10.3 | 0.02 | 3.83 | 2.06 | | 32.1 | 47.0 | 492 | 0 | 25.26 | 0.69 | | | | | | | |
| May | 4.33 | 2.01 | 12.3 | 0.02 | 4.87 | 2.23 | | 61.8 | 84.8 | 837 | 0 | 51.92 | 0.74 | | | | | | | |
| Jun | 6.54 | 2.36 | 14.4 | 0.02 | 7.29 | 2.96 | | 175.5 | 178.3 | 1344 | 0 | 174.66 | 0.99 | | | | | | | |
| Jul | 6.13 | 3.2 | 41.1 | 0.02 | 6.87 | 1.95 | | 253.2 | 1559.2 | 31242 | 0 | 146.06 | 0.65 | | | | | | | |
| Aug | 4.81 | 2.24 | 12.9 | 0.02 | 5.40 | 2.20 | | 86.3 | 129.4 | 966 | 0 | 70.90 | 0.73 | | | | | | | |
| Sep | 4.97 | 2.61 | 14.4 | 0.02 | 5.53 | 1.85 | | 105.0 | 153.4 | 1344 | 0 | 76.05 | 0.62 | | | | | | | |
| Oct | 4.22 | 2.62 | 26.7 | 0.02 | 4.61 | 1.52 | | 87.7 | 374.5 | 8565 | 0 | 44.04 | 0.51 | | | | | | | |
| Nov | 2.40 | 1.43 | 11.3 | 0.02 | 2.61 | 1.51 | | 14.3 | 36.4 | 649 | 0 | 8.00 | 0.50 | | | | | | | |
| Dec | 2.29 | 1.34 | 6.7 | 0.02 | 2.49 | 1.50 | | 11.7 | 19.2 | 135 | 0 | 6.94 | 0.50 | | | | | | | |



Inland wind climate (Wilson Airport data, Nairobi)

| | WIND SPEED (m/s) | | | | | | | ENERGY (W/m ²) | | | | | | |
|-----|------------------|------|------|------|------|------|--|----------------------------|--------|-------|-----|--------|------|--|
| | mean | std | max | min | A | k | | mean | std | max | min | A | k | |
| Jan | 4.52 | 2.75 | 25.1 | 0.02 | 4.88 | 1.45 | | 99.3 | 326.0 | 7116 | 0 | 52.27 | 0.48 | |
| Feb | 5.17 | 3.95 | 42.1 | 0.02 | 5.68 | 1.42 | | 282.2 | 1908.5 | 33578 | 0 | 82.37 | 0.47 | |
| Mar | 5.76 | 2.92 | 17.5 | 0.02 | 6.39 | 1.89 | | 159.1 | 237.2 | 2412 | 0 | 117.53 | 0.63 | |
| Apr | 3.11 | 2.08 | 10.3 | 0.02 | 3.20 | 1.11 | | 33.6 | 56.9 | 492 | 0 | 14.73 | 0.37 | |
| May | 2.49 | 2.05 | 14.5 | 0.02 | 2.30 | 0.82 | | 25.1 | 74.9 | 1372 | 0 | 5.50 | 0.27 | |
| Jun | 2.21 | 1.87 | 9.3 | 0.02 | 1.98 | 0.76 | | 17.4 | 37.0 | 362 | 0 | 3.47 | 0.25 | |
| Jul | 2.48 | 1.93 | 15.4 | 0.02 | 2.44 | 0.95 | | 23.5 | 88.7 | 1644 | 0 | 6.55 | 0.32 | |

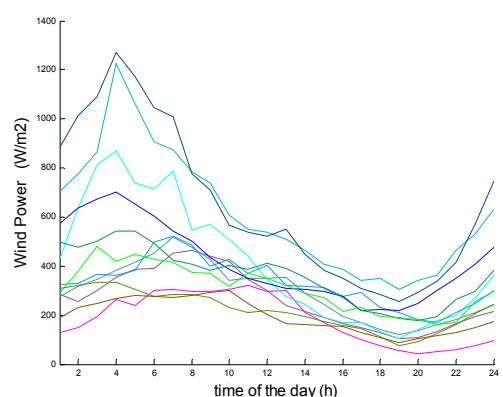
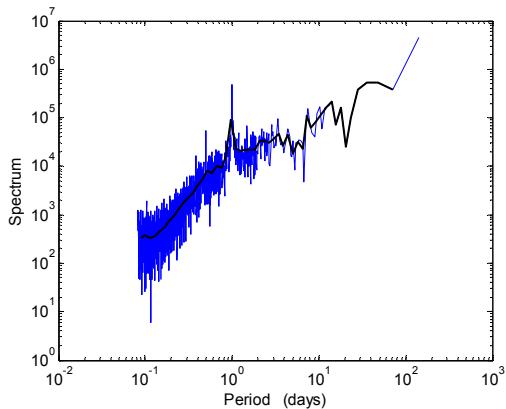
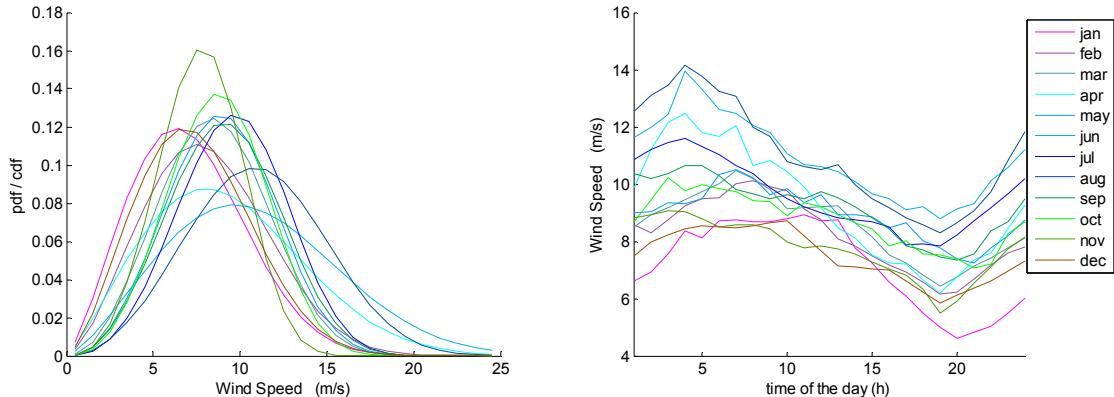
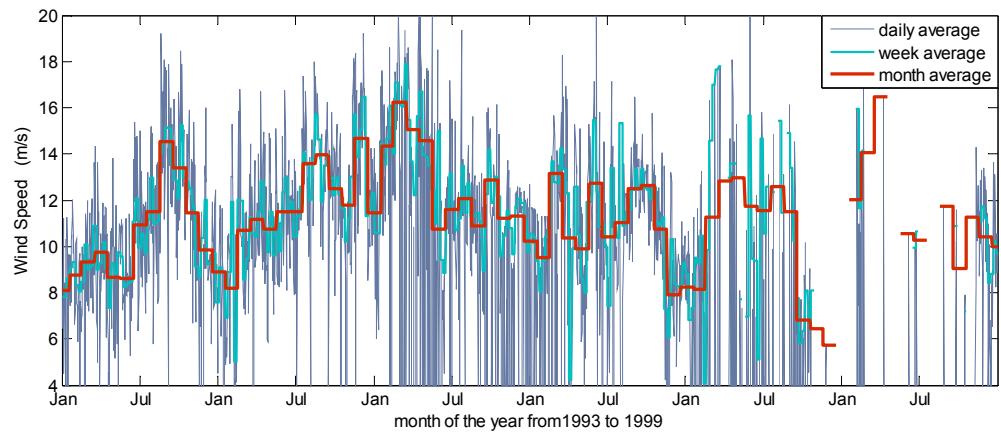
| | | | | | | | | | | | | | |
|-----|------|------|------|------|------|------|--|-------|--------|-------|---|--------|------|
| Aug | 3.18 | 2.02 | 11.1 | 0.02 | 3.34 | 1.25 | | 34.3 | 64.3 | 615 | 0 | 16.80 | 0.42 |
| Sep | 3.26 | 2.46 | 16.5 | 0.02 | 3.35 | 1.10 | | 50.3 | 136.6 | 2021 | 0 | 16.94 | 0.37 |
| Oct | 5.61 | 3.37 | 42.2 | 0.02 | 6.19 | 1.66 | | 227.7 | 1524.8 | 33818 | 0 | 106.95 | 0.55 |
| Nov | 4.59 | 2.81 | 28.4 | 0.02 | 4.89 | 1.36 | | 109.4 | 463.4 | 10308 | 0 | 52.59 | 0.45 |
| Dec | 5.85 | 3.05 | 29.9 | 0.02 | 6.51 | 1.88 | | 177.9 | 517.7 | 12029 | 0 | 124.43 | 0.63 |



North Kenya wind climate (Marsabit, typical Turkana jet wind climate)

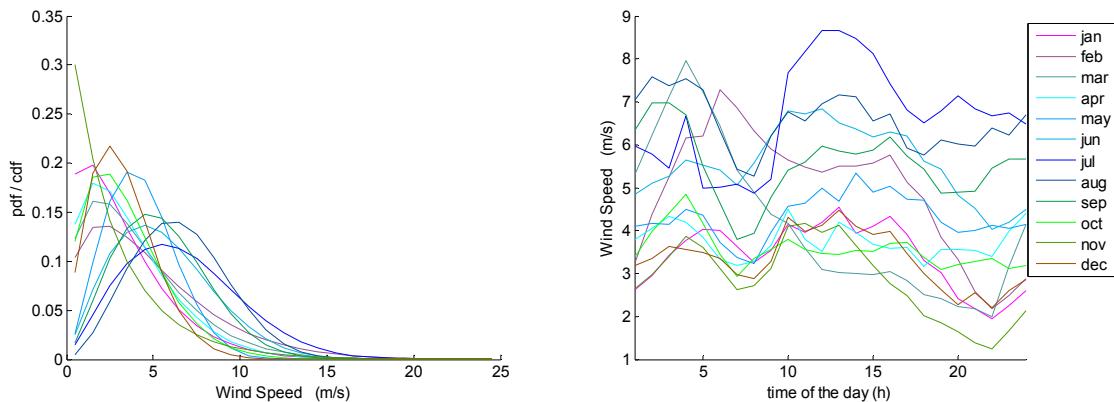
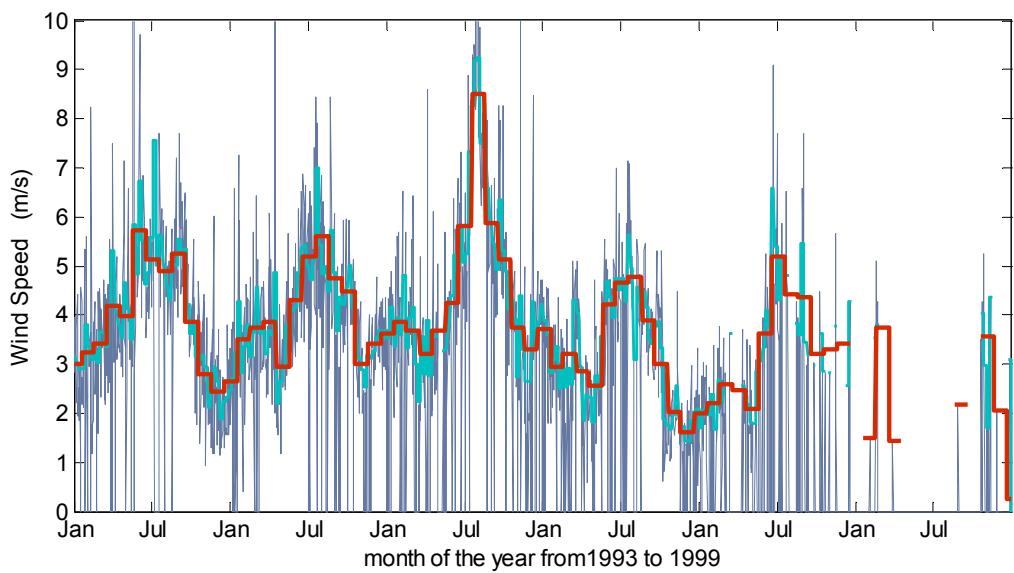
| WIND SPEED (m/s) | | | | | | | ENERGY (W/m ²) | | | | | | |
|------------------|-----|-----|-----|---|---|--|----------------------------|-----|-----|-----|---|---|--|
| mean | std | max | min | A | k | | mean | std | max | min | A | k | |

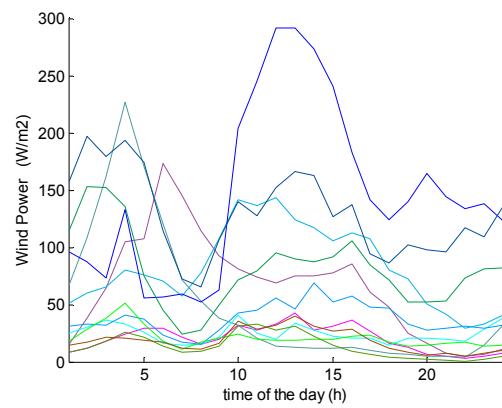
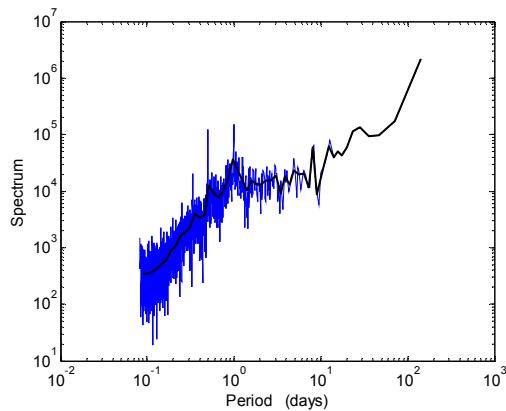
| | | | | | | | | | | | | | |
|-----|-------|------|------|------|-------|------|--|-------|--------|-------|-------|--------|------|
| Jan | 7.16 | 3.2 | 20.6 | 0.02 | 8.04 | 2.34 | | 269.0 | 346.4 | 3934 | 0 | 234.25 | 0.78 |
| Feb | 8.22 | 3.32 | 20.6 | 0.02 | 9.20 | 2.52 | | 386.2 | 545.1 | 3934 | 0 | 350.17 | 0.84 |
| Mar | 8.55 | 3.07 | 16.4 | 0.02 | 9.56 | 3.04 | | 391.0 | 370.0 | 1985 | 0 | 393.12 | 1.01 |
| Apr | 9.30 | 4.45 | 35 | 1 | 10.52 | 2.21 | | 648.8 | 1142.7 | 19294 | 0.45 | 524.24 | 0.74 |
| May | 8.94 | 2.96 | 21.6 | 0.5 | 9.96 | 3.24 | | 431.1 | 433.4 | 4535 | 0.06 | 444.78 | 1.08 |
| Jun | 10.91 | 4.68 | 42.2 | 1 | 12.27 | 2.38 | | 990.7 | 2340.0 | 33818 | 0.45 | 831.04 | 0.79 |
| Jul | 9.61 | 2.98 | 21.1 | 2.6 | 10.68 | 3.51 | | 517.2 | 467.9 | 4227 | 7.91 | 547.75 | 1.17 |
| Aug | 11.00 | 3.76 | 31.9 | 3.1 | 12.30 | 3.11 | | 823.0 | 927.6 | 14608 | 13.41 | 836.69 | 1.04 |
| Sep | 9.20 | 2.89 | 32.4 | 1 | 10.20 | 3.21 | | 463.3 | 670.3 | 15306 | 0.45 | 477.63 | 1.07 |
| Oct | 8.73 | 2.76 | 15.6 | 0.02 | 9.69 | 3.46 | | 389.9 | 334.4 | 1708 | 0 | 409.91 | 1.15 |
| Nov | 7.75 | 2.34 | 14.4 | 1 | 8.59 | 3.62 | | 267.8 | 230.1 | 1344 | 0.45 | 285.48 | 1.21 |
| Dec | 7.49 | 3.08 | 28.6 | 1 | 8.42 | 2.48 | | 305.9 | 641.1 | 10527 | 0.45 | 268.43 | 0.83 |



North Kenya wind climate (Mandera, Ethiopian border)

| WIND SPEED (m/s) | | | | | | | | | | ENERGY (W/m ²) | | | | | |
|------------------|------|------|------|------|------|------|--|-------|--------|----------------------------|------|--------|------|--|--|
| | mean | std | max | min | A | k | | mean | std | max | min | A | k | | |
| Jan | 3.42 | 2.38 | 13.7 | 0.02 | 3.64 | 1.27 | | 50.2 | 110.0 | 1157 | 0 | 21.74 | 0.42 | | |
| Feb | 4.90 | 4.12 | 44.7 | 0.02 | 5.35 | 1.36 | | 326.4 | 2567.0 | 40192 | 0 | 68.90 | 0.45 | | |
| Mar | 4.14 | 2.9 | 17 | 0.02 | 4.51 | 1.40 | | 92.7 | 211.7 | 2211 | 0 | 41.34 | 0.47 | | |
| Apr | 3.75 | 2.57 | 14.4 | 0.02 | 4.09 | 1.41 | | 67.4 | 158.2 | 1344 | 0 | 30.76 | 0.47 | | |
| May | 4.32 | 1.98 | 14.4 | 0.02 | 4.85 | 2.26 | | 61.0 | 90.3 | 1344 | 0 | 51.46 | 0.75 | | |
| Jun | 5.57 | 2.94 | 18.9 | 0.02 | 6.30 | 2.01 | | 155.9 | 301.1 | 3038 | 0 | 112.45 | 0.67 | | |
| Jul | 6.67 | 3.38 | 26.2 | 0.02 | 7.55 | 2.09 | | 254.8 | 489.7 | 8093 | 0 | 193.72 | 0.70 | | |
| Aug | 6.54 | 2.66 | 17 | 0.5 | 7.37 | 2.60 | | 195.7 | 263.8 | 2211 | 0.06 | 180.27 | 0.87 | | |
| Sep | 5.54 | 2.56 | 18 | 0.02 | 6.22 | 2.22 | | 130.9 | 209.2 | 2624 | 0 | 108.22 | 0.74 | | |
| Oct | 3.56 | 2.17 | 15.4 | 0.02 | 3.91 | 1.56 | | 47.8 | 107.6 | 1644 | 0 | 26.96 | 0.52 | | |
| Nov | 2.85 | 2.68 | 28.3 | 0.02 | 2.83 | 0.97 | | 65.9 | 460.4 | 10199 | 0 | 10.15 | 0.32 | | |
| Dec | 3.34 | 1.84 | 14.9 | 0.02 | 3.74 | 1.84 | | 34.9 | 76.2 | 1489 | 0 | 23.47 | 0.61 | | |





Appendix III: Esilanke data, courtesy of KenTec

Project:

Esilanke school 1kW Rural

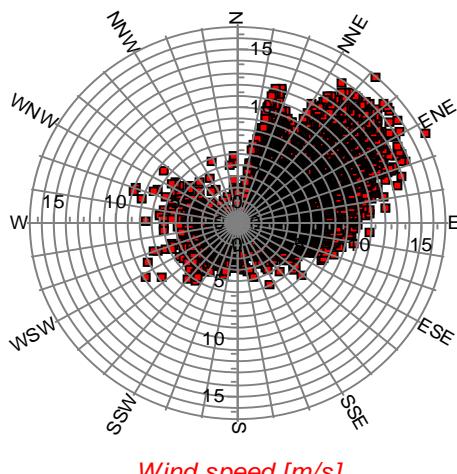
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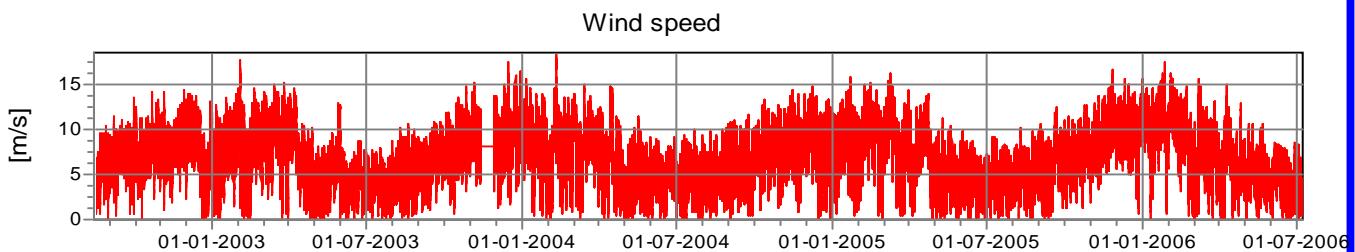
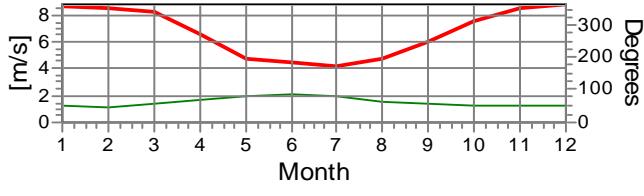
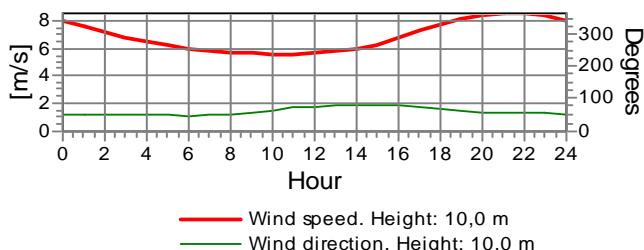
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Meteo data report, height: 10,0 m

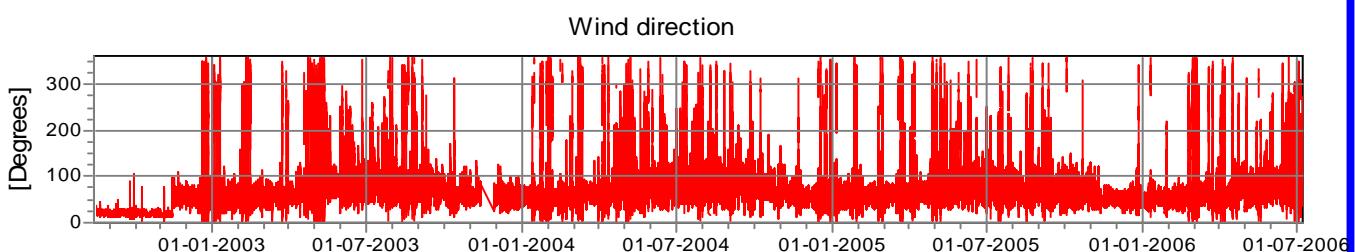
Name of meteo object: Esilanke predicted wind data

**Monthly mean values of wind speed in m/s**

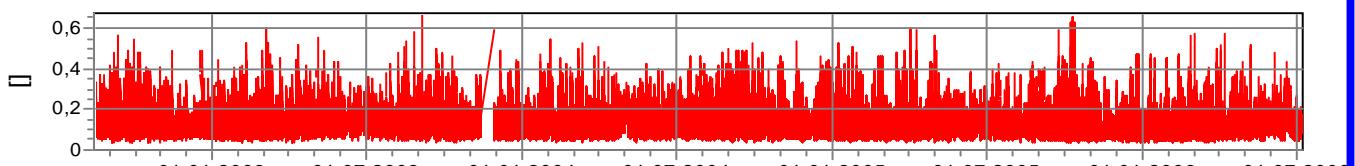
| Month | 2002 | 2003 | 2004 | 2005 | 2006 | mean | mean of months |
|----------------|------|------|------|------|------|------|----------------|
| Jan | | 7,6 | 8,4 | 8,3 | 10,4 | 8,7 | 8,7 |
| Feb | | 7,9 | 7,8 | 9,1 | 9,6 | 8,6 | 8,6 |
| Mar | | 9,1 | 8,1 | 8,6 | 7,0 | 8,2 | 8,2 |
| Apr | | 7,3 | 5,9 | 7,3 | 6,1 | 6,6 | 6,6 |
| May | | 4,8 | 4,6 | 4,7 | 5,0 | 4,8 | 4,8 |
| Jun | | 4,3 | 4,9 | 4,5 | 4,3 | 4,5 | 4,5 |
| Jul | | 4,1 | 4,4 | 4,5 | 3,3 | 4,3 | 4,1 |
| Aug | | 5,1 | 4,6 | 4,8 | 4,9 | 4,8 | 4,8 |
| Sep | | 7,0 | 6,1 | 5,5 | 5,8 | 6,1 | 6,1 |
| Oct | | 7,5 | 7,9 | 7,4 | 7,2 | 7,5 | 7,5 |
| Nov | | 8,1 | 9,0 | 8,2 | 9,2 | 8,6 | 8,6 |
| Dec | | 7,6 | 9,1 | 8,6 | 9,9 | 8,8 | 8,8 |
| mean, all data | 7,2 | 6,8 | 6,6 | 7,0 | 6,9 | 6,8 | |
| mean of months | 7,0 | 6,8 | 6,6 | 7,0 | 6,5 | | 6,8 |



Wind speed



Wind direction



Project:

Esilanke school 1kW Rural

Description:
 C:KENTEC:CLIENT:5000: Windgen Version: LstWind: data:Geng: South:AI: Nsgng: south00001011 N006
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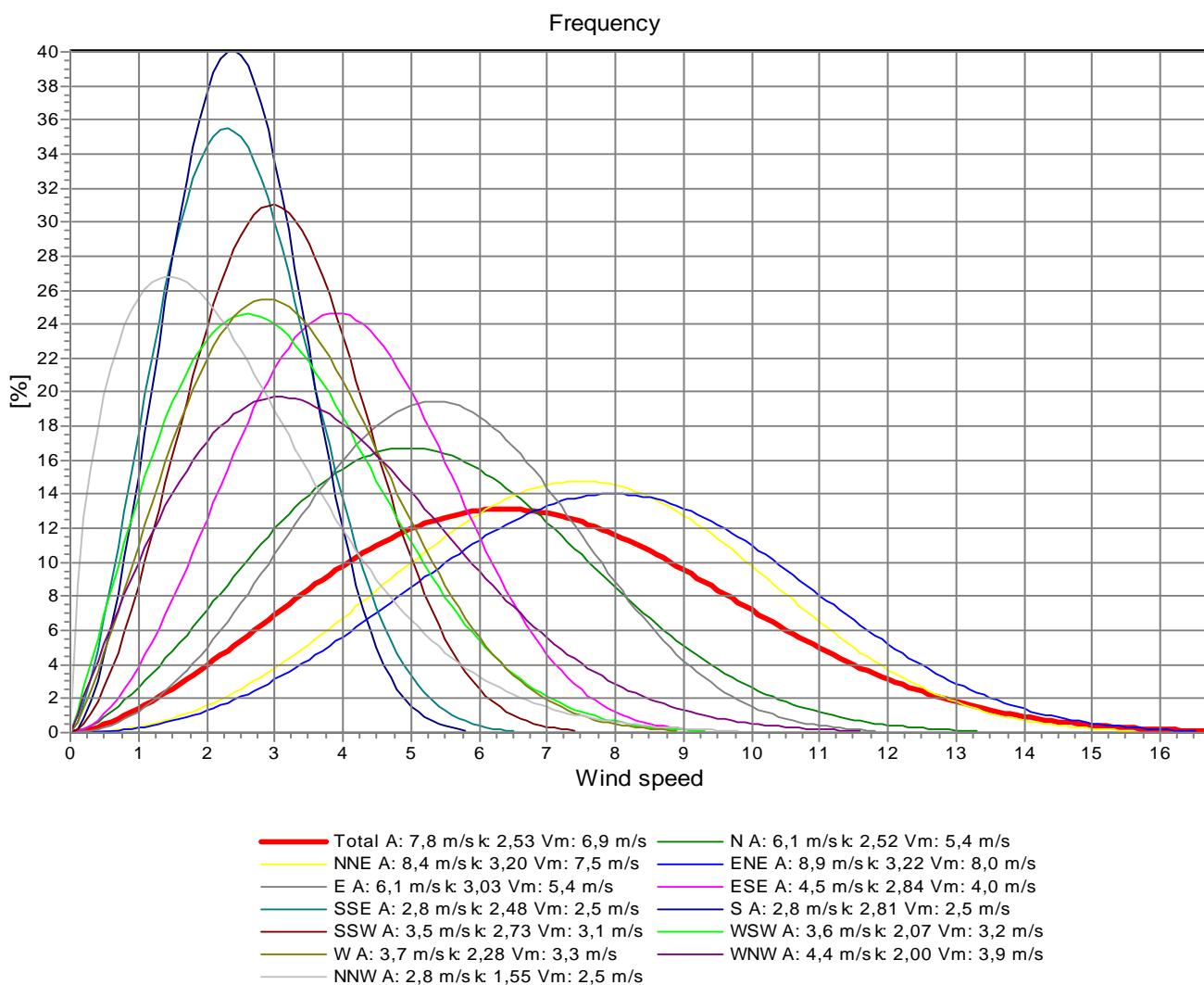
Meteo data report, height: 10,0 m

Name of meteo object: Esilanke predicted wind data

Weibull Data

k-parameter correction: 0,0080/m

| Sector | A- parameter [m/s] | Mean wind speed [m/s] | k- parameter | Frequency | Frequency [%] | Wind shear |
|--------|--------------------|-----------------------|--------------|-----------|---------------|------------|
| 0-N | 6,08 | 5,39 | 2,522 | 0,71 | 0,7 | 0,00 |
| 1-NNE | 8,42 | 7,54 | 3,200 | 20,31 | 20,3 | 0,00 |
| 2-ENE | 8,92 | 8,00 | 3,224 | 49,07 | 49,1 | 0,00 |
| 3-E | 6,10 | 5,45 | 3,031 | 18,52 | 18,5 | 0,00 |
| 4-ESE | 4,55 | 4,05 | 2,836 | 4,24 | 4,2 | 0,00 |
| 5-SSE | 2,82 | 2,50 | 2,477 | 0,95 | 1,0 | 0,00 |
| 6-S | 2,77 | 2,47 | 2,813 | 1,00 | 1,0 | 0,00 |
| 7-SSW | 3,50 | 3,12 | 2,734 | 1,66 | 1,7 | 0,00 |
| 8-WSW | 3,57 | 3,16 | 2,073 | 1,32 | 1,3 | 0,00 |
| 9-W | 3,70 | 3,28 | 2,284 | 1,14 | 1,1 | 0,00 |
| 10-WNW | 4,35 | 3,86 | 2,000 | 0,86 | 0,9 | 0,00 |
| 11-NNW | 2,81 | 2,53 | 1,553 | 0,21 | 0,2 | 0,00 |
| mean | 7,76 | 6,89 | 2,532 | 100,00 | 100,0 | 0,00 |



Project:
Esilanke school 1kW Rural

Description:
Ngong Hills
Esilanke

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Calculated:
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PARK - Main Result

Calculation: Esilanke

Wake Model N.O. Jensen (RISØ/EMD)

Calculation Settings

| | |
|-------------------------------------|--------------------|
| Air density calculation mode | Individual per WTG |
| Result for WTG at hub altitude | 0.973 kg/m³ |
| Hub altitude above sea level (asl) | 2.025,9 m |
| Annual mean temperature at hub alt. | 13,4 °C |
| Pressure at WTGs | 800,1 hPa |

Wake Model Parameters

| | |
|---------------------|-------|
| Wake Decay Constant | 0,075 |
|---------------------|-------|

WTG siting

UTM WGS84 S Zone: 37

| | | | |
|-------|---------|-----------|---|
| East | North | Z | Row data/Description |
| | | | [m] |
| 1 New | 239.084 | 9.837.969 | 2.019 KenTec KT-1000 1 3.2 !O! hub: 7,0 ... |

Key results for height 10,0 m above ground level

Terrain UTM WGS84 S Zone: 37

| East | North | Name of wind distribution | Height | Type | Wind energy | Mean wind speed |
|------|---------|---------------------------|------------------------------|--------------|-------------|-----------------|
| | | | [m] | | [kWh/m²] | [m/s] |
| A | 238.114 | 9.839.503 | Esilanke predicted wind data | 10,0 WEIBULL | 2.145 | 6,9 |

Calculated Annual Energy for Wind Farm

| WTG combination | Annual Energy | | Park | | Capacity Factor for | |
|-----------------|---------------|--------------|------------|-----------------|---------------------|--------------|
| | Result | Result-10,0% | Efficiency | Mean WTG energy | Result | Result-10,0% |
| Wind farm | 3,8 | 3,4 | 100,0 | 3,8 | 43,6 | 39,3 |

Calculated Annual Energy for each of 1 new WTG's with total 0,0 MW rated power

| WTG type | Power curve | | | | | | Annual Energy | | Park | | | |
|----------|-------------|--------|-----------|------|-------|-------|---------------|---------|------|--------|--------------|------------|
| | Terrain | Valid | Manufact. | Type | Power | Diam. | Height | Creator | Name | Result | Result-10,0% | Efficiency |
| 1 A | Yes | KenTec | KT-1000 | 1 | 3,2 | 7,0 | USER | KT-1000 | 3,8 | 3 | 100,0 | 6,5 |

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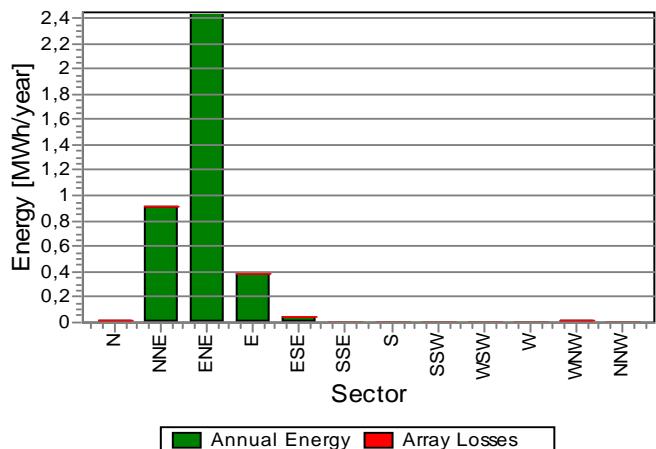
PARK - Production Analysis

Calculation: Esilanke W TG: All new WTG's, Air density 0,973 kg/m³

Directional Analysis

| Sector | 0 N | 1 NNE | 2 ENE | 3 E | 4 ESE | 5 SSE | 6 S | 7 SSW | 8 WSW | 9 W | 10 WNW | 11 NNW | Total |
|---------------------------------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| Roughness based energy [MWh] | 0,0 | 0,9 | 2,4 | 0,4 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 3,8 |
| Resulting energy [MWh] | 0,0 | 0,9 | 2,4 | 0,4 | 0,0 | 3,8 |
| Specific energy [kWh/m ²] | | | | | | | | | | | | | 475 |
| Specific energy [kWh/kW] | | | | | | | | | | | | | 3.823 |
| Utilization [%] | 30,2 | 26,2 | 24,6 | 31,7 | 32,7 | 22,5 | 18,9 | 29,1 | 30,5 | 30,8 | 31,0 | 29,0 | 25,7 |
| Operational [Hours/year] | 56 | 1.603 | 3.873 | 1.462 | 334 | 75 | 79 | 131 | 105 | 90 | 68 | 17 | 7.892 |
| Full Load Equivalent [Hours/year] | 16 | 906 | 2.444 | 387 | 39 | 2 | 1 | 6 | 7 | 6 | 9 | 1 | 3.823 |

Energy vs. sector



Project:
Esilanke school 1kW RuralDescription:
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PARK - Power Curve Analysis

Calculation: Esilanke **WTG:** 1 - KenTec KT-1000 1 3.2 IO! KT-1000, Hub height: 7,0 mName: KT-1000
Source: KenTec

| Source/Date | Created by | Created | Edited | Stop wind speed [m/s] | Power control | CT curve type |
|-------------|------------|------------|------------|-----------------------|---------------|----------------|
| 26-09-2005 | USER | 26-09-2005 | 30-10-2006 | 25,0 | Stall | Standard stall |

HP curve comparison - Note: For standard air density and weibull k parameter = 2

| Vmean [m/s] | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|----|
| HP value [MWh] | 0 | 0 | 0 | 0 | 0 | 0 |
| KenTec KT-1000 1 3.2 IO! hub: 7,0 m (334) [MWh] | 3 | 4 | 5 | 6 | 7 | 8 |
| Check value [%] | | | | | | |

The table shows comparison between annual energy production calculated on basis of simplified "HP-curves" which assume that all WTG's performs quite similar - only specific power loading (kW/m²) and single/dual speed or stall/pitch decides the calculated values. Productions are without wake losses.

For further details, ask at the Danish Energy Agency for project report J.nr. 51171/00-0016 or see WindPRO manual chapter 3.5.2.

The method is refined in EMD report "20 Detailed Case Studies comparing Project Design Calculations and actual Energy Productions for Wind Energy Projects worldwide", jan 2003.

Use the table to evaluate if the given power curve is reasonable - if the check value are lower than -5%, the power curve probably is too optimistic due to uncertainty in power curve measurement.

Power curve

Original data from Windcat, Air density: 1,225 kg/m³

Wind speed Power Ce Wind speed Ct curve

| [m/s] | [kW] | [m/s] | |
|-------|----------|-------|------|
| 1,0 | 0,0 0,00 | 1,0 | 0,10 |
| 2,0 | 0,0 0,00 | 2,0 | 0,10 |
| 3,0 | 0,0 0,00 | 3,0 | 0,10 |
| 4,0 | 0,1 0,38 | 4,0 | 0,80 |
| 5,0 | 0,2 0,37 | 5,0 | 0,82 |
| 6,0 | 0,3 0,33 | 6,0 | 0,85 |
| 7,0 | 0,5 0,30 | 7,0 | 0,82 |
| 8,0 | 0,8 0,31 | 8,0 | 0,78 |
| 9,0 | 1,1 0,31 | 9,0 | 0,74 |
| 10,0 | 1,3 0,26 | 10,0 | 0,68 |
| 11,0 | 1,4 0,21 | 11,0 | 0,62 |
| 12,0 | 1,4 0,17 | 12,0 | 0,55 |
| 13,0 | 1,5 0,14 | 13,0 | 0,49 |
| 14,0 | 1,5 0,11 | 14,0 | 0,43 |
| 15,0 | 1,5 0,09 | 15,0 | 0,38 |
| 16,0 | 1,5 0,07 | 16,0 | 0,32 |
| 17,0 | 1,5 0,06 | 17,0 | 0,28 |
| 18,0 | 1,4 0,05 | 18,0 | 0,25 |
| 19,0 | 1,3 0,04 | 19,0 | 0,21 |
| 20,0 | 1,3 0,03 | 20,0 | 0,20 |
| 21,0 | 1,1 0,03 | 21,0 | 0,19 |
| 22,0 | 1,0 0,02 | 22,0 | 0,17 |
| 23,0 | 0,8 0,01 | 23,0 | 0,16 |
| 24,0 | 0,6 0,01 | 24,0 | 0,15 |
| 25,0 | 0,5 0,01 | 25,0 | 0,14 |
| | | 26,0 | 0,13 |
| | | 27,0 | 0,12 |
| | | 28,0 | 0,11 |
| | | 29,0 | 0,10 |

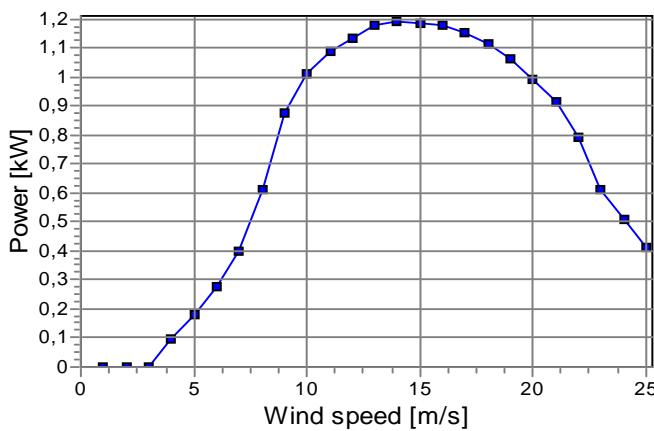
Power, Efficiency and energy vs. wind speed

Data used in calculation, Air density: 0,973 kg/m³

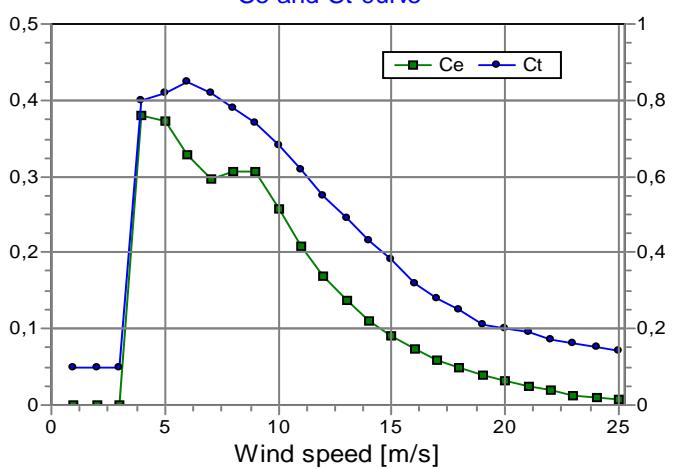
| Wind speed [m/s] | Power [kW] | Ce | Interval [m/s] | Energy [MWh] | Acc.Energy [MWh] | Relative [%] |
|------------------|------------|-------------|----------------|--------------|------------------|--------------|
| 1,0 | 0,0 0,00 | 0,50- 1,50 | 0,0 | 0,0 | 0,0 | 0,0 |
| 2,0 | 0,0 0,00 | 1,50- 2,50 | 0,0 | 0,0 | 0,0 | 0,0 |
| 3,0 | 0,0 0,00 | 2,50- 3,50 | 0,0 | 0,0 | 0,0 | 0,5 |
| 4,0 | 0,1 0,38 | 3,50- 4,50 | 0,1 | 0,1 | 0,1 | 2,9 |
| 5,0 | 0,2 0,37 | 4,50- 5,50 | 0,2 | 0,3 | 0,3 | 8,1 |
| 6,0 | 0,3 0,33 | 5,50- 6,50 | 0,3 | 0,6 | 16,7 | |
| 7,0 | 0,4 0,30 | 6,50- 7,50 | 0,5 | 1,1 | 28,9 | |
| 8,0 | 0,6 0,31 | 7,50- 8,50 | 0,6 | 1,7 | 44,9 | |
| 9,0 | 0,9 0,31 | 8,50- 9,50 | 0,7 | 2,4 | 62,5 | |
| 10,0 | 1,0 0,26 | 9,50-10,50 | 0,6 | 3,0 | 77,7 | |
| 11,0 | 1,1 0,21 | 10,50-11,50 | 0,4 | 3,4 | 88,4 | |
| 12,0 | 1,1 0,17 | 11,50-12,50 | 0,2 | 3,6 | 94,8 | |
| 13,0 | 1,2 0,14 | 12,50-13,50 | 0,1 | 3,7 | 98,0 | |
| 14,0 | 1,2 0,11 | 13,50-14,50 | 0,1 | 3,8 | 99,4 | |
| 15,0 | 1,2 0,09 | 14,50-15,50 | 0,0 | 3,8 | 99,8 | |
| 16,0 | 1,2 0,07 | 15,50-16,50 | 0,0 | 3,8 | 100,0 | |
| 17,0 | 1,2 0,06 | 16,50-17,50 | 0,0 | 3,8 | 100,0 | |
| 18,0 | 1,1 0,05 | 17,50-18,50 | 0,0 | 3,8 | 100,0 | |
| 19,0 | 1,1 0,04 | 18,50-19,50 | 0,0 | 3,8 | 100,0 | |
| 20,0 | 1,0 0,03 | 19,50-20,50 | 0,0 | 3,8 | 100,0 | |
| 21,0 | 0,9 0,03 | 20,50-21,50 | 0,0 | 3,8 | 100,0 | |
| 22,0 | 0,8 0,02 | 21,50-22,50 | 0,0 | 3,8 | 100,0 | |
| 23,0 | 0,6 0,01 | 22,50-23,50 | 0,0 | 3,8 | 100,0 | |
| 24,0 | 0,5 0,01 | 23,50-24,50 | 0,0 | 3,8 | 100,0 | |
| 25,0 | 0,4 0,01 | 24,50-25,50 | 0,0 | 3,8 | 100,0 | |

Power curve

Data used in calculation

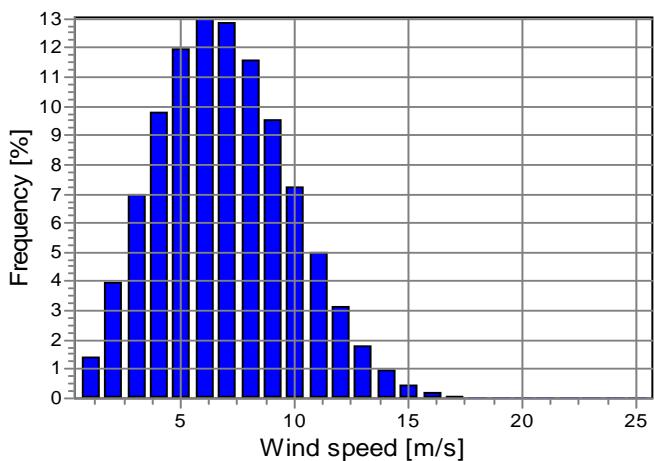
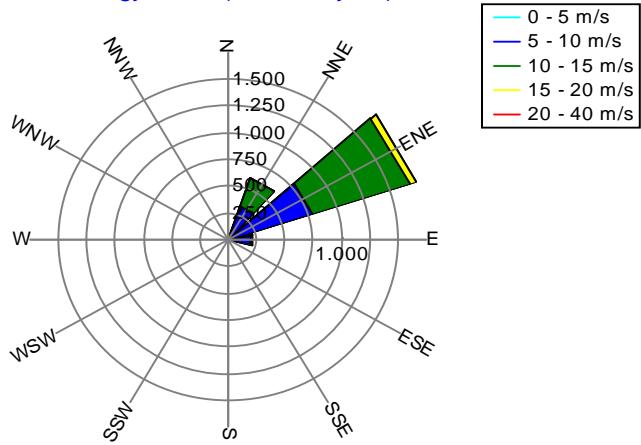
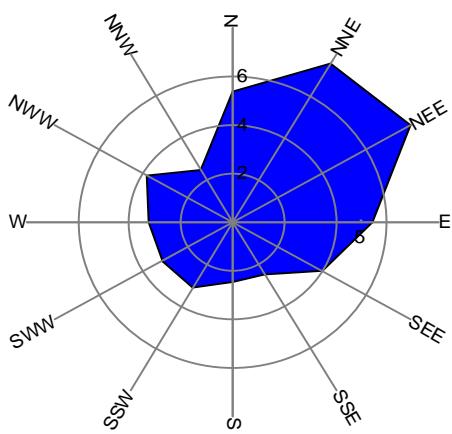
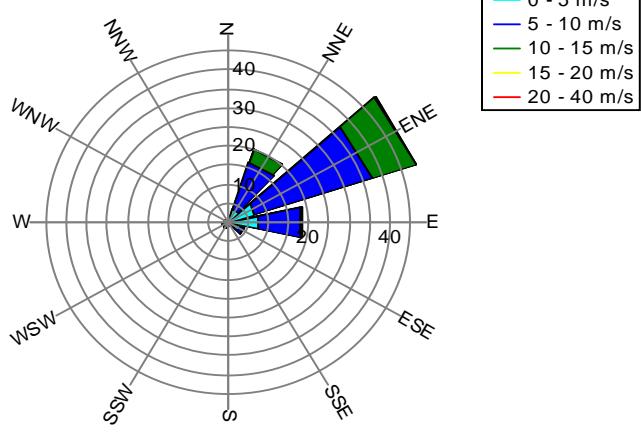


Ce and Ct curve



Project:
Esilanke school 1kW RuralDescription:
Ngong Hills
EsilankePrinted/Page
30-10-2006 09:35 / 4
Licensed user:
KenTec Denmark ApS
Rosenstien 12
DK-8800 Viborg
+45 8663 8139
www.kentec.dk - mail@kentec.dk
Calculated:
30-10-2006 09:35/2.5.5.74**PARK - Wind Data Analysis****Calculation:** Esilanke **Wind data:** A - Esilanke predicted wind data; Hub height: 10,0**Weibull Data**

| Sector | A- parameter | Wind speed | k- parameter | Frequency | Wind gradient exponent |
|--------|--------------|------------|--------------|-----------|------------------------|
| | [m/s] | [m/s] | | [%] | |
| 0 N | 6,08 | 5,39 | 2,522 | 0,7 | 0,150 |
| 1 NNE | 8,42 | 7,54 | 3,200 | 20,3 | 0,150 |
| 2 ENE | 8,92 | 8,00 | 3,224 | 49,1 | 0,150 |
| 3 E | 6,10 | 5,45 | 3,031 | 18,5 | 0,150 |
| 4 ESE | 4,55 | 4,05 | 2,836 | 4,2 | 0,150 |
| 5 SSE | 2,82 | 2,50 | 2,477 | 1,0 | 0,150 |
| 6 S | 2,77 | 2,47 | 2,813 | 1,0 | 0,150 |
| 7 SSW | 3,50 | 3,12 | 2,734 | 1,7 | 0,150 |
| 8 WSW | 3,57 | 3,16 | 2,073 | 1,3 | 0,150 |
| 9 W | 3,70 | 3,28 | 2,284 | 1,1 | 0,150 |
| 10 WNW | 4,35 | 3,86 | 2,000 | 0,9 | 0,150 |
| 11 NNW | 2,81 | 2,53 | 1,553 | 0,2 | 0,150 |
| All | 7,76 | 6,89 | 2,532 | 100,0 | |

Weibull Distribution**Energy Rose (kWh/m²/year)****Mean wind speed (m/s)****Frequency (%)**

Appendix IV: DWEK Concept paper

Project Concept Note Developing Wind Energy in Kenya

Dev. by Energy for Sustainable Development, Bobs Harries Engineering Limited and Craft Skills

Introduction

Wind energy has a long history in Kenya and East Africa and has been used for more than 25 years. In Kenya, two industries are specialized in manufacturing small wind energy systems: BHEL has been manufacturing the Kijito windpumps since 1979 and Craftsheets Enterprises the Wind Cruiser aero generators since 1998. The current wind energy data estimates that 25% of Kenya is compatible with current wind energy technology.

The wind energy market is evolving from pre-commercial to pioneer development stage and to date about 400 windpumps and small aerogenerators have been installed in Kenya. Private and public sector activities include:

- Importation of small wind turbines from the US by Renewable Energy System distributors
- Kenyan consulting companies providing wind energy expertise
- University research centres involved in improving the knowledge of the Kenya wind resource and the applicability of the systems made in Kenya,
- NGOs using wind energy systems in their projects
- Local utility companies Kengen and KPLC operating wind turbines.
- Financing of pilot wind rural electrification projects by international co-operation institutions.

However, the low awareness of wind energy technology in Kenya and the low income of rural people (80% of rural household earn less than US\$ 2/day/capita) still limits the expansion of the market for small wind energy systems in Kenya. Furthermore, on a larger scale, the lack of reliable data on wind and the economics of wind energy in Kenya is another factor limiting expansion.

All sizes and uses of wind energy are applicable in Kenya: grid-connected wind parks, hybrid wind-diesel power generation scheme for isolated grids, small wind energy systems for decentralised electrification and water supply (windpumping) in remote rural areas.

Grid-connected wind parks can turn out to be very complementary solutions to the current power generation schemes (especially when hydro and thermal energies are the main sources of power). They are therefore capable of contributing significantly to the improvement of energy security and the promotion of emission-free power generation. The progress of the technology has enabled notable reduction in the costs of generating

electricity to as low as US\$ 0.05/kWh in good wind resource conditions, i.e. much lower than the generating costs from grid-connected thermal diesel power stations (> US\$ 0.10/kWh).

Wind power generation can also bring major environment and economic improvements in all areas relying solely on diesel generation. Incorporating wind energy in the power generation scheme of isolated grids through hybrid wind-diesel configuration can decrease the polluting emissions by 50% while the generating cost of electricity are significantly lowered (US 0.08-0.15/kWh for wind electricity against US 0.3/kWh and above for diesel electricity in remote areas).

Small scale wind energy systems, ranging from 1 to 20 kW, constitute solutions particularly adapted to the electricity and water supply of isolated settlements or towns, health centres, schools, industries, commercial centres... located in rural areas. While contributing to rural development, using locally manufactured wind energy systems made in also stimulates the industrialization of region.

There is need to create an appropriate environment favourable to wind energy dissemination. This project proposes the implementation of a coherent national wind energy development plan that addresses the different requirements necessary to develop and implement small, medium and large wind energy projects.

This project has been initiated by the Kenyan wind industry sector. The project will be developed to fit within the government's strategic plans for energy security and supply, rural electrification and water supply.

Project Objectives and Approach

The objectives of this project are:

- To maximise the use of Kenya's available wind energy resource by facilitating the uptake of small, medium and large wind energy systems
- To strengthen the Kenyan wind energy sector by reinforcing its capacity through linkages and partnerships with international wind research, manufacture, investment, consulting and financing institutions
- To support the emergence of a viable market for small wind energy systems in Kenya

The project has three components:

Grid connected wind parks

Grid connected wind parks are a promising way for improving the energy security and supply. However, their development strongly depends on the identification of suitable sites where the environment and infrastructure barriers are minimal and wind resource adequate.

The ultimate goal of this project component is to remove the current barrier of insufficient information and contribute to a favourable environment for investment in grid-connected wind parks. It focuses first on the identification of all the potential wind farm sites in Kenya, then on assessing the economy of the identified sites with respect to accessibility to the national grid, power purchase price, Kenyan and East African power sector master plans, access to carbon financing, socio-economic, environmental and legal factors related to land issues etc.

To reinforce the pertinence and applicability of the studies, interested wind project developers will be encouraged to participate in these feasibility studies. The outputs will be feasibility studies and reports that will be made publicly available to facilitate investments, development and implementation of grid-connected wind park projects in Kenya.

Hybrid wind-diesel power generation for the isolated grids of Kenya

Kenya has 8 isolated grid networks powered by diesel. The current knowledge of the wind resource around the isolated grids of Kenya is very partial. Given the potential for cost savings and emission reductions that would result from developing small wind parks in Marsabit, Lamu and Lokitaung, it is strategic to draw clearly the prospects of hybrid wind-diesel power generation scheme for all the isolated grids of Kenya.

This component focuses on the detailed assessment of the wind resource around the isolated grids of Kenya and establishing the economic viability of a hybrid wind-diesel option. The current institutions in charge of isolated power generation (Isolated Power Stations (MoE), KenGen and KPLC) and the interested private investors will be associated to project development. It will also analyze the option of private/public sector partnerships to develop these systems.

This component will facilitate the implementation of hybrid wind-diesel power plants where viable.

Wind-based decentralised electrification and water pumping for community development in rural Kenya – *Promotion of the small wind energy systems (SWES) made in Kenya*

While the prospects for rural water supply and decentralised electrification projects based on SWES are large in Kenya, it is still very difficult to realize such projects. Indeed on top of suffering from wind data scarcity, development of small wind projects faces the barrier of technology unawareness in rural Kenya and the absence of a sufficiently developed supply chain for SWES country-wide.

The ultimate goal of this component is to support the growth of the Kenyan wind industry and enable the SWES market to reach sufficient state of commercialization in Kenya.

This component will be focused on four activities:

- Identifying the suitable areas with respect to wind resource, population density and local economy vibrancy; and developing a detailed wind atlas for those areas,
- Demonstrating the effectiveness of small wind energy projects and their impacts on rural development through implementation of pilot projects
- Creating awareness, marketing and setting up of SWES supply chain in target districts; enhancing local/regional capacity for installation, operation and maintenance of SWES
- Incorporating wind energy into the national and regional strategic plans for rural electrification and water supply

The project team will work closely with the relevant national authorities, local government and authorities, and District and Constituency Development Committees.

The output will be the implementation of 20 wind-based decentralised electrification and water pumping pilot projects executed to enhance productive uses of water and electricity and rural development.

This project will be a reference for developing wind energy in other Eastern African Countries

Project Partners

This project for developing wind energy in Kenya has been initiated by the Kenyan Wind Industry Sector. The project participants include Energy for Sustainable Development, Bobs Harries Engineering Limited and CraftSkills Enterprises.

Energy for Sustainable Development

Energy For Sustainable Development (ESD) is a consulting firm specializing in energy assessment, energy policy, planning, modeling, product development and commercialization. ESD has developed particular expertise in renewable energy and energy efficiency, regional and local level energy planning, modeling and forecasting, energy resource and technical assessments, product development and commercialization, economic planning, and the implementation and monitoring of commercial energy projects.

ESD Africa has a 15-year track record of working in the energy sector in Africa, with particular emphasis on renewable energy, rural and household energy, energy efficiency and Carbon Management through the Clean Development Mechanism (CDM)

ESD Africa has been involved in the wind resource measurement and analysis in the Lamu area together with KenGen under a project funded by

e8. They have also undertaken feasibility studies for wind-diesel off-grid rural electrification projects in Lamu district. ESD Ventures, an arm of ESD formed with objective of initiating low carbon businesses, is developing a wind farm project in Marsabit with a local partner and a British company

Kenyan Small Wind Energy System Manufacturers

Bobs Harries Engineering Ltd

Bobs Harries Engineering Ltd is a Kenyan company that has been manufacturing the Kijito, a wind powered mechanical water pump, since 1979. Since then more than 400 Kijito windpumps have been manufactured 300 of which are operating in Kenya. More than 60 Kijito windpumps supply people with water in the driest areas of Kenya (Eastern, North Eastern and Rift Valley provinces).

These machines run through a range of rotor diameters capable of pumping heads of 100-500ft.

BHEL has progressively oriented their activity to wind power generation. In March 2007 the company carried out their first wind-based decentralised electrification project at Esilanke Primary School (1kW wind battery charging, DANIDA supported, Kajiado District, Kenya).

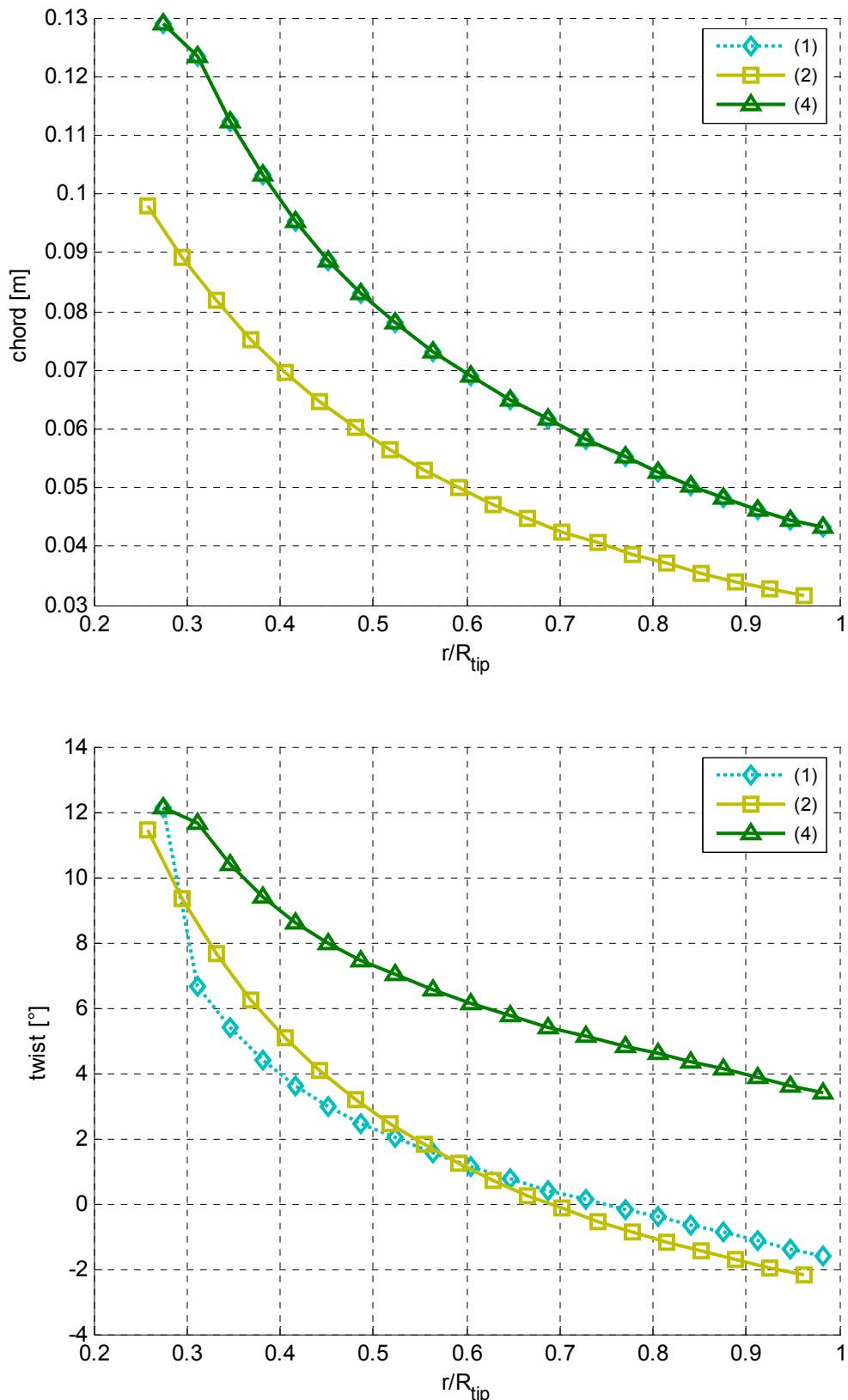
The company is therefore moving into developing wind solutions for battery charging and hybrid wind-diesel power mini grids.

Craftskills Enterprises

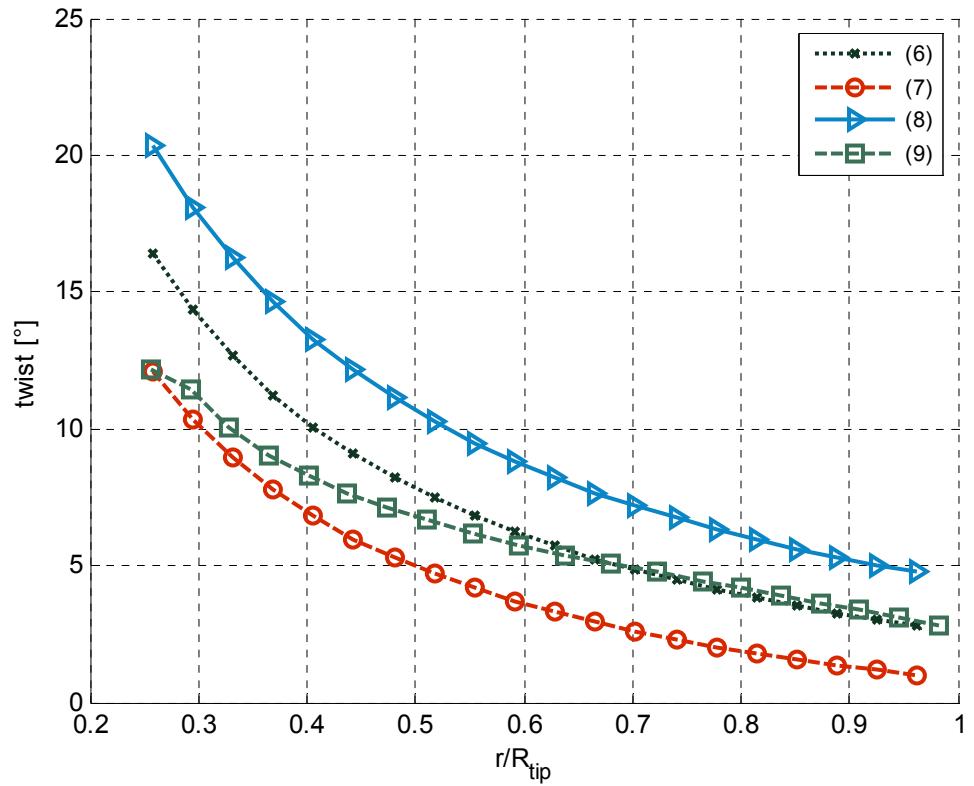
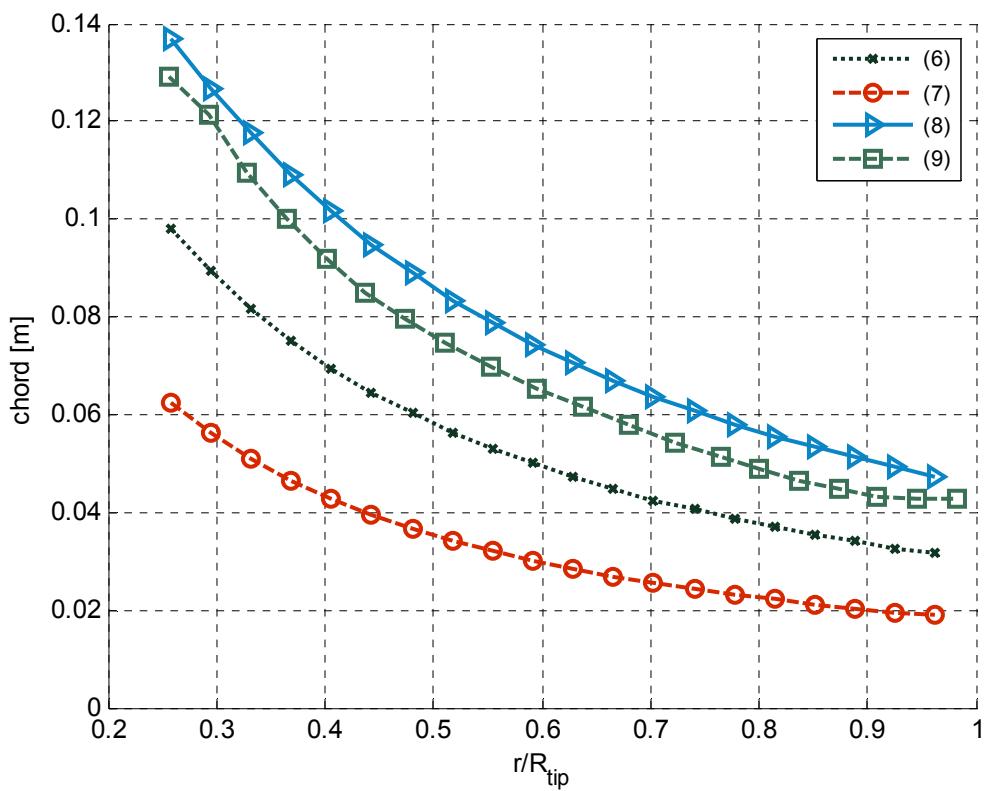
Craftskills Enterprises is a company specialized in Renewable Energy; especially wind turbines and their accessories. They started operating in the year 1998 in Kibera Nairobi and were registered in 2002. Since 50 Craftskills Enterprises wind turbines and solar hybrids have been installed in Kenya, Tanzania, Rwanda and Cameroon. In Kenya their turbines are flying in North Eastern province, Nairobi, Eastern, Rift valley, Coast, Nyanza and Central provinces with remarkable performance and durability.

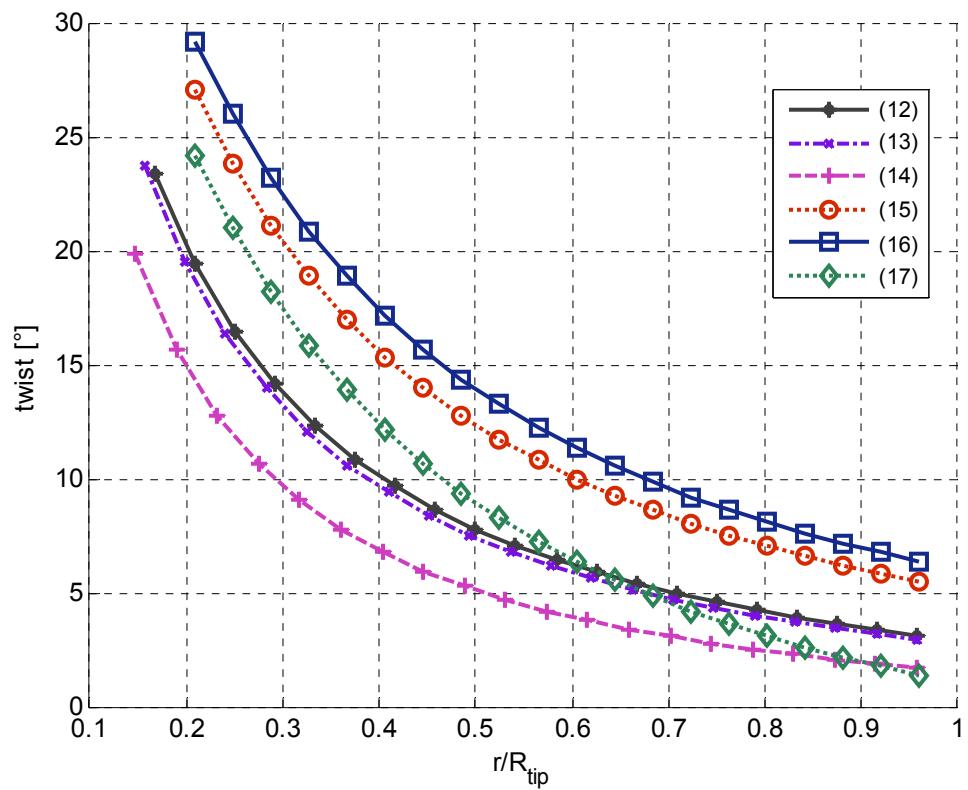
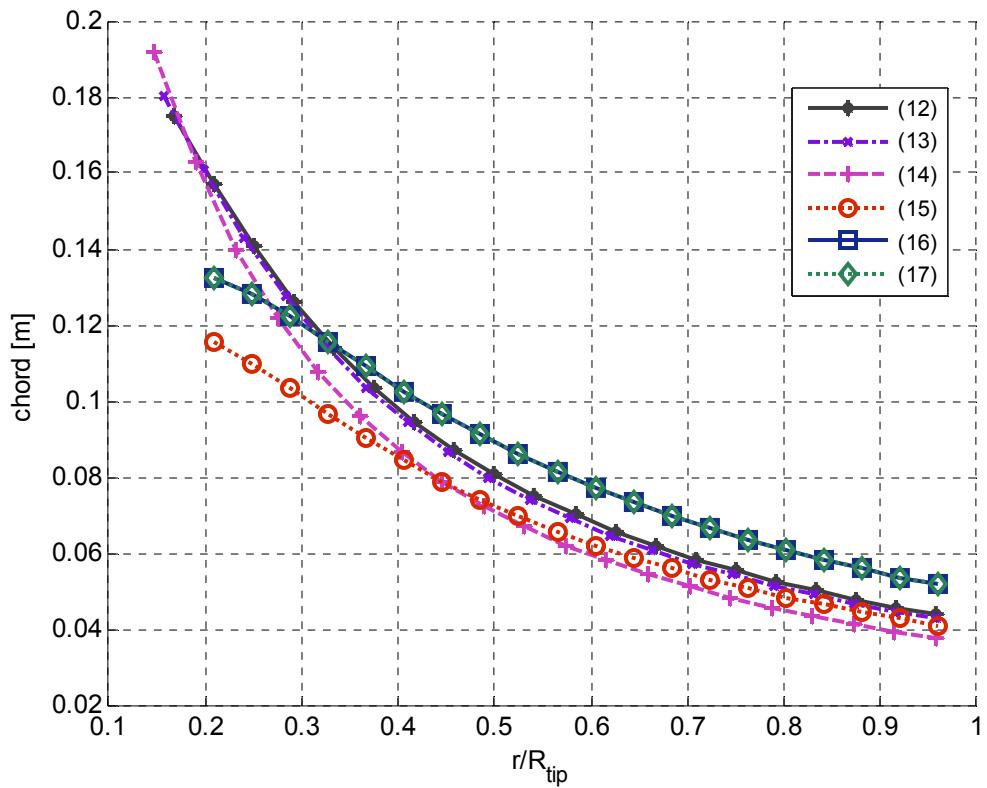
Craftskills Enterprises manufacture wind turbines, charge controllers and towers locally utilizing 90% locally available materials. Turbine size ranges from 150watts at 12volts to 12kilowatts at 400volts. They are providing electricity in rural and semi-urban homes, schools, community power projects, NGO offices, hotels and lodges. Craftskills Enterprises are also gearing to cater for large wind power systems and wind farms.

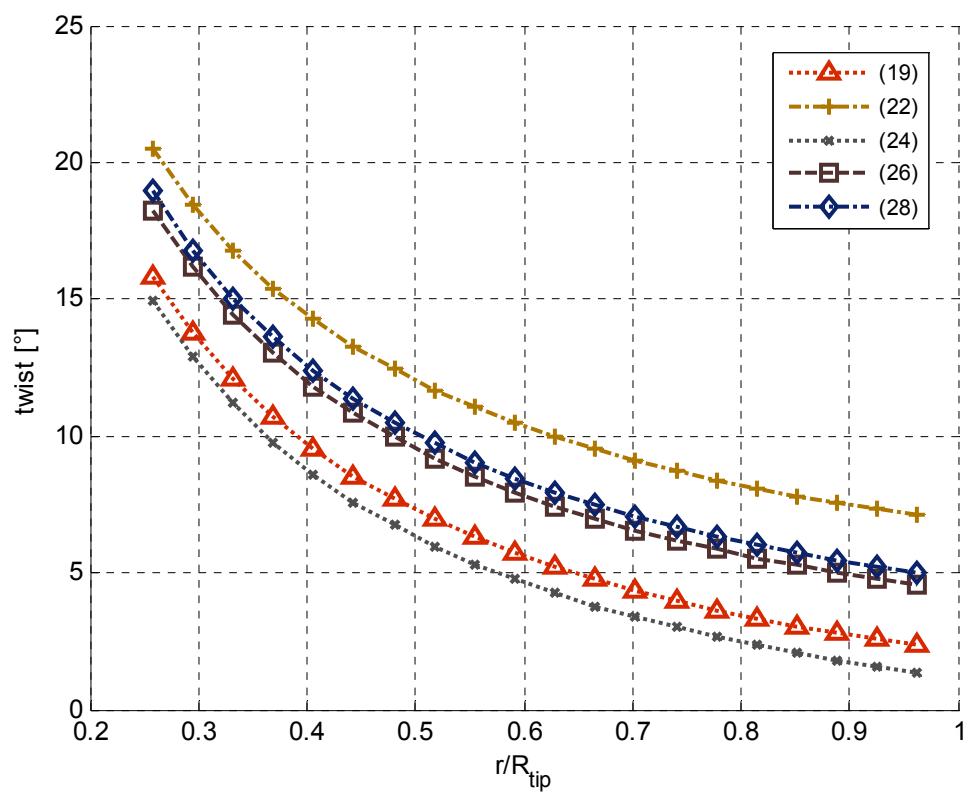
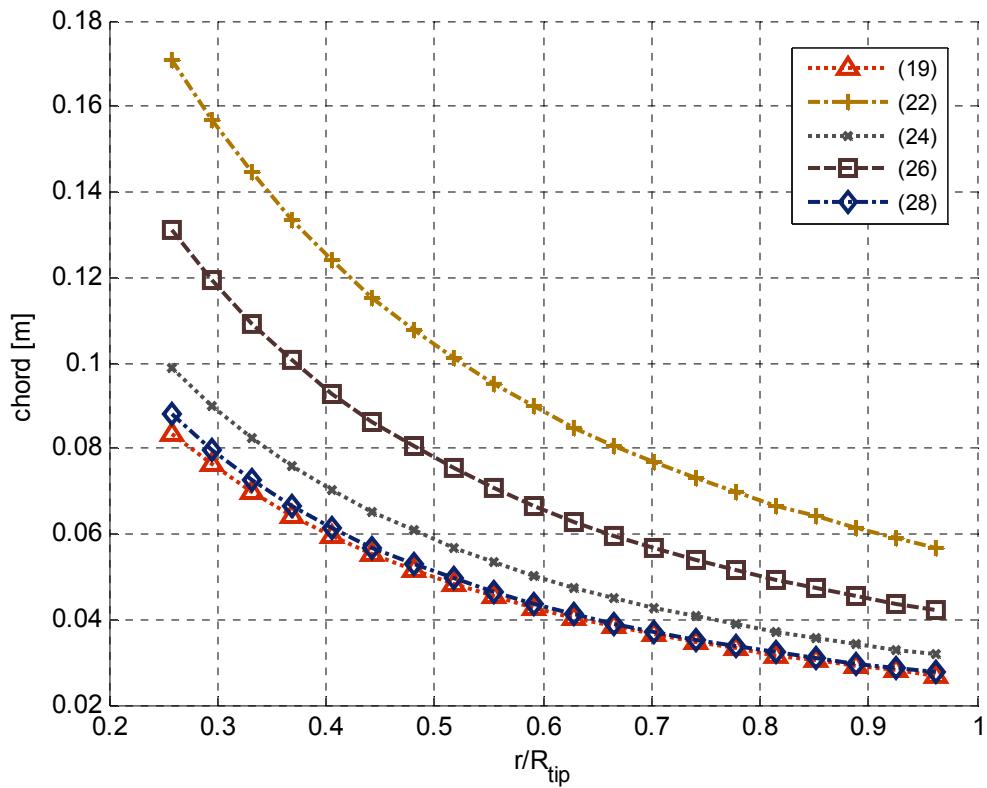
Appendix V: Chord and twist distributions

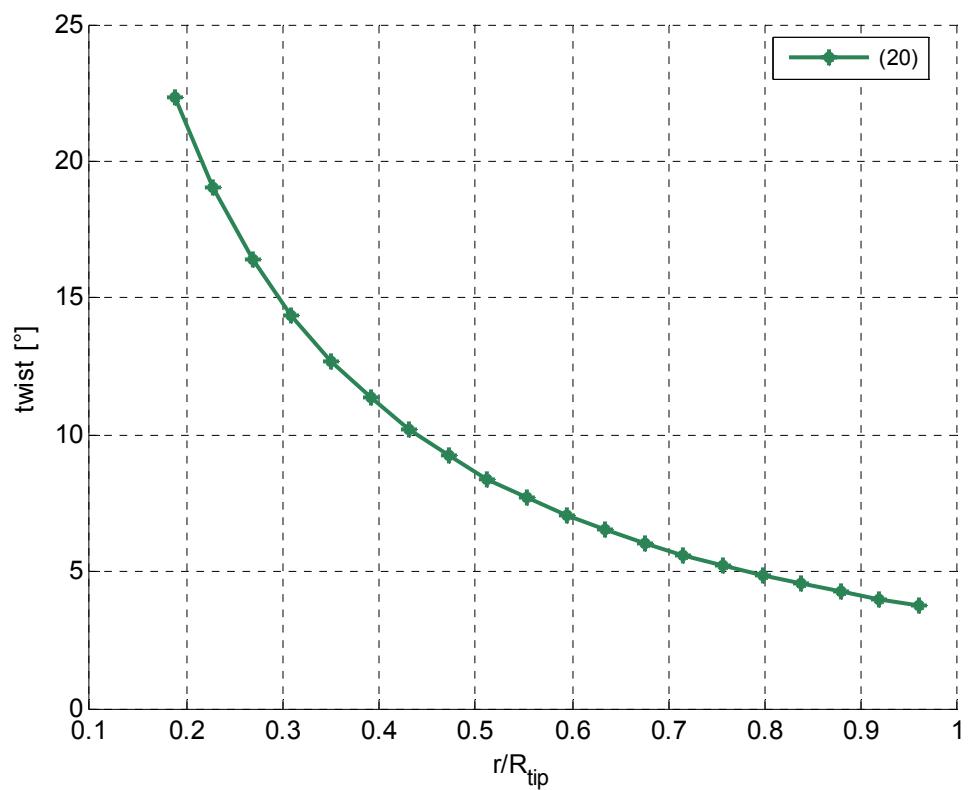
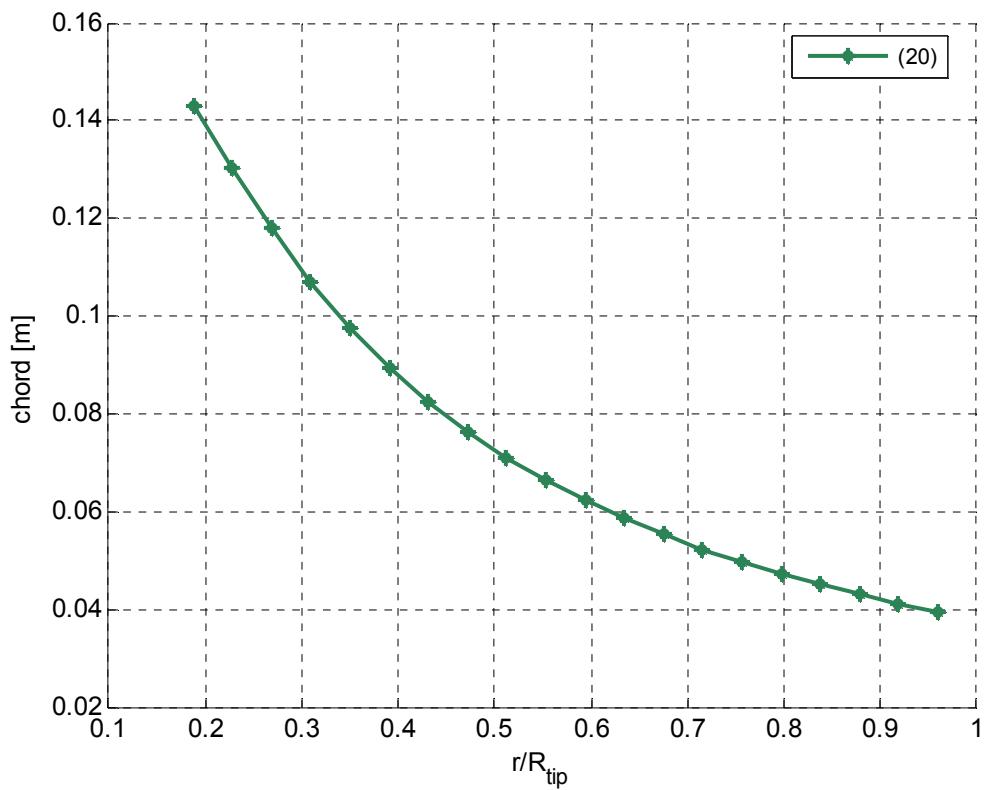


Blade designs (1) and (3), and (4), (5) and (10) are identical. Designs (18) to (28) are identical to design (4) as well.



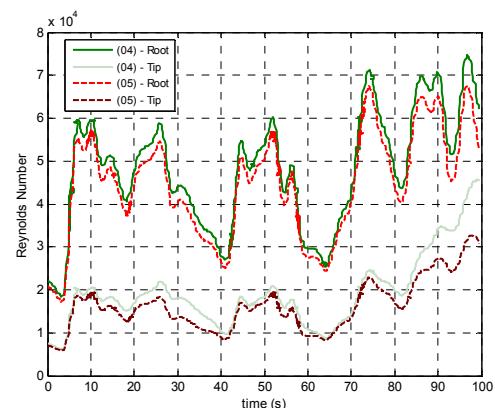
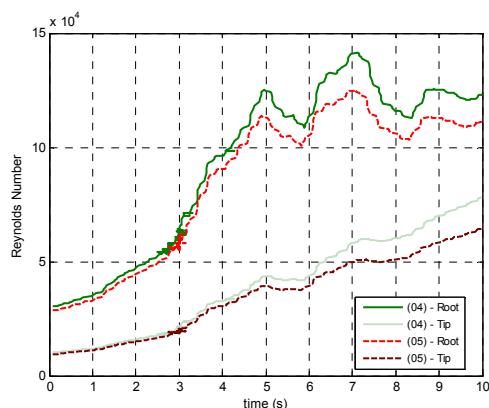
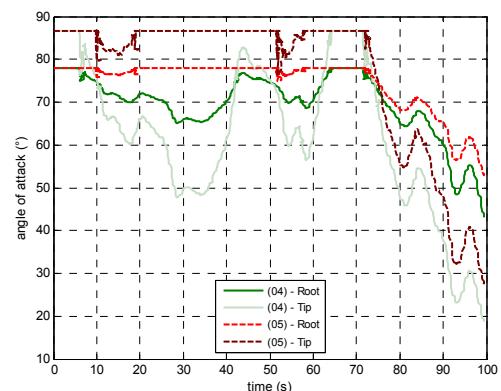
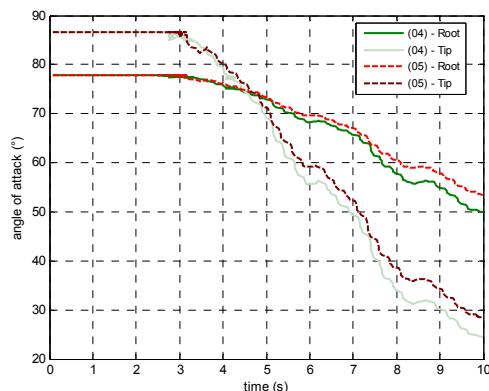
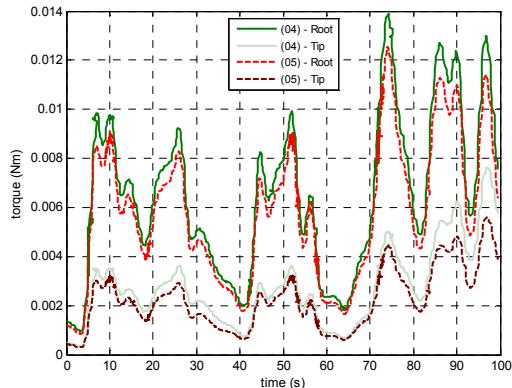
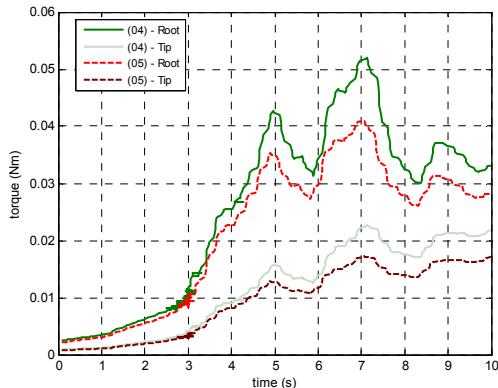




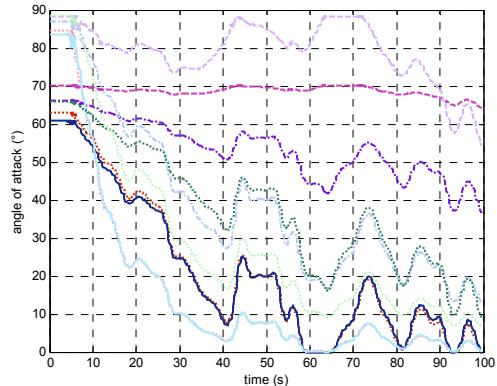
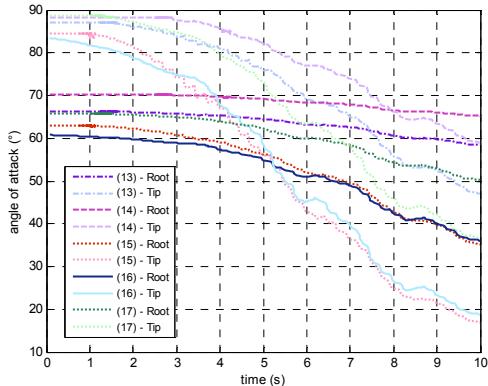
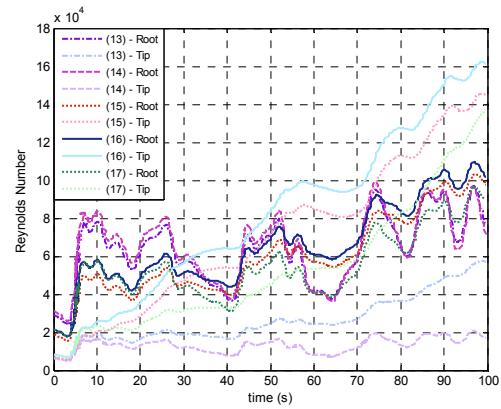
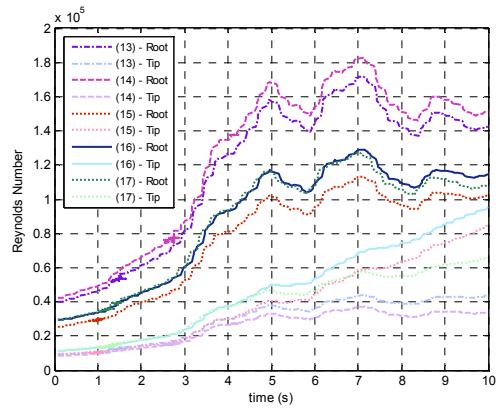
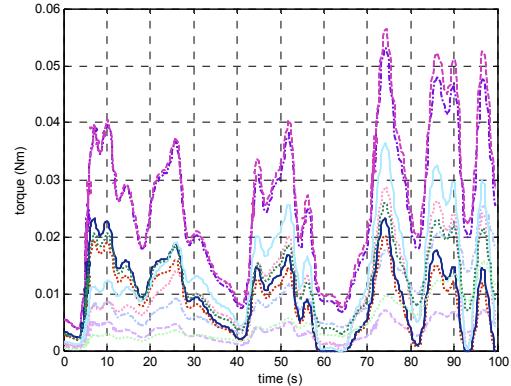
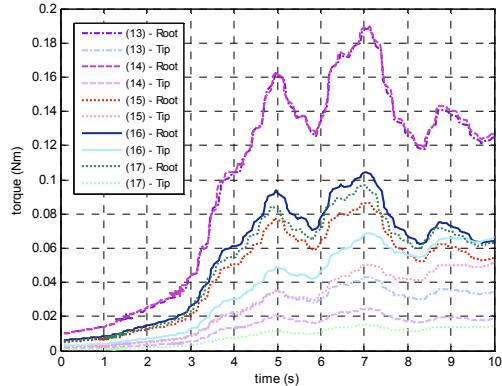


Appendix VI: Details about design choice effects on SWT performances

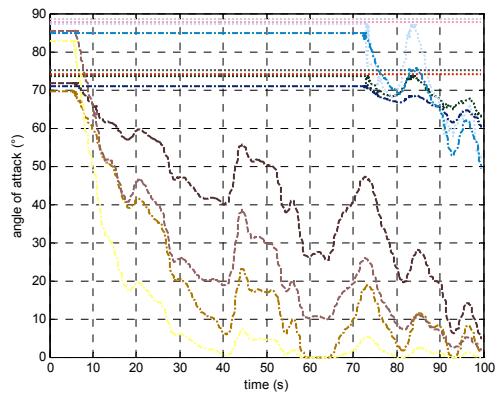
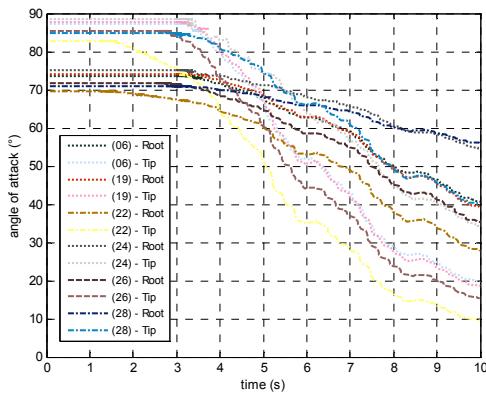
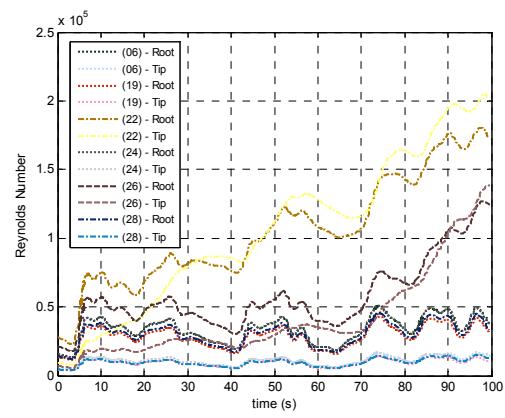
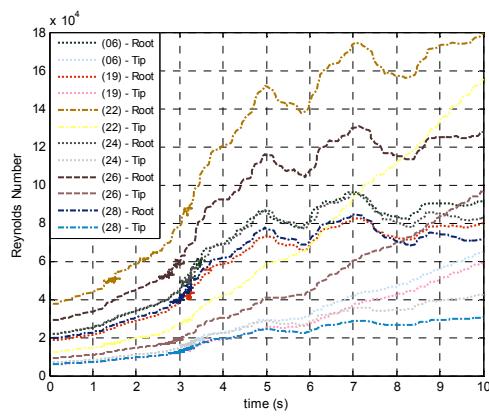
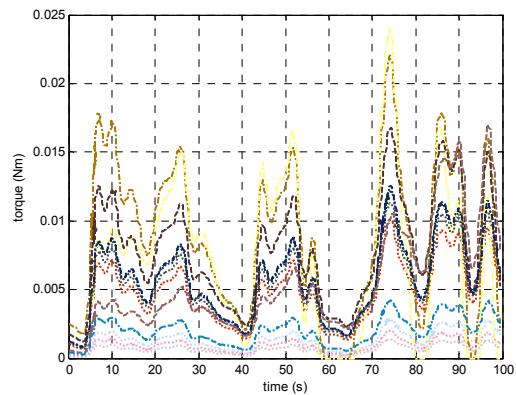
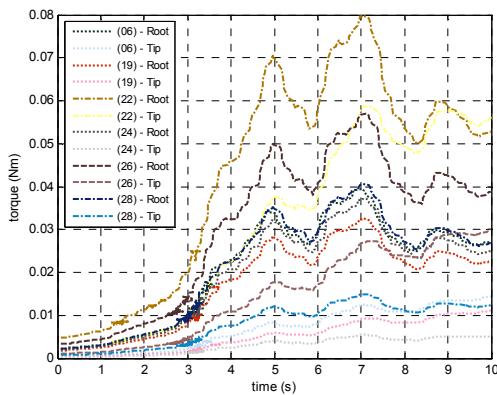
The effect of the yawing control system



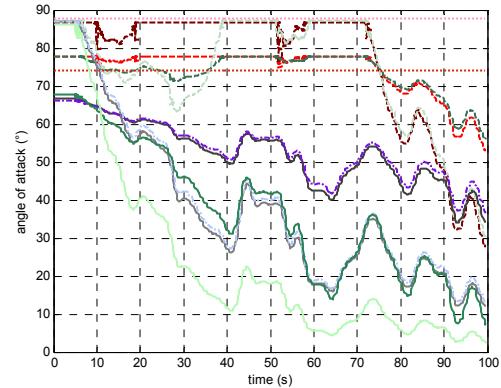
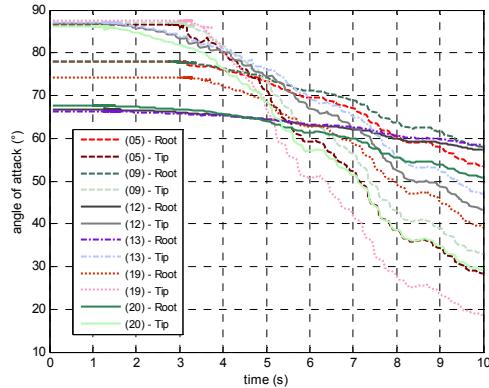
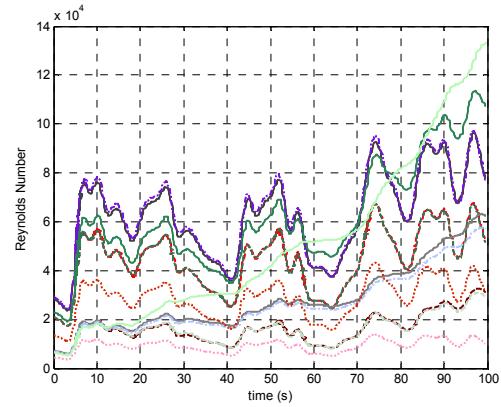
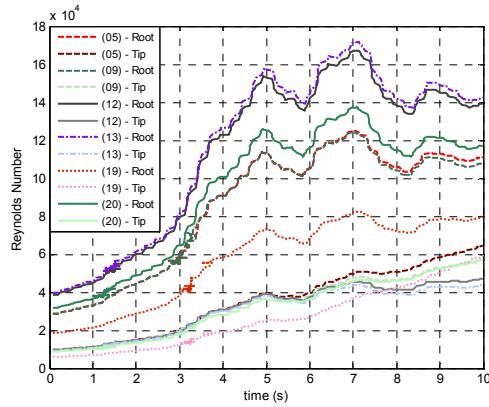
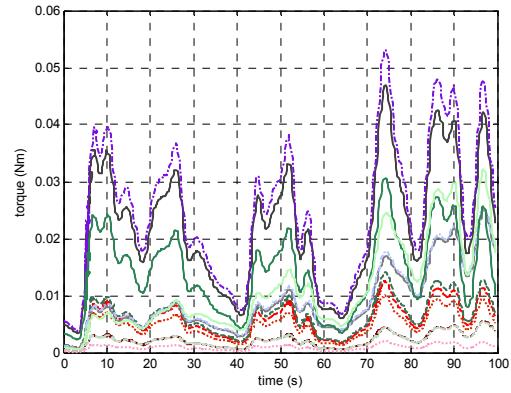
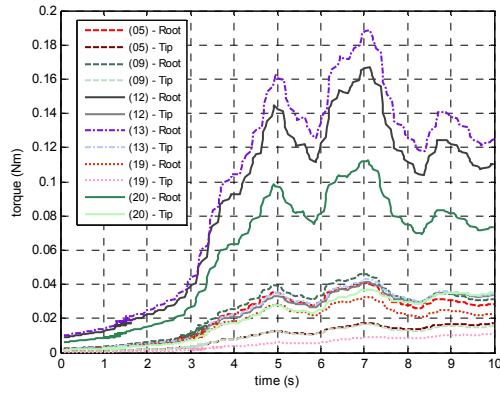
The effect of changing the number of blades



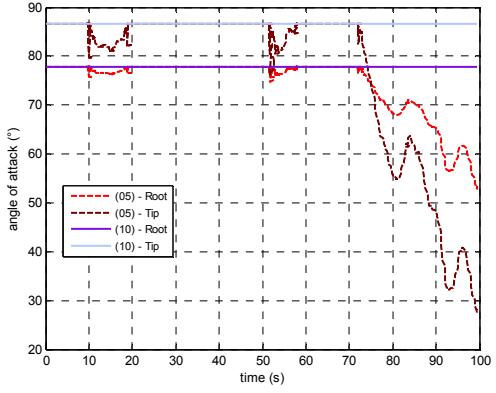
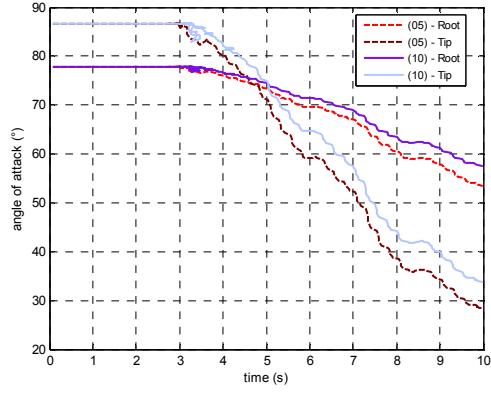
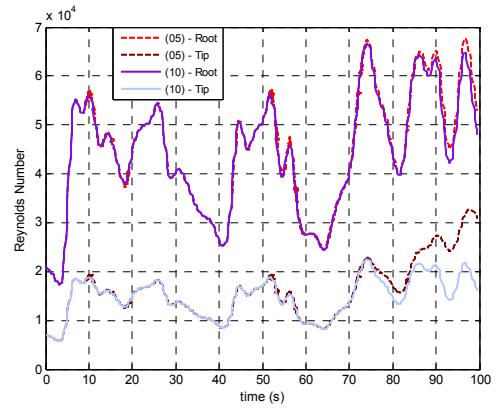
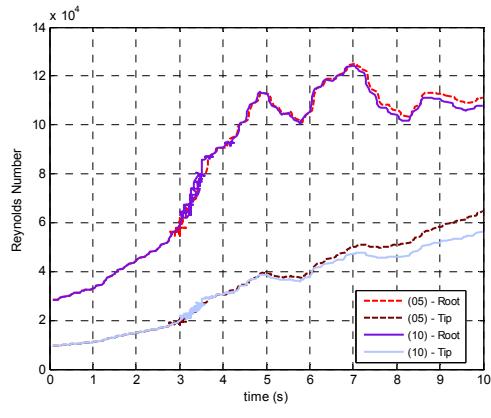
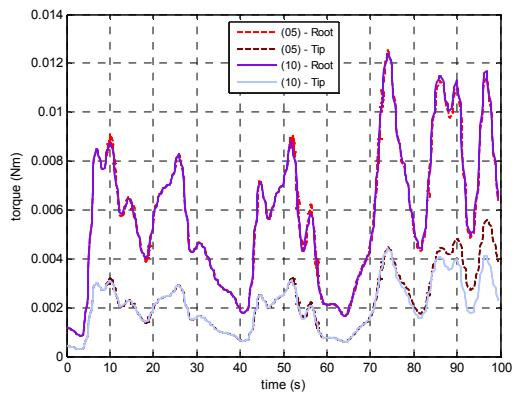
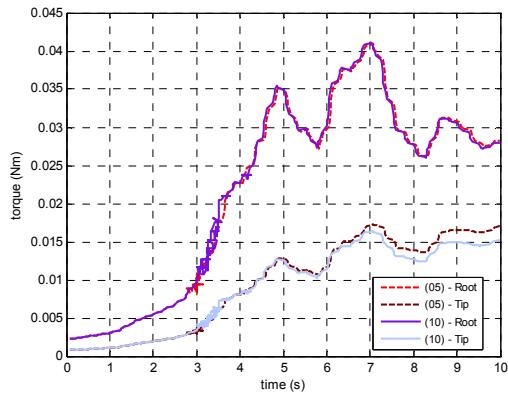
The effect of changing the airfoil



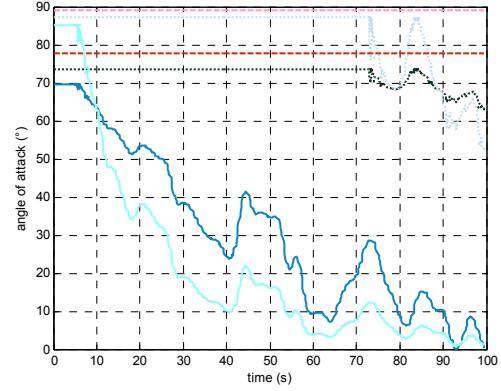
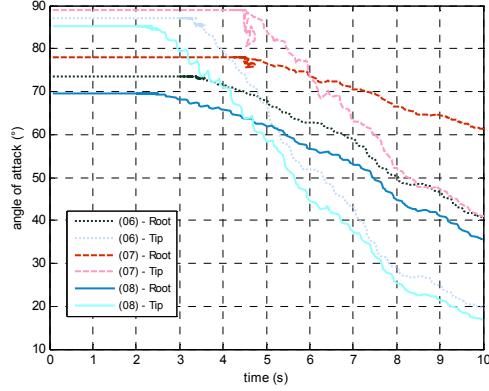
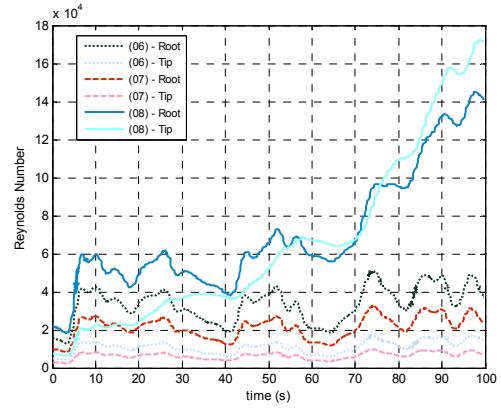
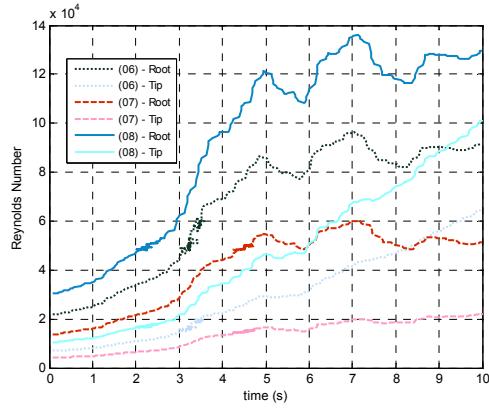
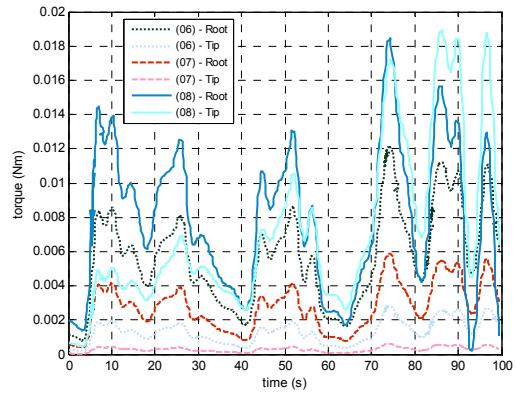
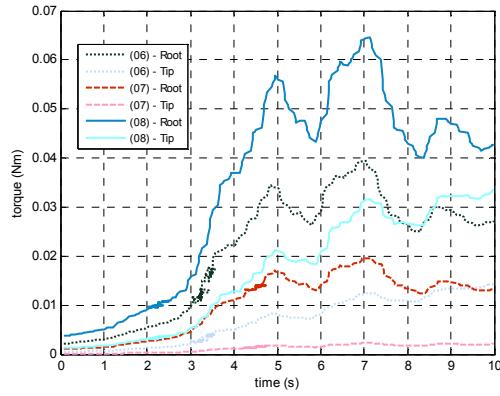
The effect of increasing blade length



The effect of changing the generator



Effect of changing the design criteria



Appendix VII: Questionnaires delivered to Esilanke's community

Evaluation of the wind electrification of Esilanke Primary School

Parents' Satisfaction

QUESTIONNAIRE

PUPIL'S FAMILY NAME:

PUPIL'S FIRSTNAME:

BROTHER/SISTER AT Esilanke Primary School:

.....
.....
.....
.....

DATE: 2007

Are the parents able to read and answer this questionnaire own their own?

Yes – No

Is (are) their child (children) helping them by traducing it and reporting the parents' answers?
Yes – No

If Yes, Name of the child (children) who are helping them:

.....
.....
....

Are both the father and mother participating in answering this questionnaire?

Yes – No

If No, who is present?

Father: Yes – No

Mother: Yes – No

About the family

General information

Family Name:

First Name: Father:

Age: Father:

Mother:

Mother:

Still alive: Father:

Mother:

Address:

.....
.....
....

Telephone: Email:

Arrival date at Esilanke Primary School/Esilanke Community:

.....

Distance from household to school:

The family

How many children are composing the family?

| Age | Sex (M/F) | Activity* | if working, what is he/she doing? |
|-------------|-----------|-----------|-----------------------------------|
| Children 1: | | | |
| Children 2: | | | |
| Children 3: | | | |
| Children 4: | | | |
| Children 5: | | | |
| Children 6: | | | |

*For Activity, please specify between: Pupils at EPS, College, University, Working, Taking care of Household, if another activity, please specify it.

Financial resources of the family

What are the family's sources of income?

- Husband regular salary

Please specify the husband's profession:

.....

- Wife regular salary

Please specify the wife's profession:

.....

- Farming

Please specify the farming products you sell:

.....

- Business

Please specify the business activity:

.....

- Other:

What is the average amount of your family's monthly income?

- < 1000 KSh/month
- 1001< <2000 KSh/month
- 2001< <4000 KSh/month
- 4001< <7000 KSh/month
- 7001< <10000 KSh/month
- 10001< <15001 KSh/month
- 15001< <20000 KSh/month
- >20001 KSh/month

What is its maximum value: KSh

Occurring in : (Please specify the month(s) of the year)

What is its minimum value: KSh

Occurring in : (Please specify the month(s) of the year)

What are the factors which influent the variability of the income amount? (Weather, cost of raw material...)

.....
.....
.....

Living conditions

Are you satisfied with the living conditions of your family?

Yes – No

Please tell whether the following points are an issue for you and your family? How much?

| Points | It is ... | | | |
|--|--------------------|------------------|---------------|--------------|
| | An important issue | A moderate issue | A minor issue | Not an issue |
| Access to sufficient amount of clean water for drinking/cooking purposes | | | | |
| Access to sufficient amount of clean water for hygiene purposes | | | | |
| Access to sufficient amount of water for farming purposes | | | | |
| Access to sufficient amount of food for the whole family | | | | |
| Health / Diseases | | | | |
| Access to health care | | | | |
| Energy | | | | |
| Business opportunities | | | | |
| Cost of energy | | | | |
| Cost of water | | | | |
| Cost of food | | | | |
| Financial resources of the family | | | | |
| Security | | | | |
| Telecom network | | | | |
| Infrastructures (Roads, transportation means...) | | | | |
| Access to electricity | | | | |
| Development of Esilanke Community | | | | |
| Other 1: | | | | |
| Other 2: | | | | |
| Other 3: | | | | |

For the points you have classified as “important”, “moderate” and “minor” issue, could you specify at what period of the year (months) these issues occurs and what are the consequences on the living conditions.

.....

.....

.....

.....

.....

.....

.....

.....

.....

.....

.....

.....

Energy and light

What are the sources of energy/light used by the family?

| | Uses | | | Quantity | Cost |
|----------|---------|-------|-----------------|----------|------------|
| | Cooking | Light | Other (Specify) | (/week) | (KSh/week) |
| Wood | | | | | |
| Paraffin | | | | | |
| Charcoal | | | | | |
| Cow dung | | | | | |
| Battery | | | | | |
| | | | | | |
| | | | | | |

Please specify the sources of light, heat and energy used by the family:

Sources of light:

.....

Sources of heat:

.....

.....

The electrification of Esilanke Primary School

General questions

Have you ever been to the School since the installation?

Yes-No

When a parent goes to the school, what are the reasons for?

- Meeting with teacher(s)
- Community event, which one(s):

- Watch the TV
- Other:

How satisfied/dissatisfied are you with the electrification of Esilanke Primary School?

- I am very much satisfied
- I am very satisfied
- I am satisfied
- I do not feel special satisfaction, dissatisfaction
- I am dissatisfied
- I am very disappointed

Impact of electrification

How would you evaluate the impact of the electrification of Esilanke Primary School on:

| Situation | Impact |
|-----------|--------|
| | |

| | Very much positive | Very positive | Positive | Null | Negative | Very negative |
|--|--------------------------|------------------|----------|------|----------|------------------|
| Improving the water situation | | | | | | |
| Improving the food situation | | | | | | |
| Improving the studying conditions | | | | | | |
| Improving the teaching conditions | | | | | | |
| Improving school management | | | | | | |
| Increasing Pupil attendance at school | | | | | | |
| Starting a boarding school project at Esilanke Primary School | | | | | | |
| Improving the security at the school | | | | | | |
| Improving the security in the neighbour area of the school | | | | | | |
| Attracting teachers | | | | | | |
| Providing good living conditions for the teachers and their family | | | | | | |
| Organising of events for Esilanke community | | | | | | |
| Disseminating electricity access within Esilanke Community | | | | | | |
| Accessing electricity for my own household | | | | | | |
| Enabling the development of Esilanke Community | | | | | | |

What do you think about the morning/evening classes?

| | Yes | No |
|--|-----|----|
| It improves the studying conditions. | | |
| Pupils benefit from better lighting conditions for doing their homework. | | |
| My children attend it regularly. | | |
| My children will improve their school results by attending it. | | |
| I have heard that they are so many power shortages that classrooms were lighted only a few morning/evening for the purpose of morning/evening classes. | | |

After the electrification of Esilanke Primary School, what are your expectancies for the future?

| | Yes | No |
|--|-----|----|
| My children will have better school results. | | |
| Security will be better. | | |
| My household will access electricity. | | |
| Esilanke Community will reach development. | | |

Maintaining the installed equipment

Maintenance is the key-step to ensure the sustainability of the power installation and therefore a long project life. For example, battery water level must be refilled regularly; wind turbine and power system must be inspected once a year.

According to you, who has to finance the maintenance?

| | Yes | No |
|---------------------------|-----|----|
| The parents of the pupils | | |
| The school staff | | |

| | | |
|---------------------------------------|--|--|
| Esilanke community | | |
| The Government | | |
| The Ministry of Education | | |
| The donors of the equipment | | |
| The company manufacturing the devices | | |
| The company installing the devices | | |
| Maintenance should be free | | |

It is important that the beneficiaries of the electrification and the users of the system participate to the operation and maintenance costs.

As parent of pupils from Esilanke Primary School, would you be ready to participate to the operation and maintenance costs?

Yes – No

How much a term would your family be ready to pay for the maintenance of the power supply equipment of Esilanke Primary School?

KSh

Would you agree to pay a monthly fee for morning/evening classes in order to operate and maintain the power supply equipment?

Yes – No

According to you, what would be a reasonable monthly fee for morning/evening classes?

- KSh 5 / month / pupil
- KSh 10 / month / pupil
- KSh 20 / month / pupil
- KSh 40 / month / pupil
- KSh 50 / month / pupil
- More, how much: KSh / month / pupil

Development of Esilanke Community

Would you like that Esilanke Community reach development?

Yes - No

Access to electricity for all Esilanke households

What kind of electric devices does the family own?

- None
- Light bulbs, how many:
- Fluorescent lights, how many:
- Radio
- TV black and white
- TV Colour
- Other(s), please specify:
.....
.....

If a development plan would be built with Esilanke Community targeting the electrification of the area. Would you be ready to pay for it?

Yes – No

A part of the investment should be financed by Esilanke Community. Once the power supply and distribution system is installed, Esilanke Community would have to pay the whole operation and maintenance charges.

How much a month would you be ready to pay for getting electricity at home?

- < KSh 200 / month
- KSh 200 – 400 / month
- KSh 400 – 600 / month
- KSh 600 – 800 / month
- KSh 800 – 1000 / month
- KSh 1000 – 1500 / month
- KSh 1500 – 2000 / month
- Even more, electricity is really something needed. Please specify: KSh / month

Mobile Phone charging service

How many mobile phones do you have in the family?

- 0
- 1
- 2
- 3
- More, please specify:

If you do not have any mobile phone in the family, is it because:

- It is too expensive. Our family can not afford it.
- The network coverage is too bad. Mobile phones are useless.
- It is very difficult to find a place where to recharge the batteries.
- The last one(s) we had is (are) broken. Are you going to replace it? Yes - No
- The last one(s) got stolen. Are you going to replace it? Yes - No
- Other reason, please specify:
.....

If you have at least one mobile in the family, please continue answering the questionnaire. Otherwise you are done! Thanks for having answered this questionnaire!

How do you access the phone service?

- Through Safaricom scratch cards
- Through Celtel scratch cards
- Other:

What are the main issue(s) connected to mobile phone owning. Please rank the following sentences from 1 to 3 according to their importance (1: most important).

Rank

- It is expensive to buy a mobile phone.
- Scratch card are expensive.
- The network coverage is too bad.
- It is very difficult to find a place where to recharge the batteries.

In average, how much a month does your family spend for reloading your account/purchase scratch card?

KSh / month

Where do you usually recharge the batteries of your mobile phone(s)?

- At home. Please specify through which mean (battery...):
.....
- In a shop. Please specify the name of the shop and the town/settlement:
.....
- At Esilanke Primary School.
- Somewhere else. Please specify:
.....

How many times a week do you recharge your mobile phone?

- Less than 1 (every second week for instance)
- 1
- 2
- 3-4
- 5-6
- Everyday

If it would be possible to charge the batteries of the mobile phone at Esilanke Primary School, would you go to Esilanke Primary School to recharge the batteries of your mobile?

Yes – No

Would you be ready to pay for it?

Yes – No

According to you, what would be a reasonable fee for charging the batteries of mobiles at Esilanke Primary School?

KSh / charging

-Fluid Mechanics

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