

2014

Analysis of onshore wind - solar PV - battery bank power generation system development for Toamasina port

Hary Lys Jean Louis Soloniainanirinanandrianina
World Maritime University

Follow this and additional works at: http://commons.wmu.se/all_dissertations



Part of the [Power and Energy Commons](#)

Recommended Citation

Soloniainanirinanandrianina, Hary Lys Jean Louis, "Analysis of onshore wind - solar PV - battery bank power generation system development for Toamasina port" (2014). *World Maritime University Dissertations*. 475.
http://commons.wmu.se/all_dissertations/475

This Dissertation is brought to you courtesy of Maritime Commons. Open Access items may be downloaded for non-commercial, fair use academic purposes. No items may be hosted on another server or web site without express written permission from the World Maritime University. For more information, please contact library@wmu.se.

WORLD MARITIME UNIVERSITY

Malmö, Sweden

**ANALYSIS OF ONSHORE WIND - SOLAR PV -
BATTERY BANK POWER GENERATION
SYSTEM DEVELOPMENT FOR TOAMASINA
PORT**

By

SOLONIAINANIRINANANDRIANINA HARY LYS JEAN LOUIS

Madagascar

A dissertation submitted to the World Maritime University in partial
fulfilment of the requirements for the award of the degree of

MASTER OF SCIENCE

In

MARITIME AFFAIRS

(PORT MANAGEMENT)

2014

DECLARATION

I certify that the material in this dissertation that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views, and are not necessarily endorsed by the University.

Signature: 

Date: 22 September 2014

Supervised by: Aykut Ölçer
World Maritime University

Assessor: Shuo Ma
World Maritime University

Co-assessor: Iraklis Lazakis
University of Strathclyde

ACKNOWLEDGEMENT

First and foremost, my thanks go to the Almighty God, for his mercy, love and guidance at every step of my life.

I wish to express my sincere gratitude to my distinguished supervisor, Dr. Aykut Ölçer for his advice, guidance and assistance throughout my dissertation.

I owe special thanks to my donor and “Agence Portuaire Maritime et Fluviale (APMF)” for their support and offering me the opportunity to study at the World Maritime University (WMU).

Furthermore, my appreciation extends to WMU Librarian, Mr Christopher Hoebeke and Librarian Assistant Ms Anna Volkova for their assistance in data collection. In addition, my special gratitude goes to WMU personnel and faculty, their contribution to the success of my training at WMU is invaluable.

Last but not least, I would like to express my appreciation to friends and family for their supports.

ABSTRACT

Title of dissertation: **Analysis of onshore wind - solar PV - battery bank power generation system development for Toamasina port**

Degree: **MSc**

The dissertation presents a techno-economic feasibility and environmental evaluation of a hybrid renewable energy generation system, comprised of onshore wind turbines, solar PV arrays and battery bank, to meet the electricity requirement of Toamasina port.

The study undertakes a brief look at the current state of power generation in the Island of Madagascar, and in the area where the port of Toamasina is located. In addition, further descriptions and discussions on relevant wind, solar and battery technologies are undertaken.

Furthermore, the technical and economic performances of the technologies of wind, solar and battery which constitute the hybrid power generation system are assessed. HOMER, optimization software is used for the assessment, modeling and sizing of the system. Thousands of cases are implemented through simulation by HOMER, to achieve an optimal system primarily based on the Net Present Cost (NPC) of the whole system.

Project appraisal is carried out to investigate the viability of the project. The appraisal takes into consideration, not only, the overall direct costs of the entire hybrid system, but also the saved costs of greenhouse gases (GHG) emissions, also called costs of externalities. All these costs are put into factored to calculate the Payback period, the Net Present Value (NPV) and the Internal Rate of Return (IRR) of the investment to outline the project viability.

Lastly, recommendations in the application of Lean Enterprise model for port is filed, with principal goal to reduce or cut wastes in electricity consumption generated during port activities. The Lean Enterprise model applied to port is presented along with various necessary steps to be considered throughout Lean application to port of Toamasina.

Keywords: Renewable, energy, wind, solar, battery, turbine, Toamasina Port, global warming potential (GWP), carbon dioxide equivalent (CO₂e), feasibility, viability, appraisal, externalities, emissions

TABLE OF CONTENTS

DECLARATION	ii
ACKNOWLEDGEMENT	iii
ABSTRACT.....	iv
TABLE OF CONTENTS.....	v
LIST OF TABLES	viii
LIST OF FIGURES	ix
LIST OF ABBREVIATIONS.....	xi
I- INTRODUCTION	1
I-1. Background	1
I-2. Research objectives	3
I-3. Research questions.....	3
I-4. Methodology	4
I-5. Scope of Research.....	5
I-6. Limitations.....	6
I-7. Port of Toamasina	6
II- LITERATURE REVIEW	10
II-1. Wind energy	10
II-2. Solar energy.....	11
II-3. Energy storage	12
II-4. Hybrid Photovoltaic/Wind energy and Battery system	12
II-5. Lean	13
III- TECHNOLOGIES	14
III-1. Wind turbine.....	14
III-11. Overview of energy and power in the wind	15
III-12. Wind turbine power output	16
III-13. Wind energy projects	17
III-14. Cost of wind energy	18
III-15. External costs of wind energy.....	21
III-2. Solar Photovoltaic (PV).....	23
III-21. Photovoltaic solar panels (PV)	24
III-22. PV technologies	25

III-23.	Total PV system costs	26
III-24.	Environmental impacts from the solar PV technologies	28
III-3.	<i>Battery system</i>	29
III-31.	Overview of energy storage	29
III-32.	Lead-Acid Batteries.....	30
III-33.	Lithium-ion Batteries	32
III-34.	Metal-Air Batteries	33
III-35.	Sodium-Sulfur Batteries.....	33
III-36.	Vanadium-Redox Flow Batteries	34
III-37.	Zinc-Bromide Flow Batteries	35
III-38.	Opportunities and challenges of energy storage.....	35
III-4.	<i>Converters</i>	37
IV-	A FEASIBILITY STUDY OF WIND-SOLAR-BATTERY POWER GENERATION SYSTEM	39
IV-1.	<i>HOMER</i>	40
IV-2.	<i>Overview of the present electricity supplies into Toamasina port</i>	41
IV-3.	<i>System description and configuration</i>	41
IV-4.	<i>System modelling</i>	42
IV-41.	PV modules.....	43
IV-42.	Wind turbine.....	45
IV-43.	Battery bank	46
IV-44.	Power converter	49
IV-5.	<i>Configuration results analysis</i>	50
IV-6.	<i>Cost structure of the system</i>	53
IV-7.	<i>Project appraisal</i>	55
IV-71.	Annual power bill.....	56
IV-72.	Ecological cost	56
IV-73.	Ships' waiting cost	58
IV-74.	Excess of electricity.....	59
IV-75.	Without-Project Case, and With-Project Case (costs in US\$)	59
IV-76.	Payback Period	60
IV-77.	Net Present Value (NPV).....	60
IV-78.	Internal Rate of Return (IRR)	61
V-	CONCLUSION AND RECOMMENDATIONS	62
V-1.	<i>Conclusion</i>	62
V-2.	<i>Recommendations</i>	63
V-21.	Port energy policy	63

V-22. Lean concept.....	64
V-221. Lean prinviples	65
a) Understanding waste.....	65
b) Setting the direction	67
c) Understanding the big picture.....	67
d) Detailed mapping	68
e) Checking the plan fits the direction.....	68
V-222. Lean implementation model for port of Toamasina	68
a) Continuous improvement culture	70
i. Teamwork	71
ii. Kaizen	71
b) Workplace Organization Lean Tools	71
i. 5S system	72
ii. Visual Workplace.....	73
iii. Point-Of-Use Storage (POUS)	74
c) Workplace Analysis Tools	74
i. Layout Analysis.....	74
ii. Principles of Single Minute Exchange of Die (SMED)	75
iii. Standardized Work.....	75
d) Workplace Optimization Tools	75
i. Quality at the Source.....	76
ii. Total Productive Maintenance (TPM)	76
iii. Value stream map	76
iv. Current state value stream map	77
v. Future state value stream map	77
vi. Value stream implementation plan.....	77
List of References	78

LIST OF TABLES

TABLE III-311: BATTERY TECHNOLOGIES AND APPLICATION SPECIFICATIONS	29
TABLE III-312: COSTS OF ENERGY STORAGE TECHNOLOGIES	29
TABLE III-32: TECHNICAL PARAMETERS FOR LEAD ACID BATTERIES	31
TABLE III-33: TECHNICAL PARAMETERS FOR LIB	32
TABLE III-35: TECHNICAL PARAMETERS OF NAS BATTERIES	34
TABLE IV-411 : AVERAGE MONTHLY SOLAR RADIATION (IN $\text{kWh}/\text{m}^2/\text{DAY}$)	44
TABLE IV-412: PV CHARACTERISTICS	44
TABLE IV-421: WIND TURBINE DESCRIPTION	45
TABLE IV-431 BATTERY DESCRIPTIONS	46
TABLE IV-441: CONVERTER DESCRIPTIONS	49
TABLE IV-51: CONSTRAINTS AND ECONOMICS	50
TABLE IV-52: OPERATING AND ECONOMIC PERFORMANCES	50
TABLE IV-61: CASH FLOW SUMMARY (IN US\$)	53
TABLE IV-751: WITHOUT/WITH PROJECT CASE COSTS (IN US\$)	59
TABLE IV-752: PROJECT COSTS SUMMARY (IN US\$)	60
TABLE V-2211: LEAN THINKING	65

LIST OF FIGURES

FIGURE I-61: APMF HEADQUARTER	7
FIGURE I-62: PART OF TOAMASINA PORT FACILITY LAYOUT	9
FIGURE III-12: POWER CURVE FOR 200kW ITALTECHWIND WIND TURBINE	16
FIGURE III-131: TYPICAL INSTALLED CAPITAL COSTS FOR	17
LAND-BASED WIND PROJECT	17
FIGURE III-132: TYPICAL INSTALLED CAPITAL COSTS FOR	18
OFFSHORE WIND PROJECT	18
FIGURE IV-11I: WIND POWER TOTAL GLOBAL CAPACITY	21
FIGURE III-2: SOLAR PV TOTAL GLOBAL CAPACITY.....	24
TABLE III-22: TYPICAL COST AND PERFORMANCE VALUES OF SOLAR PV SYSTEMS	25
FIGURE III-231: PV SYSTEM PRICE TRENDS	27
FIGURE III-232: SOLAR PV GLOBAL CAPACITY AND ANNUAL INVESTMENT	27
FIGURE III-41: WIND ENERGY TYPE CONVERTER	37
FIGURE III-42: INVERTER MODULE SET	38
FIGURE IV-2: HYBRID SYSTEM ARCHITECTURE	42
FIGURE IV-41: HOURLY LOAD PROFILE FOR A YEAR.....	43
FIGURE IV-42: WIND RESOURCE.....	43
FIGURE IV-43: SOLAR RESOURCES.....	43
FIGURE IV-422: ITALTECHWIND 200KW WIND TURBINE POWER CURVE	46
FIGURE IV-432: BATTERY CAPACITY CURVE.....	47
FIGURE IV-433: BATTERY LIFETIME CURVE.....	48
FIGURE IV-442: FLEXPHASE CONERTER EFFICIENCY.....	49
FIGURE IV-53: MONTHLY AVERAGE ELECTRICITY PRODUCTION	51

FIGURE IV-54: BATTERY BANK STATE OF CHARGE	52
FIGURE IV-55: MONTHLY STATISTICS	52
FIGURE IV-56: FREQUENCY HISTOGRAM OF BATTERY STATE OF CHARGE	52
FIGURE IV-62: DISCOUNTED CASH FLOW SUMMARY.....	53
FIGURE VIII-E-3: SUB-PANAMAX MONTHLY RATE	58
FIGURE V-2212: WASTE DUE TO OVERPRODUCTION	66
FIGURE V-2213: WASTE DUE TO WAITING TIME	66
FIGURE V-2214: WASTE CAUSED BY UNNECESSARY MOTION DUE TO UNORGANIZED WORK AREA... 67	
FIGURE V-2215: LEAN CYCLE AND PHASES	68
FIGURE V-2221: LEAN IMPLEMENTATION MODEL FOR PORT	69
FIGURE V-2222: TYPICAL POWER DEMAND BREAKDOWN FOR OFFICE.....	70
FIGURE V-2223: WORK SPACE AFTER WORKPLACE ORGANIZATION	73
FIGURE V-2224: VISUAL WORKPLACE	73

LIST OF ABBREVIATIONS

AC	Alternative Current
APMF	Agence Portuaire Maritime et Fluviale
a-Si	Amorphous Silicon
a-Si/ μ c-Si	micromorph silicon
BOS	Balance of System
CAPEX	Capital Expenditures
cd-Te	Cadmium-Telluride
CIGS	Cadmium – Indium – Gallium - Diselenide
CIS	Copper – Indium - Diselenide
COE	Cost of Energy
CSP	Concentrating Solar Panel
CPV	Concentrated Photovoltaic
DC	Direct Current
DECC	Department of Energy and Climate Change
EPA	United States Environmental Protection Agency
GHG	Greenhouse gases
GW	Giga Watt
GWP	Global Warming Potential
HOMER	Hybrid Optimization of Multiple Energy Resources
ICC	Initial capital cost
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IRR	Internal Rate of Return
JIRAMA	Jiro sy Rano Malagasy
kW	kilowatt
kWh	kilowatt hour

LCOE	Levelized Cost of Energy
LIB	Li-ion Battery
mc-Si	multi-crystalline
MW	Mega Watt
MWh	Mega Watt hour
MICTSL	Madagascar International Container Terminal Services Ltd.
MOT	Ministry of Transport
MW	Megawatt
MWh	Megawatt hour
NASA	National Aeronautics and Space Administration
NPC	Net Present Cost
NPS	Northern Power System
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
O&M	Operations and Maintenance
PM	Particulate Matters
PV	solar Photovoltaic
QC	Quay Crane
QGC	Quay Gantry Crane
REN21	Renewable Energy Policy Network for the 21 st Century
RES	Renewable Energy System
sc-Si	Single Crystalline
SHC	Solar Heating and Cooling
SMMC	Société de Manutention des Marchandises Conventionnelles
SOC	State of Charge
SPAT	Société du Port à Gestion Autonome de Toamasina
VRB	Vanadium Redox Battery

I- INTRODUCTION

I-1. Background

Maritime transport holds key strategic economic importance in global trade. In 2012, the total of global seaborne trade was estimated at more than 9 billion tons (Asariotis, et al., 2013). By volume, 80 per cent of global merchandise trade are handled by ports worldwide. Challenges and opportunities have been born of new and complex environment which, today, confronts maritime transport. Among the challenges the issues of energy security and costs, climate change and environmental sustainability were cited to be the “most unsettling” and given higher rank on the policy agenda of shipping and port businesses, by the Review of Maritime Transport 2013.

The International Energy Agency (IEA) includes the inability to meet the required electricity demand, and oil and gas price escalation to be among the energy security risks (Mueller, 2014). The IEA report, entitled “Contribution of Renewables to Energy Security”, evaluated the potential of renewable energy to eliminate risks to energy supply, and asserted that the deployment of wider range of renewable energy sources, including wind, solar, geothermal, hydro, bioenergy, could lower risks and ultimately provide energy security. Furthermore, in November 2012, the UK Department of Energy and Climate Change (DECC) recommended, via the “Energy Security Strategy” publication, to boost the deployment of renewable energy to enhance energy security.

On the other hand, ports and shipping are concerned with environmental issues. Even though their emissions are relatively insignificant compared to those of the total transport sector, the port and shipping industries are responsible for releasing 3.3% of global carbon dioxide (CO₂), 14% of nitrous oxides (NO_x), 7% of sulfur dioxide

(SO_x), and some quantity of particulate matters (PM). Electrification of port operations has been adopted by a numbers of ports to reduce emissions. Lonati et al. (2010) sees the electrification of ports as the “maximum potential” to reduce emissions in port premises. Yet ports will remain major contributors to global greenhouse emissions if the power sources of the electricity supplied to the ports are not clean. Renewable energy sources for ports coupled with electrification of port operations would be the potential combination to deal with emissions curtailment. Furthermore, the introduction of the concept of Lean Enterprise or Lean Manufacturing into port activities has been promoted since few years, in order to drive improved efficiency and secure savings while cutting wastes. In port and shipping industries, ‘Lean, Green and Efficiency’ have been often brought together. Lean has always been used in the manufacturing companies. The concept has originated from the Toyota Company to eliminate wastes within the process of the activities.

The state of energy security in Madagascar has deteriorated these recent years. Those areas largely dependent on electricity generated by fossil fuel thermal power plant are the most likely affected by power shortage or blackouts in the country. The share of electricity production in the area, where the port of Toamasina is located, is comprised of, 34 per cent generated by hydro power plant whereas 66 per cent supplied from fossil fuel power plant. The power supply security of Toamasina port is at risk due to frequent shortages and/or blackouts. Port of Toamasina faces substantial energy challenges that impact its competitiveness and environmental goals. Port of Toamasina is the major port of the Island. It handles more than 80 per cent of the flux of merchandises entering and leaving the island. These challenges can be effectively addressed by installing a renewable energy generation plant to supply the electricity demand of Toamasina port, while, at the same time, seeking to reduce and/or eliminate electricity wastes, consumed for non-value adding processes or services, via embracement of Lean concept. This project would help Toamasina port to take advantage of the natural geographical advantages of abundant solar and wind energy. In addition, this is a pathway to energy security, price stability and

emissions reductions for the port. It is, further, worth noting that the global boom in renewable energy has dramatically driven down the costs of the technologies and, is providing an alternative for base load power generation.

I-2. Research objectives

This research will seek to achieve the following principal objectives:

- Discuss onshore wind turbines, solar PV arrays and battery technologies commercially available in the current global markets.
- Perform a feasibility study along with technico-economic and environmental evaluation of hybrid wind, solar and battery to generate, supply and meet the required power demand derived from port activities. The sizing and modelling will conclude an optimal system configuration vis-à-vis the system net present cost (NPC), cost of energy (COE) and excess of electricity generation.
- Accomplish a project appraisal of the hybrid renewable energy generation system taking into consideration the opportunity costs of GHG emissions and electricity bill.
- File recommendations vis-à-vis the introduction of Lean concept into port business while describing steps for its application.

I-3. Research questions

In fulfilling those objectives, the following questions shall be addressed:

- What are the characteristics, the technical, economic and environmental performances of the commercially available wind, solar and battery technologies? Which of these technologies would fit the proposed hybrid system in order to deliver the expected power output?

- What sizes and how many of each and every components can yield the optimal hybrid power generation system, considering the port requisite electricity demand, NPC, COE and excess of electricity generated?
- Can the costs associated with the realization of the renewable energy generation plant be a viable investment?
- How can electricity consumption wastes due to non-adding value process be reduced or even eliminated?

I-4. Methodology

In order to fulfil the objectives of this research, information on the available renewable energy generation technologies including wind and solar PV, and battery energy storage technologies were retrieved from various relevant literatures which are listed in the references section of this work. This literature is comprised journals, articles, books, book section, electronic sources, periodicals and reports. The costs data, technical and economic performance of individual technologies have been explored through similar sources, specifically those which were published and prepared by the well-known institutions, government department, companies and organizations such as the International Energy Agency (IEA), the United States Environmental Protection Agency (EPA), Berkeley Lab, the National Renewable Energy Laboratory (NREL), the International Renewable Energy Agency (IRENA), and a numbers of renewable energy project developers contacted by emails and telephones. Furthermore, 22 years of wind and solar resources in the port area were collected from the NASA Meteorology and Solar Energy database of the area. Additionally, the electric load of the port was collected locally.

The analysis of data of the existing renewable energy generation technologies was carried out to scrutinize their performance and availability, determine whether the technology is proven mature and, subsequently decide on the technologies which would constitute the power generation system.

HOMER software was used in analysing the collected data, modelling and sizing the system. The collected data was fed into the software as inputs. Thousands of cases were carried out to evaluate their technical and economic performances, and to ultimately achieve an optimal system vis-à-vis NPC, COE and excess of electricity generation.

The quantity and costs of the greenhouse gases (GHG) emissions generated from burning fossil fuel to produce today's power supply to port of Toamasina were calculated. This cost of GHG emissions, also known as externalities cost was taken into account during investment appraisal.

The costs and benefits of undertaking the project were quantified in order to perform project appraisal using appraisal techniques including Payback Period, Net Present Value (NPV), and Internal Rate of Return (IRR).

On the other hand, recommendations to introduce Lean into port business and description of the steps for Lean application are presented.

The methodology results in an appraisal of the entire project viability in taking into consideration, not only, the direct costs borne by the project, but also, the cost of externalities.

I-5. Scope of Research

The dissertation aims at achieving technical and economic feasibility, and environmental analysis of implementing renewable energy generation project, composed of wind turbines, solar PV and battery bank, to supply power to port. The annual electricity bill, amount of excess of energy production and saved GHG emissions will be assessed. The project appraisal will be carried out using the appraisal methods and techniques of Payback time, NPV and IRR for the project lifetime. Conclusions and recommendations will be made on the viability of the project, port energy policy and application of Lean Enterprise model for port.

The dissertation is structured into five main chapters. Chapter one is introduction, where methodology, research objective and questions are presented. Chapter two is a literature review on wind, solar, battery and Lean. Chapter three is technologies, which describes and discusses wind turbines, solar PV, and battery technologies. Chapter four is feasibility study of wind-solar-battery power generation system, which details the system modelling and optimization, in addition to project cost structure and appraisal. Chapter five is conclusion and recommendations, which summarizes and draws conclusion on the findings with respect to research objectives and problem statement outlined at the beginning of this research. Recommendations on drafting energy policy for port and, introduction of Lean Enterprise into port business are touched upon in this chapter. The last section is list of references.

I-6. Limitations

The study does not quantify the hidden or indirect emissions associated with power generation. Therefore, the GHG emitted during electricity generation is considered none or zero for the purpose of the costs and benefits evaluations. Similarly, communication costs that might be induced throughout the project preparation and installation periods are not evaluated in this study. Moreover, electric cables size and length needed during the actual onsite installation of wind turbines, solar PV panels, battery bank and converter are not determined in this research.

Furthermore, the impact evaluation of the project realization on local employment lies beyond the scope of this research.

I-7. Port of Toamasina

Madagascar is located in the Indian Ocean in the Southern Hemisphere. Separated by the Mozambique Canal from Africa's main land, Madagascar is 400 km off the south eastern coast of Africa. Its total area is estimated to be 587 041 km² with 4828 km of coastline. The coastline shelters 17 ports.

Toamasina Port has a vast hinterland including, but not limited to, Toamasina area and Antananarivo, the capital city where industrial and commercial functions have been accumulated in both of these regions. Toamasina Port is the Principal Port of Madagascar. Eighty percent (80%) of the maritime trade and ninety five percent (95%) of the container traffic of the country are handled at the port of Toamasina. The latter is administered by the Société du Port à Gestion Autonome de Toamasina (SPAT). The major institutions and companies related to the port of Toamasina includes the Ministry of Transport (MOT), Agence Portuaire Maritime et Fluviale (APMF), Société du Port à Gestion Autonome de Toamasina (SPAT), Madagascar International Container Terminal Services Ltd. (MICTSL) and Société de Manutention des Marchandises Conventionnelles (SMMC) .

The MOT has overall jurisdiction over ports, marine, river transport, air transport and railway transport. On the other hand, APMF, a commercial and public corporate entity, regulates the maritime areas, harbour and rivers, besides the implementation of the national related policy. The rehabilitation, improvement and maintenance of the infrastructures related to harbour, rivers and navigational routes lie under APMF control. In other words, APMF oversees the management maritime and rivers related matters.

FIGURE I-61: APMF HEADQUARTER



Photo courtesy: APMF

Furthermore, SPAT manages the port of Toamasina, meaning port safety, dredging work, maintenance and new construction of port facilities are under the umbrella of the SPAT. The SPAT is the regulator of companies operating in Toamasina port via concession contracts or permission contracts.

In Toamasina port, the container terminal is operated by MICTSL, whereas, SMMC deals with the general cargoes. The quays structure and the container storage area is described as follows:

Firstly, quay A has three berths: East A, North A and West A, which are mainly for cabotage. Secondly, quay B accommodates two berths, North B and West B, to handle oil and International general cargoes respectively.

Thirdly, quay C is divided into four berths: C1, C2, C3 and C4. The berths C1, C2 and C3 measure 497 meter-long with draft of 14 meters. Berth C4 is 320-meter long and reaches 14-meter deep. C4-Annex, another 150 meter-long, extends at the end of C4 with the same draft. The C2, C3, C4 and C4-Annex, berths for container vessels, are supported by three separated container yards comprised of a 5ha-yard adjacent to C4, a 2.4ha-yard and 10ha-container yard located 1000 meters from berth C4. To store export laden and empty containers, the 5ha is sufficient for only 700 ground TEU slots which account for an equivalent to the annual operational capacity of 230000TEUs, using Rubber Tired Gantry (3 RTGs) cranes system and an average of three-day dwelling time. However, using RTG system (6 RTGs), the 10ha-container yard (455 meters X 220 meters) represents 2088 ground TEU slots and 220000TEUs of laden import containers with the assumption of an average of 7-day dwell times. Moreover, the 2.4ha container yard is capable to handle 120000TEUs per annum with 3 RTGs. Berth C4 is to accommodate vessels of up to 420000 DWT, or with load of 4000TEUs to 5000TEUs. Container traffic is forecasted to grow 426 000 TEUs in 2020. Equipped with three Quay Gantry Cranes (QGC), berth C4 has the capacity to handle an estimated 448 000 TEUs. On the other hand, C1 is used to handle RORO vessels and bulk carriers of up to 55000DWT carrying cargoes such as grain, ore, cement and other bulk cargoes.

Last but not least, quay D has two berths, D1 and D2, each of which is 350 meters long and 16 meters deep giving a total length of 700 meters for the D1 and D2. A container yard of 40ha is located adjacent to D1 and D2. In addition, the quay is situated 200 meters from quay C, where bridge is built in between.

FIGURE I-62: PART OF TOAMASINA PORT FACILITY LAYOUT



Photo courtesy: (Japan International Cooperation Agency -JICA, 2009)

II- LITERATURE REVIEW

II-1. Wind energy

Wind technologies have been available and evolved over the years. Almost relevant and detailed information is widely available for potential users. Tegen, et al. (2013) reported not only data on cost of wind energy, but also provided a summary of past trends along with future projections. Similar statistics on trends and forecasts have been investigated by Wiser & Bolinger (2013) but with particular focus on US. Whereas, Mukasa, et al. (2013) emphasized more on Africa wind sector. The European side was done by Wilkes & Moccia (2012). Lantz, Wiser & Hand (2012) presented the same matters but with global perspective. Philibert & Holttinen (2013) fulfilled detailed studies of the technologies based on these trends, and drafted new vision.

Demands for these data are constantly increasing from project developers and decision makers. BiGGAR Economics (2012), for example, assessed the direct and indirect impacts of onshore wind sector, on behalf of RenewableUK and the DECC. Data are, generally, utilized to compare between technologies in order to unveil their economic and technical competitiveness. Shafee & Dinmohammadi (2013) implemented a comparative study of onshore and offshore wind turbines. The economic and technical feasibility study of Buffalo renewable energy project carried out by Roberts & Mosey (2014), is another relevant case of the vital use of these data, for project planning and implementation.

On the other hand, Puglia (2013) undertook investigations on cost-efficient maintenance strategies for wind technologies for either onshore or offshore. Krohn,

Morthorst & Awerbuch (2009) examined the economics of wind energy. Similarly, Carbon Trust (2009) scrutinized not only the economic benefits, but also the environmental and security benefits of offshore wind energy. Also, Snyder & Kaiser (2000) studied offshore wind energy cost-benefit vis-à-vis their economics and ecological involvement.

In terms of energy project, optimization of a selected configuration brought most attention during the study, planning and development stages. Eminoglu & Ayasun (2013) proposed a model and design optimization of wind turbine systems. Besides, Afanasyeva (2011) embraced studies on wind farm installations optimization method.

Lago, et al. (2009) assessed the environmental concerns regarding wind energy.

II-2. Solar energy

Solar energy has been exploited using different technologies. Chu & Meisen (2011) reviewed diverse solar energy technologies. The solar PV cost analysis is carried out by IRENA (2012).

Chawla, et al. (2014) presented global report on renewable energy, tracking trends, policy, investment and energy transition from around the world. Besides, the Renewable energy Division of IEA set out roadmap for solar PV energy technology (IEA, 2013). Besides, Electric Power Research Institute surveyed on solar PV operations and maintenance costs, and challenges (EPRI, 2010). Whereas Goodrich, James, & Woodhouse (2012) investigated on solar PV cost drivers and reduction opportunities. Feldma, et al. (2012) undertook similar research on PV pricing along with near-term forecasts.

Lisell & Mosey (2010) performed a feasibility study of economics and performance of solar PV. Salam, et al. (2013) studied design of solar PV project intended to supply power for lighting in Oman, using HOMER. Solar energy is cost competitive

today (Yaqub, Sarkni, & Mazzuchi, 2012). They determined the economic feasibility of solar PV project with self-sustaining financial scheme.

Hansen, Nygaard & Pedersen (2014) investigated the potential investment in solar energy in Africa.

The environmental impacts of solar power were investigated in Beylot, et al. (2011) and Sunshot (2012).

II-3. Energy storage

Energy storage is perceived to be cost-adding component to energy generation system. Delmon, et al. (2013) attempted to quantify the value of the energy storage, in terms of benefits that are not expressed within the electricity markets. Pawel (2013) presented a framework energy cost of storage assessment. The benefits of energy storage systems, along with their characteristics are the subject of the research done by José González del Pozo (Pozo, 2011). The Stockholm Royal Seaport was taken as case study in the research.

Gyuk, et al. (2013) reviewed the energy storage technologies and outlined the challenges encountered in fully integrating the technologies into the power generation and distribution system. In addition, Schlogl (2013), Bradbury (2010) and Carnegie, et al. (2013) reviewed the energy storage technologies. Poullikkas (2013) presented an overview of batteries employed for large scale storage. After thorough analysis, Schmiegel & Kleine (2014) proved that larger battery with larger capacity yielded higher economy in a power system generation.

II-4. Hybrid Photovoltaic/Wind energy and Battery system

Photovoltaic/wind/ battery configuration continue to be explored and exploited by a numbers of developers for small, medium and large scaled hybrid renewable power plant. Notton, Diaf & Stonyanov (2011) studied two sites in the mediterranean to

appraise profitability of such a configuration. Ma, Yang & Lu (2014), and Liqun & Chunxia (2013) undertook a feasibility of the system for off-grid application supplying power to remote village in Shanghai and remote island in Hong Kong. Alike studies were undertaken by Bekele & Boneya (2012), but for the benefit of the Ethiopian remote area. Koussa, et al. (2011) studied a case of rural area electrification by means of wind/solar/battery architecture. HOMER software were used to model and size the energy generation system. A multitude of modelling and sizing methods have been used and developed. Engin (2013) employed mathematical model for sizing and simulating PV/wind power hybrid system, and its annual performances. The purpose of the hybrid power generation system was for security lighting.

Budischak, et al. (2013) determined real cost of energy generated by wind/solar/battery hybrid configuration, to meet 99.9% of power demand. Their reasearch outcome confirmed the cost competitiveness of a hybrid system comprised of wind, solar and battery.

II-5. Lean

Bartholomew, et al. (2007) presented practical ways of Lean implementation and enhancement, in view to yield customer satisfaction and sound environment benefits. In addition, Boone, et al. (2011) outlined tools and techniques for organizations in reducing energy consumption and GHG emissions.

On the other hand, Loyd, et al. (2009) examined Lean Enterprise management implementation tools and principles in the entire port business. The study underlined keys to successful Lean implementation, issues encountered in keeping enhancement efforts, and few suggestions for complementary concerns. Bergmiller & McCright (2009) reported that “Lean and Green Program” steer to enhance business results.

Alves, et al. (2011) analyzed a significant numbers of lean projects and detailed the outcome benefits.

III- TECHNOLOGIES

The project proposal consists of onshore wind turbines, solar PV arrays and battery bank as an energy storage system. Besides the technical and economic specifications of each and every technology, the availability of the technologies in the local, national and regional markets is also among the parameter taken into consideration in the decision making process when selecting the technologies which will constitute the system.

III-1. Wind turbine

Electricity generation attempts from wind energy were started since the late nineteenth century, by Professor James Blyth of the Royal College of Science and Technology, now Strathclyde University. His first wind electricity generating device was built in 1887 (Boyle, 2012). A diversity of machines and devices have been designed and constructed to harness wind energy over the years.

The technology has become sufficiently mature since the 1980s. Since then, the costs of wind turbines have fallen constantly and the capacity of wind turbines has increased notably. Now wind turbines are one of the most cost-effective and economically competitive electricity generation techniques thanks to technology, reliability, capacity and cost improvement.

Furthermore, wind turbines have been installed onshore and offshore, where wind speeds are relatively high. Wind turbines have been developed into two principal categories comprised of vertical axis wind turbines and horizontal axis wind turbines. Nonetheless, the vertical axis wind turbines have not been commercially successful due to issues with power quality and low efficiency with some designs.

III-11. Overview of energy and power in the wind

Wind energy systems embrace a multitude of fields of knowledge including meteorology, aerodynamics, electricity, civil and mechanical engineering. The wind energy is kinetic energy, calculated as,

$$\text{Kinetic Energy (in Joule)} = \frac{1}{2}mv^2$$

Where:

m is mass in kg

v is velocity in m/s

Moreover, kinetic energy per unit of time is equal to power (P),

$$P \text{ (in J/s)} = \frac{1}{2}mv^2$$

$$m = \rho AV$$

Where:

m is the mass of air per second

ρ is the air density in kg/m³

A is the area in m²

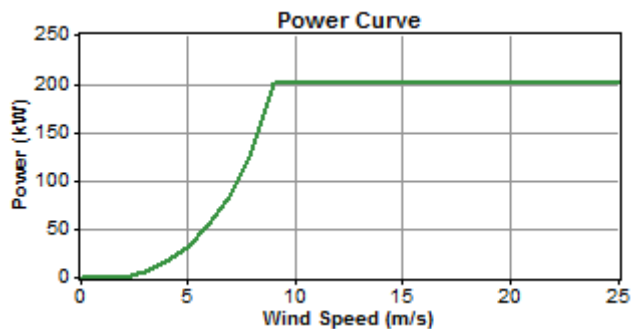
V is the velocity in m/s

Therefore the power in the wind $P = \frac{1}{2}\rho AV^3$ is proportional to the density of the air, the area through which the air is passing (that is to say the wind turbine rotor) and the cube of the wind velocity. The air density is lower at high altitudes such as mountainous places. Conversely, in cold climate regions, air densities are higher, by 10% or more, than in warm regions. Vis-à-vis the formula, it is demonstrated that velocity influences on the power generated due to the “cube law”. It is clear that wind turbines deployment strategy, with respect to installation sites, is substantially, a function of these three variables. Nevertheless, remark has to be made that losses are incurred through power extraction or conversion processes of wind energy.

III-12. Wind turbine power output

Wind speed largely determines the power output. Additionally, the power curve, shown in Figure III-12, is specific for every turbine and, is characterized by several parameters including swept area of rotor, aerofoil choice, number and shape of blade, optimum tip ratio, speed of rotation, gearing efficiency, generator efficiency, aerodynamic efficiency (power coefficient), cut-in wind speed, cut-out wind speed, and rated wind speed.

FIGURE III-12: POWER CURVE FOR 200kW ITALTECHWIND WIND TURBINE



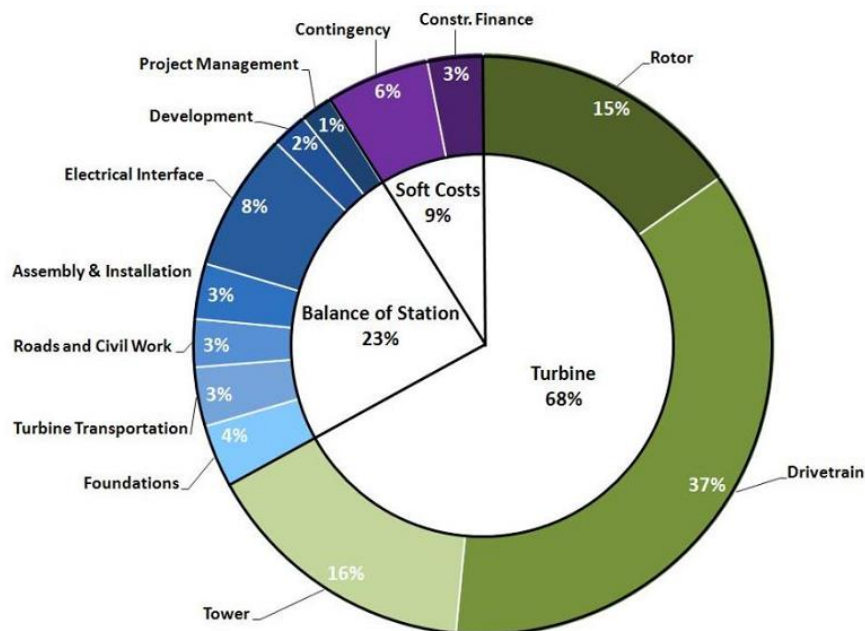
Source: italtechwind Company

Tip speed, in meters per second, is the measure of the tangential velocity of the rotor at the tip of the blades. It is a useful measure of wind turbine rotor speed, plotted against the aerodynamic efficiency called power efficiency. Power efficiency is defined as “the ratio of the power output from the turbine to the theoretical power in the wind” (Boyle, 2012). A wind turbine is at its best or maximum or optimum efficiency at a particular tip speed ratio, also described as its optimum tip speed ratio. Moreover, cut-in wind speed and cut-out wind speed refer to the wind speed at which wind turbine power generating starts, and shuts down respectively. At rated wind speed, the wind turbine generates its rated power. The rated power is useful in determination of annual energy production, for example.

III-13. Wind energy projects

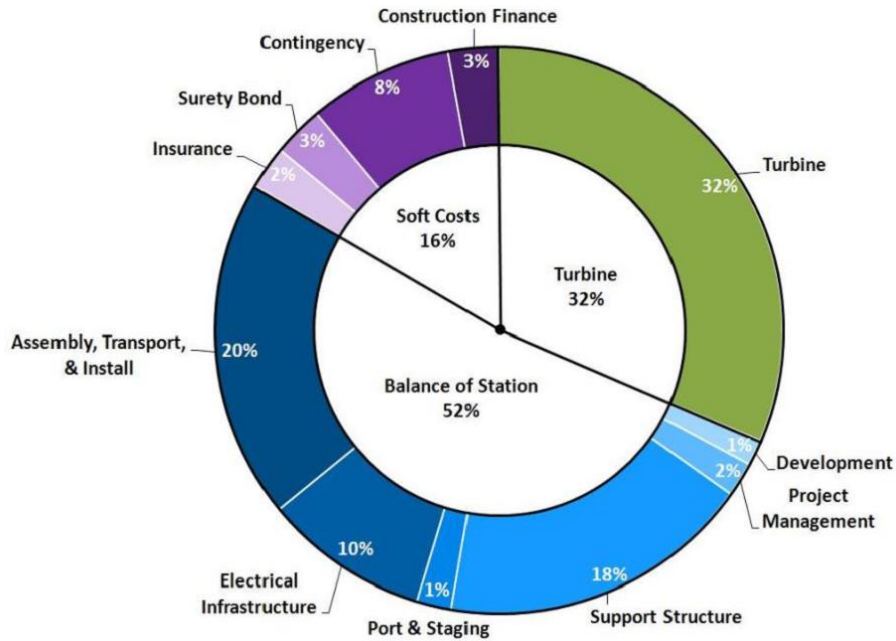
There are mainly two different aspects of wind projects consisting of land-based wind projects, also known as onshore wind projects, and offshore wind projects. Land-based wind turbines are commercially available in almost all countries around the world. These onshore wind farms are installed either in hinterland or coastal regions. Literatures and research have qualified onshore wind technology as mature; whereas offshore wind technology is an early technology. As result, offshore wind projects investments, including initial capital investment and, operating and maintenance costs are relatively high compared to those of land-based wind farms. The COE generated by either wind technology follow the same cost patterns, meaning the offshore wind COE is comparatively high. Figure III-131 and Figure III-132 outline the costs breakdowns of onshore wind farm and offshore wind farm respectively.

FIGURE III-131: TYPICAL INSTALLED CAPITAL COSTS FOR LAND-BASED WIND PROJECT



Source: (Tegen, et al., 2013)

FIGURE III-132: TYPICAL INSTALLED CAPITAL COSTS FOR OFFSHORE WIND PROJECT



Source: (Tegen, et al., 2013)

For the purpose of this research, onshore wind turbine is selected, mainly due to the comparatively high initial capital cost (ICC) and, operations and maintenance cost (O&M) of offshore wind project.

III-14. Cost of wind energy

Wind is capital intensive technology, though it requires no additional fuel cost throughout its entire lifetime. Furthermore, wind energy is among the most cost-effective renewable technology vis-à-vis the cost per kWh of power generated. Generally, five elements constitute the determinants of wind energy economics. The capital cost, usually known as capital expenditure (CAPEX) dominates up to about

84% of the total installed cost. CAPEX includes the costs of the wind turbine itself, civil works, grid connection, and other related works.

In addition to CAPEX, O&M cost along with the capacity factor, and lifetime of the wind turbine influence the wind energy cost. The latter is inflated by the cost of capital. The overall cost related to a wind project can be structured into balance of the system (BOS), turbine cost and soft cost. CAPEX, also known as ICC, as previously stated is made up of the entire wind turbine cost and the balance of the system (BOS):

$$ICC = \textit{Turbine cost} + \textit{BOS}$$

The turbine cost is the sum of the individual cost of wind turbine elements which are mainly comprised of rotor, drive train, nacelle, tower, control and safety system, and condition monitoring. On the other hand, the BOS includes foundation or support structure, roads, civil works, assembly, installation, electrical interface, engineering permits and transportation.

$$\textit{BOS} = \textit{foundation} + \textit{transport} + \textit{civil work} + \textit{installation} + \textit{electric interface} \\ + \textit{permits}$$

Where:

$\textit{Foundation cost} = 302.24 \times \textit{hub height} \times \textit{rotor swept area})^{0.4037}$. This cost scaling function was developed by the National Wind Technology Center of the National Renewable Energy Laboratory (Fingersh, Hand, & Laxson, Wind Turbine Design Cost and Scaling Model, 2006).

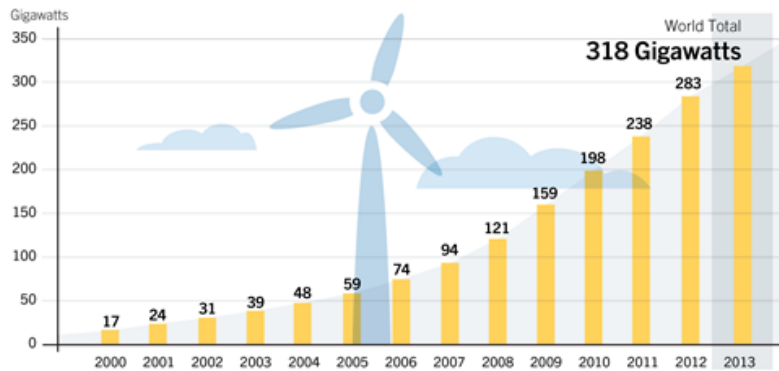
Over the past few years, the costs of wind energy have gradually headed downwards driven by a decline in the overall capital costs due to harsh competition within wind industry. At the same time, the technological advances, including taller tower, longer blades and smaller generators for low wind speed, have increased capacity factors. Turbine designs tend to be developed with reduced costs and increased yield, leading to, not only, production of larger machines with fewer operations and maintenance costs, but also, a boost in technologies and strategies to ameliorate the economics of wind power in a wider range of operating conditions particularly in low-wind areas.

China, Denmark, Germany, India, Spain, the United States and Japan are the world's leading wind turbine manufacturers. Wind turbines come in three main categories in terms of size of rated output, including small sized wind turbines, medium sized wind turbines and large sized wind turbines.

For the purpose of this study, a medium-sized 200kW italtechwind manufactured wind turbines were selected. The 200kW size was preferred considering the base load of Toamasina port. The size is then not too big or too small. The simplest rule of thumb for wind project developers is to target small numbers of wind turbines in a single project, which means fewer moving part for the project, hence saving in O&M cost. In addition to the reasons recently stated, other factors were examined during the decision making process including the available facilities in the area of the port to accommodate the wind turbines, and the unit cost of transportation of different sizes of wind turbine. For, example, a 2MW wind turbine would be extremely expensive to transport to the intended project site; besides, facilities and infrastructures to accommodate and handle this large wind turbine are not available in the area. Even if they were made available, the associated costs would be exorbitant. Furthermore, land-based configuration was decided due to its competitiveness vis-à-vis the unit cost of energy produced.

Land-based wind energy generation is cost competitive in terms of per kWh produced, even without subsidy support schemes. It is estimated that a drop of 15%, between 2009 and 2014, in global levelized costs per MWh of wind energy has been registered (REN21, 2014). Nonetheless, offshore wind increased, primarily because of the increase in water depths and distance from shore. Despite the higher costs of offshore wind generation, the global wind energy generation has been increasing. In 2013, for example, REN21 (2014) reported that a capacity of over 35 GW has been installed, making the actual global total capacity beyond 318 GW (Figure III-14).

FIGURE IV-1II: WIND POWER TOTAL GLOBAL CAPACITY



Source: (REN21, 2014)

III-15. External costs of wind energy

Wind energy not only reduces emissions of GHG and other pollutants, but also avoids significant external costs of conventional fossil-based electricity generation. Nonetheless, in Madagascar, the present national electricity markets or pricing model do not include the external effects and their costs. It is crucial to identify, quantify and introduce them into the costs of the generated electricity.

Among the most important economic benefits of wind energy is that it diminishes the exposure of our businesses to fuel price volatility. Moreover, the benefit is substantial when the external costs of power generation are taken into consideration in the cost of power produced. Economic savings of wind energy can, therefore, be calculated by comparing the external costs with those of the fossil fuel technologies and relating these costs proportionally to fossil fuel power generation. That will outline the total avoided external costs via the carrying out wind power generation.

Certainly, from the life-cycle perspective, wind energy is not a zero-carbon technology, because GHG emissions take place during manufacturing, transport, installation, operation and decommissioning of wind turbines. Nonetheless, these are

considered to be very limited. Global estimates by the Intergovernmental Panel on Climate Change (IPCC, 2011) indicate that those emissions lie between 8 and 20 gCO₂/kWh. However, the construction of wind turbines, their operation and location can exhibit non negligible impacts on the environment including effects on landscapes and wildlife, and habitat and ecosystem alteration. Visual impacts on landscapes and seascapes are valued to be the most important environmental cost of wind energy implementation. But the degree of impacts varies with the areas of wind project development. For example, Bassi, Bowen & Fankhauser (2012) reported that:

- Norwegian households would be willing to pay up to about €110 - €130 annually to replace wind power with hydropower;
- Swedish households would be willing to pay around €29 per annum to have wind turbines installed in an offshore location and €12 to move onshore wind farm from mountain to lowland location;
- Scottish households would be willing to pay €12 to reduce impacts on landscape and €6 on wildlife.

The willingness to pay varies substantially, ranging from 0.3 to 4 p/kWh (Bassi, Bowen, & Fankhauser, 2012). Therefore visual impacts have not yet been able to be universally measured. On the contrary, noise from wind project development, which is categorized under the environmental impacts of wind energy projects, can be measured. Wind turbines produce two kinds of noises, including mechanical noise from gearboxes and generators, and aerodynamic noise from blades. The mechanical noise has been almost non-existent with modern wind turbines. The aerodynamic noise is a function of tip speed, and is generated by the blades' rotation producing a broad-band swishing sound. Wind turbines noise level, at 350m, is estimated between 35 dB and 45dB, which is roughly equal to rural night-time background noise level ranging between 20dB and 40dB. Hence, wind farm noise is relatively low, and is a small-scale problem in absolute terms.

Besides, wind farms cause biodiversity and habitat disturbances and, bird fatalities due to collisions with wind turbines. But global statistics prove very low Figures

ranging from 0.2 to 53.2 fatalities per MW per year (IPCC, 2011). A recent study asserted that wind energy projects are responsible for only 0.003 per cent of bird mortalities caused by human activities (Lago, et al., 2009).

However, it is vital to understand the difference between the high levels of general support toward wind energy projects and local effects associated with specific wind project developments comprised visual impacts, effects on landscapes or seascapes, and sound emissions of the turbines. Wind energy, being clean, sustainable and renewable energy, has traditionally gained strong and stable public support. Experience gained by wind farm developers showed that opposition to wind projects occurred generally during the planning phase. The acceptability is strong after commissioning (Lago, et al., 2009)

Hence, the adverse impacts of wind power generation on the environment are relatively insignificant when to be taken into consideration in the computation of the costs of wind energy, and while undertaking the project appraisal.

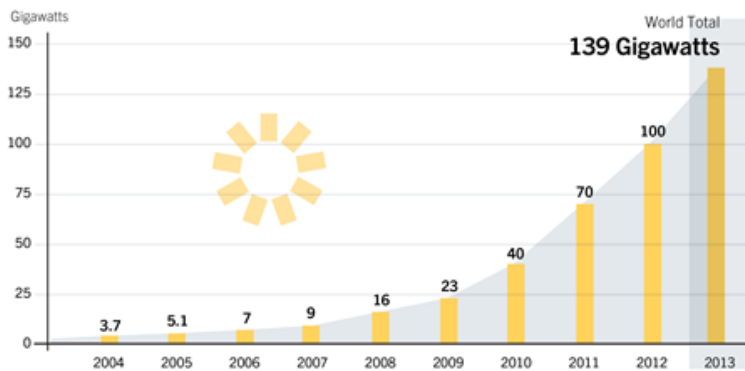
III-2. Solar Photovoltaic (PV)

Solar power provides a substantial energy resource for the earth. One year world energy consumption is equivalent to only one hour of solar energy hitting the earth surface (IEA, 2010). Three solar technologies are currently available worldwide, including PV cells, concentrating solar panel (CSP) and, solar heating and cooling (SHC). CSP systems use concentrated solar radiation to produce energy and drive chemical reaction. This technology is mainly preferred for comparatively large scale plants with clear skies, hence a vivid sun. On the other hand, SHC directly extracts thermal energy straight from the sun to heat and cool residential or commercial building. In addition, PV cells convert sunlight into direct current (DC) electricity. PV cells are interconnected to make up PV module. PV modules can be connected to meet the required power which can be as small as a few watts or as high as tens of

megawatts (MW). This section and the research will focus only on PV technology, with respect to the main objective of the wind, solar, battery hybrid system.

PV technology is reliable and commercially available, and is spreading at a significant pace worldwide. Figure III-2 shows the solar PV total global capacity, recorded from 2004 to 2013. PV supplies about 0.1% of overall global energy production (IEA, 2010).

FIGURE III-2: SOLAR PV TOTAL GLOBAL CAPACITY



Source: (REN21, 2014)

III-21. Photovoltaic solar panels (PV)

Solar PV is widely used to generate electricity worldwide. PV power generation system consists of solar panels which are composed of solar cells containing a photovoltaic material. Solar cells convert solar radiation into direct current electricity. The PV solar concept derives from a simple idea. The concept is globally known as photovoltaic effects, in which, absorption of electromagnetic radiation energy will emit electrons from matter, such as metals, non-metallic solids, liquids or gases. The emitted electrons are called photoelectrons which were, first, discovered by Heinrich Hertz in 1887.

III-22. PV technologies

There are a few PV technologies available in the market, mainly crystalline silicon (c-Si) and thin films. Crystalline silicon (c-Si) modules account for 85 - 90% of the actual global annual market. C-Si modules come in two varieties, the single crystalline (sc-Si) and multi-crystalline (mc-Si) (IRENA, 2012). In this study, mc-Si PV manufactured by Suntech Power Holdings Company will be used for the hybrid system. This technology is widely available in the local and national market. Suntech Power Company is among the world's largest producer of solar panel.

On the other hand, thin films possess a 10% to 15% share of global PV market sales (IRENA, 2012). They are of three types, which are, the amorphous (a-Si) and micromorph silicon (a-Si/ μ c-Si); Cadmium-Telluride (CdTe); and copper-indium-diselenide (CIS) and copper-indium-gallium-diselenide (CIGS). The other technologies such as advanced thin films and organic cells, concentrator technologies (CPV) and novel PV are not yet mature and are still subject to research and development. Table III-22 outlines typical cost and performance values of solar PV systems

TABLE III-22: TYPICAL COST AND PERFORMANCE VALUES OF SOLAR PV SYSTEMS

	Module cost, factory gate or spot (2010 USD/W)	Installed cost (2010 USD/W)	Efficiency (%)	Levelized cost of electricity (2010 USD/kWh)
Residential				
c-Si PV System	1.02 – 1.24	3.8 – 5.8	14	0.25 – 0.65
c-Si PV system with battery storage	1.02 – 1.24	5 – 6	14	0.36 – 0.71
Utility scale				
Amorphous Si thin film	0.84 – 0.93	3.6 – 5.0	8 – 9	0.26 – 0.59

Source: (IRENA, 2012)

PV markets can be divided into four types with regards to end-use sectors, comprised of residential systems, commercial systems, and utility scale systems, scaling typically up to 20 kW, 1 MW, and over 1 MW, respectively. Off-grid applications are the fourth type, whose sizes vary greatly.

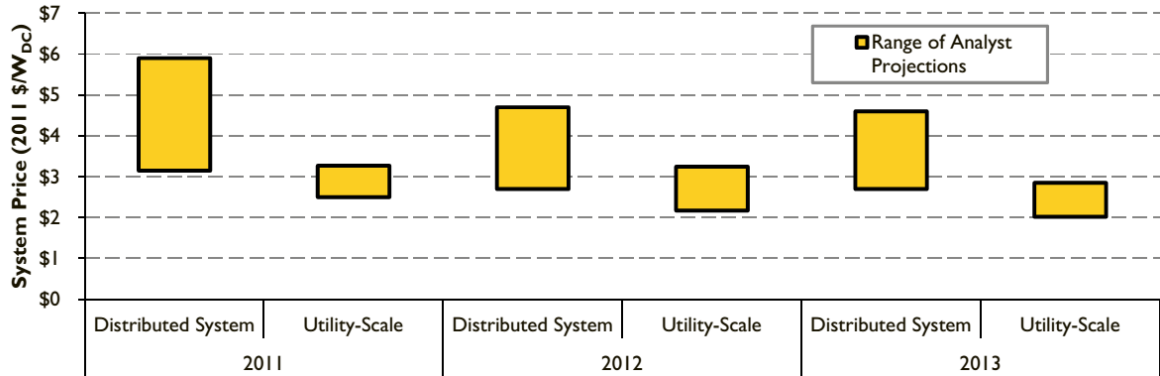
PV technologies provide valuable benefits. PV technology exploits solar energy resources as fuel to generate power. Solar power is a renewable energy meaning no fossil fuel is required to produce electricity via PV technology. In addition, the technology is small and particularly modular, and installation can therefore be carried out practically anywhere, unlike conventional power generation plants.

III-23. Total PV system costs

The PV system cost includes the costs of the PV modules, the balance of system (BOS), and installation. However, the costs of PV modules vary largely from manufacturer to manufacturer and differ for every PV technology. The PV system cost benefits from economies of scale. Therefore, large utility scale PV systems cost less than small or medium sized PV system project. Moreover, the cost depends on whether the PV solar panels are installed on the ground or on a roof.

Like all other renewable energy technologies, PV systems are subject to different uncertainties. It is yet unclear how deep the cost will drop or how high the rise will be in the short term horizon. Besides, incentives to boost the use of the technologies exist in different countries. Another determinant to influence the likely cost trend is the learning curve of the PV technologies throughout the period. Additionally, the uncertain global economic forecast could drive decisions on investments wildly leading to delays or postponement, hence slowing the deployment growth rate. All in all, PV costs will likely to fall with increased deployment accelerated by the significant PV learning rate (IRENA, 2012). The competitive nature of the solar PV market, particularly the emergence of low cost PV manufacturers currently supplying the market, will drive down the PV hardware costs, and consequently, the price of solar modules. Figure III-231 illustrates the price trends of distributed system and utility-scale system for period of 2011 to 2013.

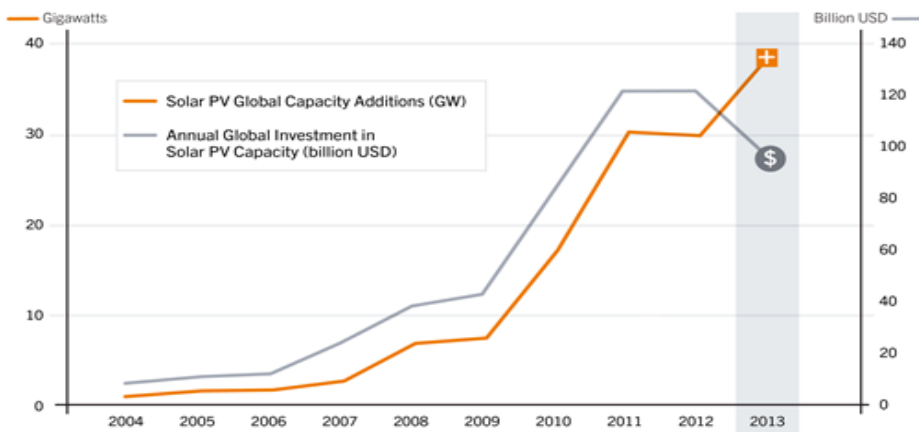
FIGURE III-231: PV SYSTEM PRICE TRENDS



Source: (Feldman, et al., 2012)

The decrease concerns not only the price of the solar PV panels, but also the associated costs for deployment of the technology, which include installation cost, and operating and maintenance costs. This fall in solar PV technology costs has produced a decline of about 22% of the total investment in 2013, although the solar PV energy sector has seen record new installations the same year (REN21, 2014). The global PV installed capacity and the associated investment experienced negative correlation since 2012. Figure III-232 shows the installed global solar PV capacity and the annual investment.

FIGURE III-232: SOLAR PV GLOBAL CAPACITY AND ANNUAL INVESTMENT



Source: (REN21, 2014)

III-24. Environmental impacts from the solar PV technologies

Solar PV is environmentally friendly, generating no noise or chemical pollutants during normal operation (Vandeligt, 2012). PV technology has been proven to be the most viable renewable energy technology for use in urban environment. It becomes a potential option for use in scenic areas and Parks to avoid pylons and wires. The impact of land use on the natural ecosystem could be an issue. However, the degree of impact depends on various factors including the sensitivity of the ecosystems and biodiversity, the distance from the area of natural beauty, and the type and size of land covered. Similarly, the visual impacts are a function of a multitude of variables including the type of scheme and surroundings of the PV systems. For instance, solar PV deployment next to an area of natural beauty would engender greater visual impact. Nonetheless, new trends have noticed that a positive aesthetic impact on building has been discerned. Architects and clients have discovered and perceived that solar PV panels can be used to embellish the aesthetic appeal of a building.

The largest part of all emissions in the solar PV life cycle takes place during material extraction, production, disposal and recycling phases (SunShot, 2012). Assessment of these emissions is beyond the scope of this study. Only direct emissions during the normal operations are subject to evaluation within the scope of this research. In addition, solar PV necessitates proper waste management and recycling technique, as all other technologies. The technical and economic feasibility of recycling PV materials is not part of the study.

III-3. Battery system

III-31. Overview of energy storage

Energy storage application is mainly classified into 3 categories, comprised of bulk storage, distributed storage and power quality. Bulk energy or energy management storage is to decouple the timing of generation and consumption. On the other hand, distributed generation or bridging power is for peak shaving. Storage is merely used for seconds to minutes to assure continuity of service when switching from one energy source to another. Besides, for power quality or end-use reliability, stored energy is only applied for seconds or less, to assure the continuity of the power. Table III-311 summarizes the battery technologies and the application category specifications; whereas Table III-312 reviews costs of energy storage and efficiency of few battery technologies

TABLE III-311: BATTERY TECHNOLOGIES AND APPLICATION SPECIFICATIONS

Category	Bulk Energy Storage	Distributed Generation	Power Quality
Technologies	Lead-acid batteries, Na/S batteries, Zn/Br batteries, Ni/Cd batteries,	Lead-acid batteries, Na/S batteries, Ni/Cd batteries, Li-ion batteries, Zn/Br batteries, V-redox batteries,	Lead-acid batteries, Li-ion batteries, ·
Discharge Power	10 – 1000 MW	0.1 – 2 MW	0.1 – 2 MW
Discharge Time	1 – 8 h	0.5 – 4 h	1 – 30 s
Stored Energy	10 – 8000 MWh	50 – 8000 kWh	0.03 – 16.7 kWh
Representative Application	Load levelling, Spinning reserve.	Peak shaving, Transmission deferral.	End-use power quality/reliability.

Source: Notton *et al.*(2010)

TABLE III-312: COSTS OF ENERGY STORAGE TECHNOLOGIES

Energy storage technologies	Capital Costs		Storage efficiency (%)
	\$/watt	\$/kW-hour	
Lead-acid battery	2.20	540	80
Lithium-ion battery	4.25	1,750	90
Sodium-sulfur battery	3.00	500	80

Source: (Red Mountain Insights, LLC, 2012)

Batteries are all electrochemical, with an electrolyte coming between two electrodes. During discharge, ions are freed from the first electrode called anode, into the electrolytic solution and lay oxides on the second electrode called cathode. Recharge process is the reverse.

In a flow battery, the flux of electrolyte via an electrochemical cell transforms the chemical energy to electricity. The electrolyte contains dissolved electroactive liquid. By hanging this liquid, flow battery can be quickly recharged. Additional electrolyte is kept externally, normally in tanks, and pumped through the cells of a reactor.

Red Mountain Insights, LLC (2012) lists the main appropriate types of batteries for utility energy storage, including Lead-Acid Batteries, Lithium-Ion Batteries, Metal – air Batteries, Sodium-Sulfur Batteries, Vanadium Redox Flow Batteries, and Zinc Bromide Flow Batteries.

Batteries are commercially available and cost effective energy storage technologies (Komor & Glassmire, 2012). Batteries are very modular technologies. The storage capacity increases with the number of batteries added to a battery bank.

III-32. Lead-Acid Batteries

Although, it is low in cost, among the oldest and most-developed battery technologies, and has various applications for power quality, uninterrupted power supply and spinning reserve; the utilization of lead-acid batteries for energy management has been restricted as result of short life cycle of the battery. The quantity of energy released is function of the battery rate of discharge.

Nonetheless, lead-acid batteries have secured a few commercial and large-scale energy management applications (Red Mountain Insights, LLC, 2012). Wet cell stand-by (stationary) batteries designed for deep discharge, for example, experience a multitude of applications encompassing grid energy storage, off-grid household electric power systems, emergency lighting in context of power supply, and large back-up for telephone and computer centers.

Lead-acid batteries fail to keep charge when discharged for excessively long periods, owing to the crystallization of lead sulphate, called sulfation. Sulfation affects all lead-acid batteries even during normal operation. However, it can be averted provided that the battery is thoroughly recharged instantly following a discharge cycle.

The first US large-scale energy storage 10 MW, 40 MWh - lead-acid battery was installed at the Southern California Edison facility in Chino, California. Still in California, at Vernon, in order to supply one hour power storage to cope with peak shaving and uninterruptible power, a 3.5 MW valve-regulated lead-acid battery system was built by Sandia National Laboratories, GNB Technologies and General Electric, in 1996.

A 20 MW, 14 MWh lead-acid battery system of the Puerto Rico Power Authority provides spinning reserve and deals with frequency control.

This project will embrace the vented lead acid battery, manufactured by Hoppecke, to serve as energy storage system. The technology is widely available

Table III-32 summarizes the technical parameters for lead acid batteries.

TABLE III-32: TECHNICAL PARAMETERS FOR LEAD ACID BATTERIES

Roundtrip efficiency (%)	Self-discharge (% energy per day)	Cycle lifetime (cycles)	Lifetime (year)	Specific energy (Wh/kg)	Specific power (W/kg)	Energy density (Wh/L)	Power density (W/L)
70-80	0.1-0.3	500-1000	5-15	30-50	75-300	50-80	10-400

Source: (Bradbury, 2010)

Regarding the environmental impact of lead acid batteries, certainly these batteries contain significant amount of toxic lead and dangerous sulphuric acid. Nevertheless, the Battery Council International asserts that 96 per cent of the lead from lead acid batteries can be recycled. The sulphuric acid can be neutralized and then can be safely disposed of.

III-33. Lithium-ion Batteries

Also referred to as Li-ion battery or LIB, the lithium-ion battery is a rechargeable battery. Cost, performance and safety characteristics differ for LIB types. Its use has been noticed predominantly in small portable applications such as in portable electronics, electric vehicle and in aerospace. Large-scale LIB is particularly expensive, estimated at more than USD 600 per kWh, due to challenges encountered in the technology; for example, the special packaging and the internal overcharge protection circuits (Red Mountain Insights, LLC, 2012). Nevertheless, the LIB enjoys the following advantages:

- High energy density(300 kWh/m³ – 400 kWh/m³, 130 kWh/ton);
- High efficiency (near 100%);
- Long cycle life (3000 cycles at 80% depth of discharge).

A multitude of these battery systems have been used in applications around the world. For example, in the United States, a 32 MWh lithium-ion battery installation project to support wind power grid integration was carried out by the Southern California Edison.

LIB may cause fires when exposed to moisture. Although LIB can be recycled, care must be taken due to the toxic electrolyte it contains.

Table III-33 summarizes the technical parameters of the batteries.

TABLE III-33: TECHNICAL PARAMETERS FOR LIB

Roundtrip efficiency (%)	Self-discharge (% energy per day)	Cycle lifetime (cycles)	Lifetime (year)	Specific energy (Wh/kg)	Specific power (W/kg)	Energy density (Wh/L)
90-98	0.1-0.3	1000-10000	5-15	75-200	150-315	200-5000

Source: (Bradbury, 2010)

III-34. Metal-Air Batteries

Metal-air batteries are not only the most compact and one of the least expensive batteries, but also environmentally friendly. Their challenges rely on electrical recharging which is problematic and inefficient. Multitudes of metal-air batteries are made of refuelable units where the absorbed metal is mechanically substituted and treated independently. Only a few of this type are electrically rechargeable with a few hundred cycles of capacity and approximately 50% efficiency. The current development on the electrical rechargeability attribute of metal-air batteries impedes the latter to compete with other rechargeable batteries. Metal-air batteries are high energy density and low cost technologies.

III-35. Sodium-Sulfur Batteries

A sodium-sulfur battery is a molten type of battery made from sodium (Na) and sulfur (S). It is constructed from low cost material, has a high energy density, long cycle of life and high charge/discharge efficiency estimated at 89-92%. Its cells are essentially appropriate for large-scale non-mobile applications, for example, for grid energy storage application. Table III-35 summarizes the technical parameters for lead acid batteries.

NaS batteries are a potential energy storage technology to endorse renewable energy generation, particularly wind farms and solar plants. Not only do NaS batteries facilitate power shifting, but also aid in stabilizing the power output of the wind farm at times of wind variations. Power shifting denotes displacing the energy generated during high wind and low demand periods, by means of storage, to periods of peak load. NaS batteries offer potential alternatives for energy storage in areas where other storage options are not feasible because of various constraints.

Under some market conditions, NaS batteries create value via “energy arbitrage” and voltage regulation. Charging the battery at abundant and/or cheap electricity periods and supplying to the grid during intervals of comparatively high electricity price, is

called “energy arbitrage”. The environmental impact of NaS battery is small as both sodium and sulphur can be safely disposed of.

TABLE III-35: TECHNICAL PARAMETERS OF NaS BATTERIES

Roundtrip efficiency (%)	Self-discharge (% energy per day)	Cycle lifetime (cycles)	Lifetime (year)	Specific energy (Wh/kg)	Specific power (W/kg)	Energy density (Wh/L)
75-90	20	2500	10-15	150-240	150-230	150-250

Source: (Bradbury, 2010)

III-36. Vanadium-Redox Flow Batteries

The vanadium redox (and redox flow) is a rechargeable flow battery type. The Vanadium Redox Battery (VRB™) is the outcome of more than 25 years of research, development, testing and evaluation in Australia, Europe, North America and elsewhere. The 2 utmost weakness of vanadium redox technology are the relatively low energy-to-volume ratio, and its system complexity.

On the contrary, this technology can provide practically unlimited capacity merely by utilizing bigger storage tanks. It can be left totally discharged for extended periods with no damaging consequences. And, even without access to a power source, solely changing the electrolyte will recharge the battery.

Other characteristics of vanadium flow batteries consist of their highly swift response to changing loads and their huge overload capacities. Studies published by the University of New South Wales recorded performance of a response time under half a millisecond for 100% load charge, and overloads up to 400% for 10 seconds. Nonetheless, the response time is generally restricted by the electrical equipment, practically estimated at 65 - 75% in term of round trip efficiency (Red Mountain Insights, LLC, 2012).

The batteries fulfil two potential applications, as follows:

- Large power storage to deal with significant surges in demand and to level out the production of immensely fluctuating generation sources, particularly wind or solar power.
- The limited self-discharge properties allow the batteries to be stored for a long time with meagre maintenance while conserving their ready state.

Besides, VRB presents an environmental issue due to the fact that they are susceptible to leakage from batteries and the dangerous nature of the electrolyte.

III-37. Zinc-Bromide Flow Batteries

A zinc-bromide flow battery is a non-perishable hybrid flow battery type with energy density ranges from 34.4 to 54 Wh/kg, and unrivalled cycle life surpassing 2000 cycles at 100% depth of discharge. The battery systems size stretches from 10 kWh (0.036GJ) to over 500 kW (1.8 GJ). Compared to lead-acid batteries, zinc-bromide flow batteries possess relatively greater energy density. Moreover, the battery can be left indefinitely entirely in a state of discharge, up to 100% depth of discharge, for later charge. Another prevailing property of the zinc bromide battery incorporates its facility to store electricity generated from any source, at a comparatively lower total cost. At present, these energy storage systems are available whether as transportable trailers of up to 1 MW (3 MWh) unit capacities; or as a building block for bigger scale applications.

The followings are examples of these batteries: ZBB Energy Corporation's Zinc Energy Storage System (ZESS), RedFlow Technologies' Zinc Bromine Module (ZBM), and Premium Power's Zinc-Flow Technology (Red Mountain Insights, LLC, 2012).

III-38. Opportunities and challenges of energy storage

Integrating an energy storage device with an energy system is a capital key to make an active generator and to convert the renewable energy generated to behave as a

conventional energy generated, that is to say, to eliminate the principal inconvenience of randomness of renewable energy. The storage functions as damper and regulator in the electric network; hence resolving the fluctuation issues in addition to exponentially ameliorating the quality of the electricity produced and the distribution quality. In other words, energy is stored when production exceeds consumption; the same energy will be used in the opposite case which will allow steady production instead of scaling up and down to meet the electricity demand instantaneously. Archetypal storage allows not only the compensation of the power disparity between the actual renewable energy production and the consumption; but also, enables a good energy management strategy to control the energy flows amidst the renewable energy generator, the energy storage and the grid. Energy storage facilities by storing energy downsize the generation capacity needed to satisfy consumption during intervals of peak demand, thus curtailing necessity for new capacity. For example, night time power generation of wind turbines is stored in these facilities to meet the steep electricity needs of daytime work hours.

The use of energy storage is economical, even though the electricity generation cost augments, marginally, the costs of storing and retrieving added to the price of the loss in the process.

All available storage technologies do not suit all applications due to limitation in power and storage capacity. A storage system is more valuable when it accomplishes multitudinous functions. Moreover, response time is another decisive concern, notably for power applications for which the system must be available instantly. In addition, the share of the cost of storage is relatively high within the COE. Therefore, minimizing the cost of energy storage of power generation project, involving energy storage technologies ranks among the challenges encountered by projects developers.

III-4. Converters

In HOMER, a converter represents a rectifier and an inverter. A rectifier converts alternative current (AC) into direct current (DC) whereas an inverter does the opposite, meaning convert DC into AC. A converter is an electric device, and commercially available worldwide.

In this study, the hybrid system consists of two buses which are the AC bus and DC bus. The converter is to be installed in between these buses. Modular converter system architecture is preferred for the project for the sake of configuration customization, transportation, handling and installation concerns. In addition, technical and economic performances including costs and efficiency of the device are of vital importance in the choice of the right converter for the system.

The project opted for modular FlexPhase Converters designed for wind energy application and battery energy storage up to 5200Kw, manufactured by Northern Power System, as shown in Figure III-41 and Figure III-42.

FIGURE III-41: WIND ENERGY TYPE CONVERTER



Source: Northern Power System

FIGURE III-42: INVERTER MODULE SET



Source: Northern Power System

This converter, with response time inferior to 1ms, utilizes not only a single control module with up to 6 bidirectional power modules, but also a purposefully designed communication processor to handle simultaneous communication channels and protocols, comprised of, but not limited to, Ethernet, MODBUS, RS-485, and CAN. This allows a real time control response to commands from a system level controller. Like all other electric devices, the components can be recycled and safely disposed of. The environmental impacts, therefore, are almost none.

IV- A FEASIBILITY STUDY OF WIND-SOLAR-BATTERY POWER GENERATION SYSTEM

Energy is a requirement for port operations. Though, energy is still an issue for Toamasina port in terms of energy security. The coastal city of Toamasina, where the port is located, has experienced frequent power shortages or blackouts these recent years. This has hampered the performance and development of Toamasina port to some extent. The energy supplied to the entire area of the coastal city of Toamasina, including Toamasina port, is generated by hydro-plant power with a small portion produced via diesel power plant. Due to the price escalation and the detrimental environmental impacts of fossil fuel, and the substantial fall in the cost of renewable energy technologies, renewable energy systems power supply has become sustainable, environmentally friendly, competitive and cost effective. The renewable energy systems (RESs) are comprised of wind, solar and energy storage systems of various technologies. Study on RESs often involves system modelling, component sizing, economic analysis, simulation and system optimization. For example, HOMER software is used for RES modelling, technico-analysis, optimization, and simulation.

Abundant research has evidenced the technical and economic viability of hybrid wind, solar, and battery systems (Ma , Yang, & Lu, 2014).

This section embraces the feasibility study of supplying Toamasina Port's electricity requirements by using merely RES composed of wind, solar energy and battery storage. A feasibility study, technical and economic assessment and system design is, therefore, carried out. Wind speed and solar radiation around the port area have been collected in order to subsequently enable to appraise the potentials of these renewable energy resources. To conclude in an optimal system, using HOMER

software, thousands of configurations on an hourly basis are simulated and compared with respect to net present cost (NPC), cost of energy (COE) and energy generated. Furthermore, a comprehensive analysis of the system and the associated economic performance is considered.

IV-1. HOMER

HOMER software designs hybrid renewable power generation system, either standalone or grid-connected configurations. The software models renewable and conventional energy technologies. HOMER, via optimization and sensitivity analysis, enables project developers to assess the techno-economic feasibility of a great number of technology options and configurations while taking into consideration technology costs and energy resources availability. HOMER delivers optimal configurations of energy generation systems with the number and size of each component, according to the system net present cost criteria. To achieve an optimal system, HOMER undertakes hourly energy balance calculations for a one year period (8760 hours) in order to simulate the operation of a system, that is to say, an hourly evaluation of load demand and calculation of the energy flows throughout every component of the system for each system configuration. The software assesses the feasibility of each system configuration along with the costs estimations over a project lifetime. The cost estimations consist of ICC, O&M and, salvage and replacement costs. Furthermore, each sensitivity variable is subject to system optimization process.

Lastly, HOMER lists configurations, sorted by NPC, after completion of system operation simulations.

IV-2. Overview of the present electricity supplies into Toamasina port

Jiro sy Rano Malagasy (JIRAMA), the National Power Company, supplies electricity to Toamasina port with the rest of the Toamasina City. The last five years the city and the port have suffered from frequent power blackouts and shortages. On the other hand, the cost per kWh of electricity has been rising constantly, due to, mainly, the heavy dependent of power generation on imported fossil fuel. The rate of electricity production from fossil fuel powered thermal plant has increased whereas energy generation from other sources, including hydropower, wind and solar, has decreased. The 2014 electricity production statistics published by JIRAMA showed that 34 per cent of the total electricity production came from hydropower plant, and 66 per cent generated from fossil fuel source. Among the 66 per cent, 25 per cent was generated using diesel oil source, and 75 per cent using fuel oil. Moreover, the scale of blackouts can represent up to 28 percent of the time. The Port of Toamasina has, certainly, been suffered from the power shortages and blackouts. The present base load of the port is estimated at an average of 3920kWh per day.

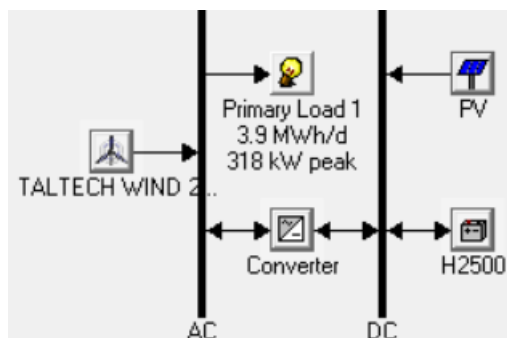
IV-3. System description and configuration

The system is principally comprised of wind turbines, PV arrays, battery bank, converter and the auxiliary components. The converter connects the AC and DC buses, thus converting, on the first hand, the DC power output from PV arrays and batteries into AC to supply the load; on the other hand, the AC power output from wind turbines into DC to be stored in the battery bank when excess energy generation occurs. On the other hand, the battery bank supplies power to the load in case of either insufficiency or unavailability of energy output from both wind turbines and PV arrays. When the battery bank is fully charged, the extra energy is fed into the city electricity grid at local tariff. Wind turbines energy is directly delivered to the AC bus, whereas PV arrays and Battery supply the DC bus. The architecture of the hybrid wind, solar and battery system is shown in Figure IV-2.

The operating scheme of the hybrid system is rather straightforward. When the difference between the actual load and the system energy output, called net load, is negative, denoting enough renewable energy to meet the load, the surplus energy goes to the battery bank or is fed into the city electricity grid in case of fully charged battery bank. Conversely, when the net load is positive, the battery bank supplies the required load.

$$\text{Net load} = \text{actual load} - \text{hybrid system energy output}$$

FIGURE IV-2: HYBRID SYSTEM ARCHITECTURE



IV-4. System modelling

The average hourly base load is estimated at 164kW, with 318kW peak load. HOMER software is used to synthesize a relatively rational hourly load profile of a year, as illustrated in Figure IV-41. The wind speed and solar radiation were collected from the site. The monthly average of these wind and solar resources are shown Figure IV-42 and Figure IV-43 respectively.

FIGURE IV-41: HOURLY LOAD PROFILE FOR A YEAR

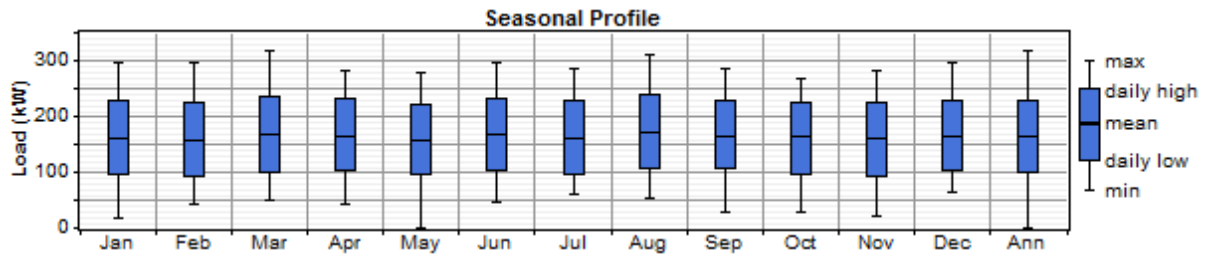


FIGURE IV-42: WIND RESOURCE

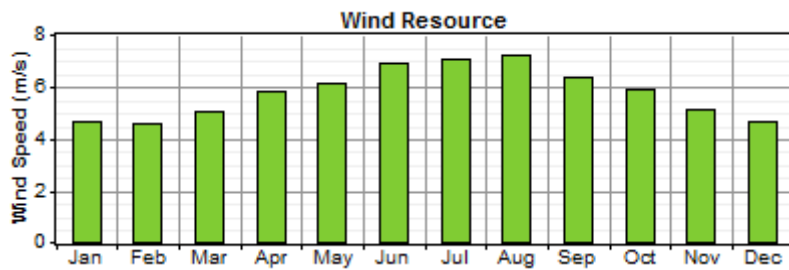
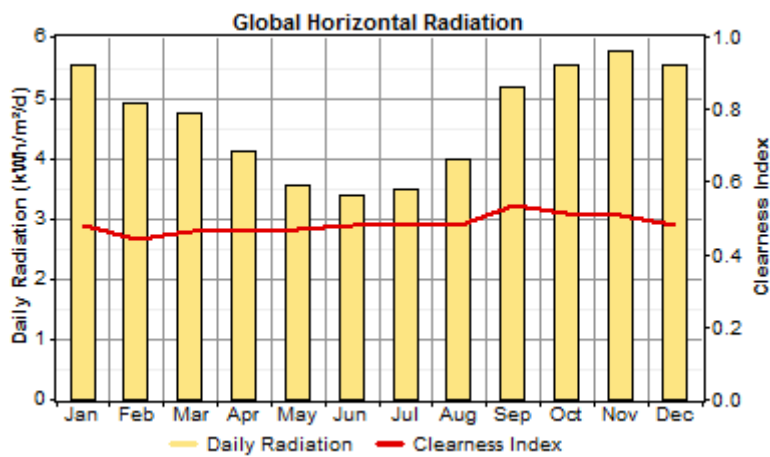


FIGURE IV-43: SOLAR RESOURCES



IV-41. PV modules

Suntech manufactured PV modules, model STP305-24/Ve were used for the study. The PV module rated power is 305W. The efficiency of the PV module in stand test

condition (STC) is 15.7%. The initial capital and replacement costs are estimated at US\$3.344/W each (NREL, 2013). The operating and maintenance cost is about US\$0.019/W annually (NREL, 2013). The PV power output (in kWh) can be determined as follows:

$$P_{PV} = f_{PV} \times Y_{PV} \times \frac{I_T}{I_S},$$

Where:

$$I_S = 1000W/m^2;$$

$f_{PV} = 80\%$, is the PV derating factor;

Y_{PV} , I_T are the rated capacity, and the global solar radiation (in kWh/m²) respectively (Ma , Yang, & Lu, 2014). The scaled annual average solar radiation hitting the Toamasina Port area is 4.64 kWh/m² per day. The monthly distribution of solar radiation is shown in Table IV-411. Additionally, the characteristics of PV module are outlined in Table IV-412.

TABLE IV-411 : AVERAGE MONTHLY SOLAR RADIATION (in kWh/m²/day)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Solar Radiation	5.534	4.903	4.741	4.112	3.560	3.366	3.482	3.981	5.173	5.531	5.759	5.547

TABLE IV-412: PV CHARACTERISTICS

Solar photovoltaic (PV)	
Manufacturer	Suntech
Model	STP305-24/Ve Polycrystalline
Maximum Power at STC (Pmax)	305 W
Optimum Operating Voltage (Vmp)	36.2 V
Optimum Operating Current (Imp)	8.43 A
Dimensions	1956 x 992 x 40 mm
No. of Cells	72 (6 x 12)
Capital Cost	US\$ 3344/kW
Replacement Cost	US\$ 3344/kW
Operating and maintenance Cost	US\$ 19 per year
Derating Factor	80%
Slope	18.1%
Lifetime	25 years
Search space for solar PV	0, 100-400kW, with an interval of 5kW

Source: Suntech Company

IV-42. Wind turbine

The italtech manufactured wind turbines were selected for the purpose of this study. The description of the wind turbine and the different incurred costs during the project lifetime, are listed in the Table IV-421.

The installed cost of wind energy is estimated at US\$ 4019/kW and the O&M is US\$ 6600 per year (NREL, 2013). The replacement cost was assumed to be the same as the ICC, US\$ 4019/kW.

TABLE IV-421: WIND TURBINE DESCRIPTION

Wind turbine	
Manufacturer	Italtechwind
Model	Italtechwind 200kW
Rated output	200 kW AC
Cut in speed	3 m/s
Cut out speed	25 m/s
Rotor diameter	35
Hub height	50
Capital Cost per unit	US\$ 803800
Replacement Cost per unit	US\$ 803800
Operating and maintenance Cost	US\$ 6600/year
Lifetime	25 years
Search space of wind turbine	0-7 units, with interval of 1

Data source: italtechwind

The model developed by Eminoglu & Ayasun (2014), is used to compute the power output, $P(v)$, from the italtech wind turbine.

$$P(v) = \frac{1650}{1 + e^{-(bv-7.5)}}$$

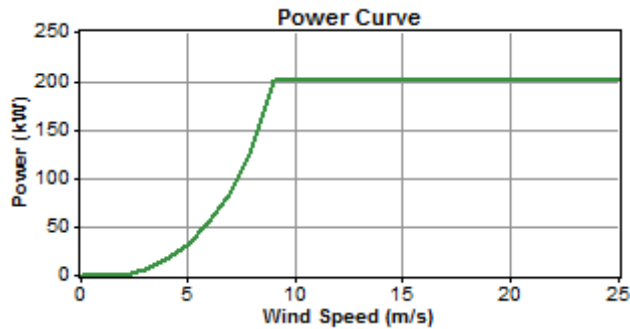
Where:

$$b = 5.822e^{-4.757} + 1.79e^{-0.767}$$

v is the wind speed (in m/s).

The power curve of this 200kW-italtech wind turbine is drawn in the Figure IV-422.

FIGURE IV-422: ITALTECHWIND 200KW WIND TURBINE POWER CURVE



IV-43. Battery bank

The battery ‘Hoppecke 20 OPzS 2500’ is used to serve as energy storage of the system. This battery is a vented lead-acid battery. The battery description is shown in Table IV-431. The ICC and O&M costs are US\$ 1507 per unit and US\$ 10 per year respectively (Ma , Yang, & Lu, 2014) and (Wind & Sun Ltd, 2014).

TABLE IV-431 BATTERY DESCRIPTIONS

Battery	
Manufacturer	Hoppecke
Model	20 OPzS 2500
Nominal capacity	2500 Ah
Nominal voltage	2V
Roundtrip efficiency	86%
Minimum state of discharge	30%
Lifetime throughput	8523 kWh
Capital Cost per unit	US\$ 1507
Replacement Cost	US\$ 1507
Operating and maintenance Cost	US\$ 10/year
Float life	20 years
Search space for battery	0-360 units, with an interval of 18

Source: Hoppecke Company

The numbers of batteries (η_{battey}) and strings (η_{string}) are computed using formulas presented by Ma , Yang, & Lu (2014), as follow:

$$\eta_{battery} = \frac{\eta_{day} \times E_{load}}{\eta_B \times V_B \times C_{single} \times DOD}$$

$$\eta_{string} = \frac{\eta_{battery} \times V_B}{36}$$

Where:

η_{day} is the number of autonomous days fully powered by the battery bank;

E_{load} is the daily power consumption (in kWh)

η_B is the efficiency of the battery and converter

V_B is the battery rated voltage

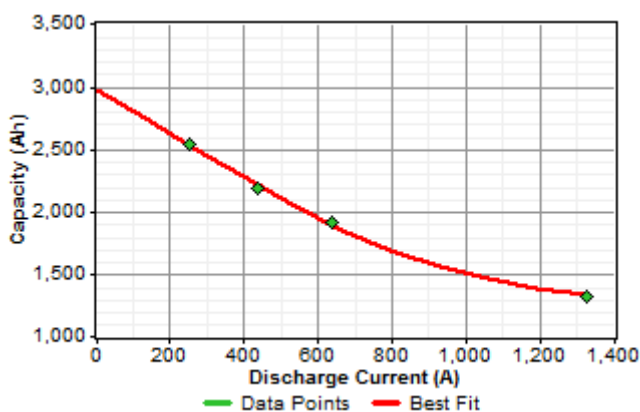
C_{single} is the single battery storage capacity

DOD is the allowable depth of discharge

Each string is composed of 18 batteries to constitute the nominal voltage of the DC bus which is 36V.

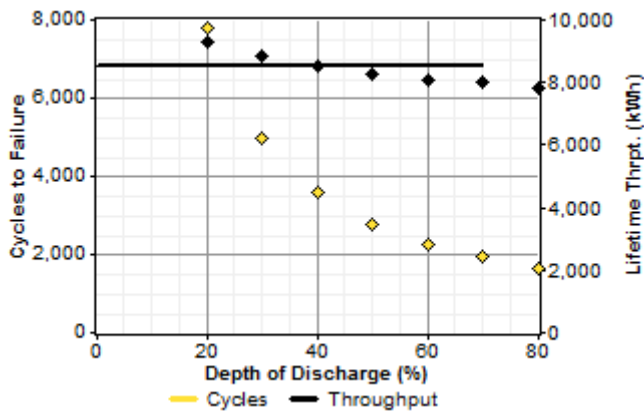
The battery is treated as a two-tank system. This is called the kinetic battery model. The model is employed to determine the maximum permissible rate of charge or discharge of the battery. This model implies that one tank, which represents part of the battery storage capacity, is immediately available for charging or discharging, whereas the other tank is chemically bound. In addition, the kinetic battery model describes the shape of the capacity curve of the battery displayed in Figure IV-432.

FIGURE IV-432: BATTERY CAPACITY CURVE



As illustrated in the battery capacity curve (Figure IV-432), the higher the discharge rate, the smaller the bound energy which can be made available before the other tank is empty, and vice-versa. The two-tank system, not only, restrains both tanks to be either fully charge or discharged at once; but also, implies that, whether the battery should charge or discharge is subject to its current state of charge and its recent charge and discharge history. In addition, the lifetime curve, shown in Figure IV-433, indicates that the number of cycles falls abruptly as the depth of discharge intensifies.

FIGURE IV-433: BATTERY LIFETIME CURVE



The lifetime throughput (Q in kWh) of one battery can be determined and is equal to the product of four variables including the number of cycles(f), the depth of discharge(d in %), the nominal voltage of the battery(V_B), and the maximum capacity of the battery(q_{max} in Ah). This can be translated in the following equation:

$$Q = f \times d \times \frac{q_{max} \times V_B}{1000}$$

Moreover, the system is equipped with the set-point state of charge. Lambert, Gilman, & Lilienthal (2006) suggested the battery set-point state of charge to be set at 80%. The set-point SOC allows the batteries to continue charging until the stipulated state of charge is attained. The set-point SOC prevents the batteries from suffering from shallow charge-discharge cycles at nearly its lowest state of charge.

IV-44. Power converter

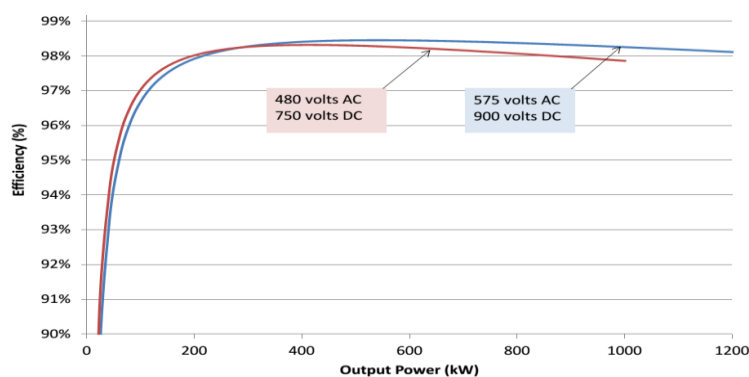
The power converters serve as an interface between the AC bus and DC bus of the system. The latter requires 205kW of power converter. The FlexPhase power converter manufactured by Northern Power System (NPS) is suggested to meet the expected overall efficiency. The converter efficiency curve is shown in Figure IV-442. On the other hand, the descriptions of the converter are summarized in Table IV-441. The ICC of converter is estimated to be US\$750 per kW according to the overall current market. The replacement cost is assumed to be equal to the initial investment cost, whereas, the O&M relatively zero.

TABLE IV-441: CONVERTER DESCRIPTIONS

Power converter	
Manufacturer	Northern Power System
Model	FlexPhase
Response time	Less than 1mS
Efficiency	90% (up to 98.7%)
Environment temperature	-40 to 50°C
Lifetime	15 year
Search space for converter	70-350 kW, with an interval of 5 kW

Data source: Northern Power System (NPS)

FIGURE IV-442: FlexPhase CONVERTER EFFICIENCY



Source: Northern Power System

IV-5. Configuration results analysis

In order to find an optimal configuration of the hybrid system, as shown in Figure IV-2, thousands of cases were carried out, while taking into consideration the constraints and economic variables set for the system, as summarized in Table IV-51.

TABLE IV-51: CONSTRAINTS AND ECONOMICS

Constraints			
Maximum annual shortage	Operating reserve in % of hourly load	As percentage of renewable output	
		Wind power output	Solar power output
19%	10%	50%	35%
Economics			
Project lifetime	Annual interest rate	Capacity shortage penalty	
20 years	6%	0 US\$	

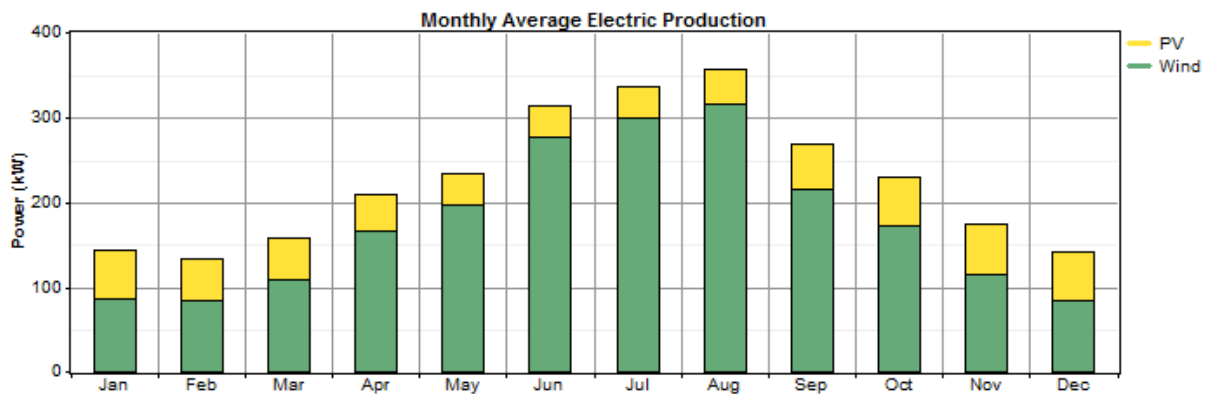
The results of the simulation, using HOMER software, revealed an optimal system comprised of 3 units of wind turbine, 310 kW PV array, 270 units of battery, and 185 kW converters. The operating and economic performances of each component of the system are summarized in the Table IV-52.

TABLE IV-52: OPERATING AND ECONOMIC PERFORMANCES

Parameters	W. Turbine	Solar PV	Battery
Total rated capacity (kW)	600		
Mean output (kW)	177	49	
Capacity factor (%)	29.5	15.6	
Total production (kWh/year)	1 553 024	424 977	
Hours of production (hours/year)	8 752	4 378	
Levelized cost (US\$/kWh)	0.140	0.213	
Rated capacity (kW)		310	
Battery number			270
Battery strings in parallel			15
Usable nominal capacity (kWh)			945
Autonomy (hours)			5.77
Lifetime throughput (kWh)			2 301 210
Energy in (kWh/year)			122 138
Energy out (kWh/year)			106 080
Battery wear cost (US\$/kWh)			0.191
Expected life (year)			20

The levelized cost per kWh for wind turbine and solar PV are US\$ 0.140, and US\$ 0.213; whereas the energy cost for the battery is zero, due to the fact that the battery is only storage of energy generated from either wind turbine or solar PV. Nonetheless, the battery wear cost of US\$ 0.191 per kWh, is relatively noteworthy. Solar PV accounts for 21% of the total annual electricity production. On the other hand, wind turbines produce 79% of the annual power out. The monthly average electricity production from both solar PV and wind turbine is displayed in Figure IV-53.

FIGURE IV-53: MONTHLY AVERAGE ELECTRICITY PRODUCTION



The battery Figures showed significant necessity of the battery bank in hybrid system. Throughout the year, the battery state of charge (SOC) values between 95% and 100% prevail at approximately 45% of the time. Moreover, the SOC values between 30% and 35% occur about 25% of the time. And the SOC values between 35% and 95% happen 30% of the time. The battery bank SOC, monthly SOC statistic utilization and its frequency histogram are presented in Figure IV-54, Figure IV-55 and Figure IV-56, respectively. In addition, it is proven that during the high wind period from April until October, the battery bank SOC is mostly in between 62% and 100%. It suggests that wind blows virtually constantly during the period, as shown in the production summary chart (see Figure IV-53), the solar energy production does not increase.

FIGURE IV-54: BATTERY BANK STATE OF CHARGE

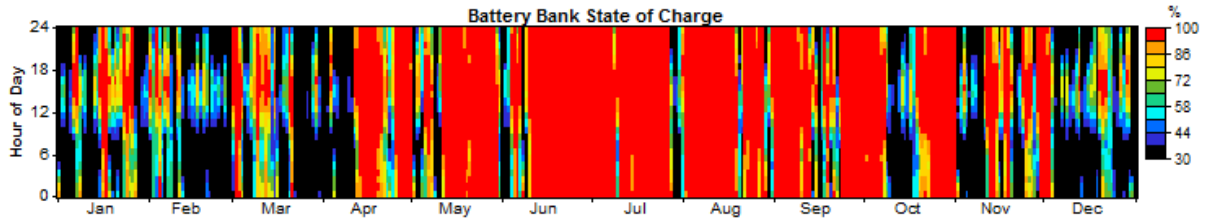


FIGURE IV-55: MONTHLY STATISTICS

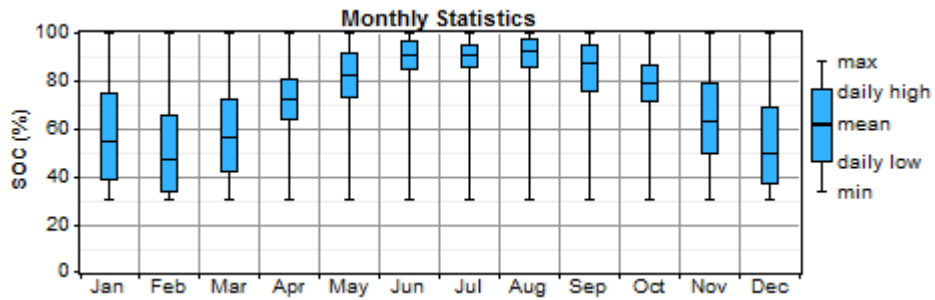
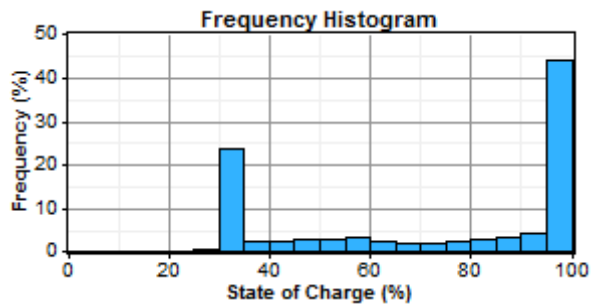


FIGURE IV-56: FREQUENCY HISTOGRAM OF BATTERY STATE OF CHARGE



IV-6. Cost structure of the system

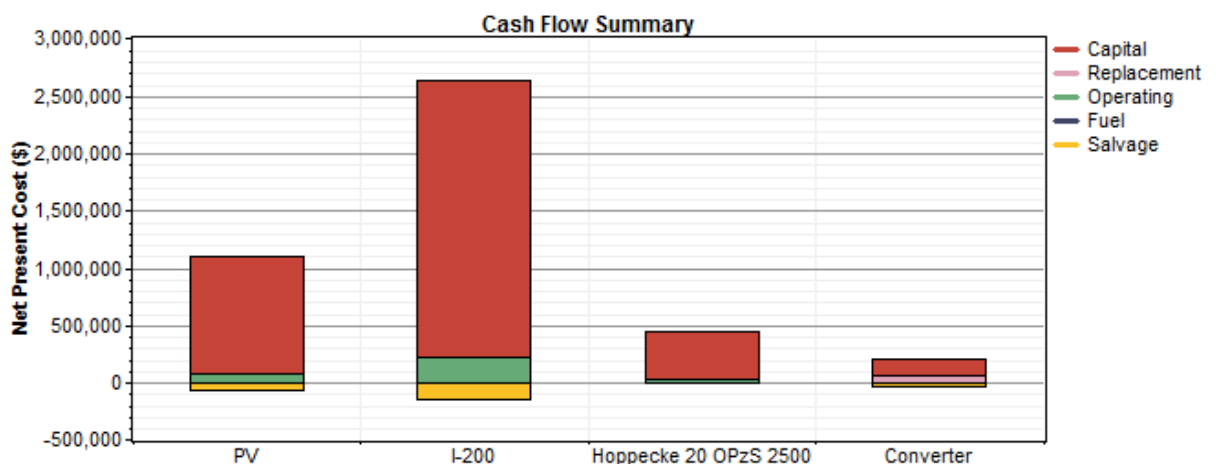
The initial capital cost (ICC) and the net present cost (NPC) of the hybrid system are UD\$ 3,993,680 and US\$ 4,133,342 respectively. The interest rate of 6% is used for all calculations. The cash flow summary is given in Table IV-61 and Figure IV-62.

TABLE IV-61: CASH FLOW SUMMARY (IN US\$)

Component	Capital	Replacement	O&M	Salvage	Total
Solar PV	1 036 640	0	67 558	(64 646)	1 039 552
Wind turbine	2 411 400	0	227 105	(150 377)	2 488 128
Battery	406 890	0	30 969	0	437 859
Converter	138 750	57 896	0	(28 842)	167 804
System	3 993 680	57 896	325 631	(243 865)	4 133 342

The lifetimes of solar PV, wind turbine and battery are 25 years, 25 years and 20 years respectively; therefore their replacement costs are zero during the 20-year project lifetime. On the other hand, converter's lifetime is 15 years, which explains the existence of the replacement cost of US\$ 57,896. Similarly, because the lifetime of some components of the system, including solar PV, wind turbines and converter, stretches beyond the end of the project period, their remaining values are to be deducted from the total system cost.

FIGURE IV-62: DISCOUNTED CASH FLOW SUMMARY



The levelized cost of energy (LCOE) can be determined using the following formula, as endorsed by IRENA (2012).

$$LCOE = \frac{\sum_{t=1}^n \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}}$$

Where:

$LCOE$ is the average lifetime levelized cost of electricity generation

I_t is the investment in year t

M_t is the replacement, salvage, operations and maintenance (O&M) costs in the year t

F_t is the fuel expenditures in the year t

E_t is electricity generation in the year t

r is the discount rate

n is the economic life of the system

The LCOE equation can be written as followed:

$$LCOE = \frac{\textit{Present Value of Total Costs of system (US\$)}}{\textit{Presnet Value of all Energy Produced over project lifetime (kWh)}}$$

The electricity generation by the system is 1978001kWh per year. However, the actual annual electric load demand from port is 1286381kWh. Moreover, the discount rate is 6% during the entire project lifetime of 20 years. The estimated annualized total cost of system is US\$ 360364.00. The fuel expenditure is zero.

The value of each variable is,

$$n = 20$$

$$r = 0.06$$

$$F_t = 0$$

$$I_t + M_t + F_t = 360\,364.00 \text{ US\$}$$

$$E_t = 1\,286\,381 \text{ kWh/year}$$

Thus,

$$\sum_{t=1}^n \frac{I_t + M_t + F_t}{(1+r)^t} = 4\,133\,342.00 \text{ US\$}$$

And,

$$\sum_{t=1}^n \frac{E_t}{(1+r)^t} = 14\,754\,688.73 \text{ kWh}$$

Therefore,

$$LCOE = \frac{\sum_{t=1}^n \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}} = \frac{4\,133\,342.00}{14\,754\,688.73} = 0.280 \text{ US\$/kWh}$$

The system LCOE is US\$ 0.280 per kWh.

IV-7. Project appraisal

The viability of the project is analysed in this section. The project feasibility is evaluated with the values of the Payback Period, Net Present Value (NPV) and Internal Rate of Return (NPV). In the analysis the ecological cost, known as cost of externalities will be included in order to quantify the associated cost of carbon dioxide equivalent emission associated with the current kWh of electricity consumption, purchased by Toamasina port from the national power generation company. The quantification of benefits of both With Project Case and Without Project Case will be carried out. These benefit estimates along with cost estimates will be assessed through the three project appraisal methods mentioned earlier.

IV-71. Annual power bill

The cost of kWh of electricity in the zone of the port is US\$ 0.19. On the other hand, the annual power load is 1286381kWh. The unsatisfied load demand per year is 147338kWh which represent roughly 10.3 per cent of the total annual power production. Therefore:

$$\text{Electricity bill} = 1\,286\,381 \times 0.19 = \text{US\$ } 244\,412.39$$

$$\text{Cost of unmet electric load} = 147\,338 \times 0.19 = \text{US\$ } 27\,994.22$$

IV-72. Ecological cost

As previously presented, power production for the region is not all generated from clean energy resources. Hydro-power plants produce only 34%, whereas, 66% is generated from burning either gas oil or fuel oil. 25% of this 66% is produced by burning gas oil, and 75% remaining is obtained by using fuel oil as an energy source. The gas oil and fuel oil are pollutant sources of energy. The effects of greenhouse gas (GHG) emissions, from the utilization of these fossil fuels as sources of power, are significantly contributing to global warming and climate change. They lead to emissions of not only carbon dioxide (CO₂) but also quantities of other greenhouse gases comprised of methane (CH₄) and nitrous oxide (N₂O). The quantification of the amount of gases emitted is consequently required in order to calculate their costs. For this purpose, the global warming potential concept is explored. Using global warming potential (GWP), for a given amount of a gas, the equivalent quantity of CO₂ that would be sufficient to cause the same effect, can be calculated. The derived quantity is quoted in units of kilograms carbon dioxide equivalent (kgCO₂e), meaning that the quantification includes the combined effect of CO₂, CH₄ and N₂O. This is known as greenhouse gas conversion factor. The conversion factors for gas oil and fuel oil are 3427.2 kgCO₂ per tonne, and 3232.7 kgCO₂ per tonne, respectively (Carbon Trust, 2013).

On the other hand, the production of a kWh of electricity consumes 274g of gas oil, or 225g of fuel oil (JIRAMA, 2013).

Assuming that the electricity generated from these three types of power plants are evenly distributed according to their share of production in the total electricity generation. That is to say, 34% of the supplied electricity into the port is from hydro plants and 66% from fossil fuel sources. But, in our case, the avoided emissions in implementing the project, is equal to the sum of the total emissions generated in producing total load minus the unmet load by the renewable energy generation. That difference represents the satisfied load demand.

$$\text{satisfied load demand} = 1\,286\,381 - 147\,338 = 1\,139\,043 \text{ kWh per year}$$

The 66 per cent of which is generated from polluted sources:

$$\text{Power generated from oil} = 0.66 \times 1\,139\,043 = 751\,768.38 \text{ kWh per year}$$

25% and 75% of the latter are 187942.10 kWh generated from gas oil thermal power plant, and 563826.29kWh from fuel oil thermal power plant. The quantity of fuel consumed is as follow:

$$\text{Gas Oil consumption (in g)} = 274 \times 187\,942.10 = 51\,496\,134.03 \text{ g}$$

$$\text{Fuel Oil consumption (in g)} = 225 \times 563\,826.29 = 126\,860\,914.13 \text{ g}$$

The quantity of emission equivalent, CO_{2e}, is:

$$\text{CO}_2\text{e for gas oil (in kg)} = \frac{51\,496\,134.03 \times 3427.2}{1000000} = 176\,487.55 \text{ kg}$$

$$\text{CO}_2\text{e for fuel oil (in kg)} = \frac{126\,860\,914.13 \times 3232.7}{1000000} = 410\,103.28 \text{ kg}$$

$$\text{Total CO}_2\text{e} = 586\,590.83 \text{ kg} = 586.59 \text{ tonnes}$$

The ecological cost for a tonne of CO_{2e} is 135 Euros (Delft University of Technology, 2013).

The exchange rate is 1 Euro = UD\$ 1.29, so 135 Euros = US\$ 173.88.

The cost of emissions is equal to:

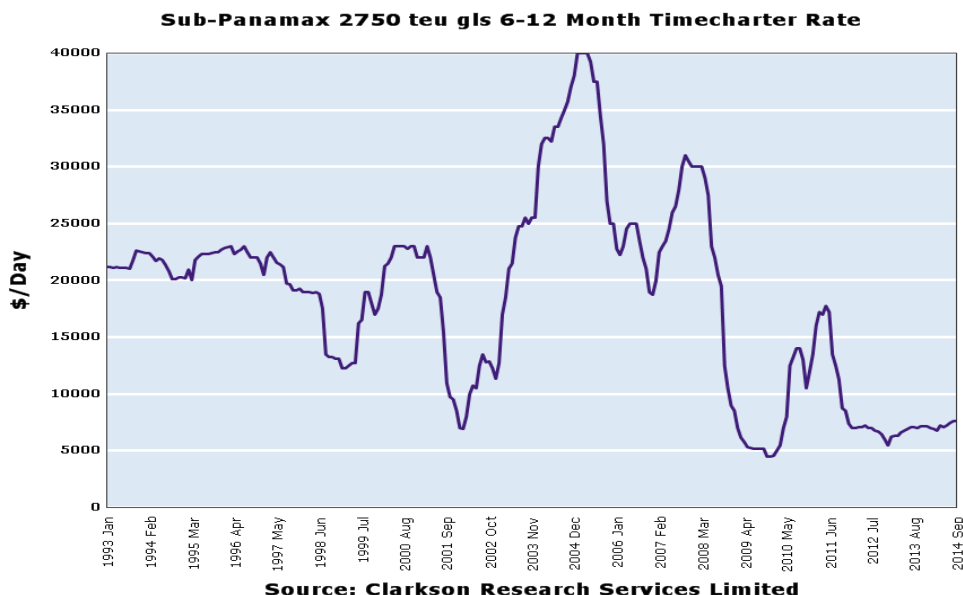
$$\text{Cost of CO}_2\text{e (in US\$)} = 586.59 \times 173.88 = \text{US\$ } 101\,996.41$$

IV-73. Ships' waiting cost

Operations of one container terminal berth in the port are widely subject to power availability due to QCs' electric load requirements while loading or unloading containers. Other berths are equipped with fossil fuel powered mobile harbour cranes. The average number of ships handled at this berth is estimated at 300 per year, with an average size of 3000TEUs.

The frequency distribution of power blackouts and shortages for the last five years revealed a threat up to 0.20 days of ships waiting time, before berthing, could be triggered by the actual electricity situation. The associated annual cost of ships' waiting time was calculated using the daily ships charter rate for similar size vessel for September 2014 retrieved from Clarksons database. The daily rate was US\$ 7600 (Clarkson, 2014). The sub-panamax monthly rate is shown in Figure IV-73. The cost of ships waiting time is, therefore, estimated at US\$ 456000 per annum.

FIGURE VIII-e-3: SUB-PANAMAX MONTHLY RATE



IV-74. Excess of electricity

The optimal hybrid system produces an annual excess of electricity of 648535 kWh. This is mainly due to the time distribution mismatch between power demand and generation. The excess of electricity can be reduced to an insignificant amount; however, that will induce an increase in the capital cost of the entire system, therefore a higher COE, because the number of the components within the system increased proportionally, particularly the battery to store the energy and release the energy as demand requires.

The excess can be fed to the local electricity grid at the national tariff.

$$\text{Sale of excess of electricity} = 648\,535 \times 0.19 = \text{US\$ } 123\,221.65$$

IV-75. Without-Project Case, and With-Project Case (costs in US\$)

All costs and benefits are grouped accordingly, as shown in Table IV-751. The Without-Project case is the case that the project would not be achieved, and the With-Project Case is the opposite.

TABLE IV-751: WITHOUT/WITH PROJECT CASE COSTS (IN US\$)

	Without-Project	With-Project
Electricity bill	244 412.39	
Cost of emissions (CO ₂ e)	101 996.43	
Cost of ship's waiting	456,000.00	
Project ICC		3 993 680.00
Sale of excess of electricity		123 221.65
Cost of unmet load		27 994.22

The project summary costs are outlined in Table IV-752. The project cash flow or costs are categorized into system costs and opportunity costs of undertaking the project.

TABLE IV-752: PROJECT COSTS SUMMARY (IN US\$)

	System costs	Opportunity costs
Project ICC	3 993 680.00	
Electricity bill		244 412.39
Cost of emissions (CO ₂ e)		101 996.43
Cost of ship's waiting		456 00.00
Sale of excess of electricity		123 221.65
Cost of unmet load		(27 994.22)
Total	3 993 680.00	897 636.25

It is indicated in the Table that the project investment will procure a net benefit of US\$ 897636.25, which is the actual annual cash flow.

IV-76. Payback Period

The Payback Period represents the amount of time to recover the initial costs of investment. The Payback Period is likely the simplest method of investment appraisal. The Payback Period calculation uses the following formula:

$$\text{Payback Period} = \frac{\text{Initial investment}}{\text{Cash Flow per Period}}$$

$$\text{Payback Period} = \frac{3\,993\,680.00}{897\,636.25}$$

$$\text{Payback Period} = 4.45 \text{ years}$$

Considering the payback period of 4.45 years, it can be concluded that the project is persuasive and good enough to be implemented.

IV-77. Net Present Value (NPV)

The NPV is used to assess the profitability of the project investment. The NPV is the difference between the discounted cash flows and the initial capital investment. The calculation formula is as follow:

$$NPV = \sum_{t=1}^T \frac{C_t}{(1+r)^t} - C_0$$

Where:

C_t : net cash flow of the period

C_0 : initial investment

r : discount rate

t : time period

$$NPV = \sum_{t=1}^{20} \frac{897\,636.25}{(1 + 0.06)^t} - 3\,993\,680.00$$

$$NPV = \text{US\$ } 6\,302\,137.07$$

The project generates positive NPV of US\$ 6,302,137.07 which implies that the project is acceptable. A project with negative NPV should be rejected.

IV-78. Internal Rate of Return (IRR)

The IRR is the discount rate at which the NPV of all cash flows from the investment equal to zero. The tool is used to measure the profitability of the investment. Generally speaking, the higher the IRR, the more attractive it is to carry out the project. As such, IRR is a means to rank various potential projects. The IRR is determined as follows:

$$NPV = 0$$

$$\sum_{t=1}^T \frac{C_t}{(1 + r)^t} - C_0 = \sum_{t=1}^{20} \frac{897\,636.25}{(1 + r)^t} - 3\,993\,680.00 = 0$$

$$r = IRR = 22\%$$

The investment yields an IRR of 22% over its lifetime of 20 years.

Considering all three project appraisal methods, including Payback Period, NPV and IRR, the investment in the project is shown as feasible and profitable. Thus, the viability of the project is proved.

V- CONCLUSION AND RECOMMENDATIONS

V-1. Conclusion

The study demonstrates that the power demand of the Port of Toamasina can be served fully by a renewable energy power generation system. The hybrid wind, solar and battery can cater for continuous power supply to meet the need in electricity for the port activities. The optimal hybrid system consists of 3 wind turbines, 310 kW PV, 270 battery bank and 185 kW converters. The levelized cost of energy (LCOE) of the hybrid system is US\$ 0.280 per kWh. The total annual energy production is the sum of 21% solar PV generation and 79% wind turbines generation. Of this overall production, an estimate of 648535kWh is the excess of electricity regarding the actual power load demand. In addition, 147338 kWh of the annual demand is unmet. Insufficient annual production is not the reason behind this unmet electric load. On the contrary the overall annual energy production by the renewable energy generation system is well above the size of annual load demand. The existence of both unmet electric load and excess of electricity is borne of the time distribution mismatch between the load demand and generation. This issue can be dealt with by adding additional numbers of battery storage to keep the generated power and release it for later use. But addition components mean additional initial capital investment and the associated lifetime costs, meaning higher COE. Nonetheless, the scale of unmet electric demand can be decreased by introducing Lean Enterprise concept into

port business, which will reduce or even eliminate the electric load consumed for non-adding value activities.

The actual optimal hybrid system is a trade-off between a numbers of parameters, including less initial capital investment, less net present cost, competitive COE, and minimal unmet load.

This project is not simply dealing with proving electricity into port of Toamasina to ensure power security for its activities. The focus is also on savings. Consuming renewable energy instead of fossil fuel generated electricity saves a lot, because renewable energy is cost competitive compared to conventional energy, while considering the cost of emissions or externalities associated with energy production.

On the other hand, the project includes recommendations to introduce Lean Enterprise into port activities to save energy, therefore, enable to close the gap of unmet load by the system. Lean implementation does not entail direct cost of investment at this stage

V-2. Recommendations

V-21. Port energy policy

With the implementation of the present project proposal, it is recommended that Toamasina port start drafting a medium term renewable energy policy for the port. This policy targets the forecasted power demand of port for 2030 horizon and beyond. It is of vital importance to have such a policy available for port. The policy serves as guidance and references to the likeliness of the future energy requirements scenario at different time interval in future, which largely facilitates gradual and constant upgrade of the present energy production facilities and infrastructures to meet the changing power needs of the port. The energy demand is, therefore, satisfied along the way, with only very reasonable investment at roughly predicted

interval, as contained in the energy policy. That will boost energy security of port, and a large sum of investment dedicated to fund relatively large energy generation project will be avoid; hence, keep the financial status of port safe and healthy. Because, it is worth reminding that Toamasina port is comparatively small port.

V-22. Lean concept

On the other hand, as stated in the conclusion, the energy generation system left a portion of annual unmet electric demand, at the same time, yielded excess in electricity production. In order to truncate the slot of unmet electric load or alternatively reduce it to zero, the first option could be investing more, particularly, in energy storage to store the excess production, and release and distribute the stored energy as required during low time production. The second option requires no investment or relatively low costs involvement, which is the application of Lean Enterprise concept into port business. Therefore, it is highly recommended that Toamasina port will opt for the introduction of Lean Enterprise model applied to port business, and, in doing so, targets energy consumption savings virtually equal to the actual unmet electric load by the system, at the end of the fifth year of Lean concept introduction. An overview of recommended stages and steps is presented later on.

Multitude of companies and organizations has harvested significant benefits of different aspects since their application of Lean concept into their activities. Toamasina port will benefit more than energy savings in integrating Lean Enterprise model in every process of its activities. Novaces, for example, mentioned that Lean Six Sigma enables ports and shippers to gear improvements in competitiveness, efficiency and safety, in addition to environment responsiveness (NOVACES, 2014). The port industry is driven to the concept. For instance, GreenPort2009 Conference endorsed “Lean and Green” strategy.

V-221. Lean principles

Going lean requires comprehension and implementation key principles of lean approach which are cardinal to the elimination of waste. The lean principles underline, in the first place, to enumerate non-value added within the organization and determine actions and/or steps to deliver a particular service across the whole value stream to feature waste. The organization is to initiate those actions that generate value flow and to endeavour for perfection in eternally reducing or even eliminating rows and layers of wastes. Therefore, the value stream within the whole port is to be clearly defined.

TABLE V-2211: LEAN THINKING

(a)	(b)	(c)	(d)	(e)
Understanding waste	Setting the direction	Understanding the big picture	Detailed mapping	Checking the plan fits the direction

Source: (Lean Enterprise Research Center, 2000)

a) Understanding waste

By simple definition, waste is any activity which does not bring value to product or service delivered by company. These non-value adding activities inflate the unit costs of service or products. These activities are, therefore to be simplified, reduced or ultimately eliminated. To do so, the very key is to recognize wastes. Waste removal portrays the core mission of lean. Leaner system leads to the identification of quality issues in the system which induces waste. This waste augments extra or unnecessary power consumption within the system. Non-value adding operations are grouped into seven wastes, including overproduction, defects, unnecessary inventory, inappropriate processing, excessive transportation, waiting and unnecessary motion.

There are value adding activity, non-value adding activity and necessary non-value adding activity. The latter group still evidence interests for the organization though they entail waste, nonetheless should be the aim of the long-term strategy.

Waste removal start from organizing seminar for the entire personnel from various departments in view to raise awareness of these wastes. Identified wastes at work are listed, and courses of action are advised to deplete or reduce the wastes. Lastly, personnel, individually or as a group, is assigned to start eliminating the waste on timely basis.

FIGURE V-2212: WASTE DUE TO OVERPRODUCTION



Photo courtesy: University of Alabama Huntsville

FIGURE V-2213: WASTE DUE TO WAITING TIME



Photo courtesy: University of Alabama Huntsville

FIGURE V-2214: WASTE CAUSED BY UNNECESSARY MOTION DUE TO UNORGANIZED WORK AREA



Photo courtesy: University of Alabama Huntsville

b) Setting the direction

Senior managers are strongly recommended to be involved in the effective policy deployment including the followings:

- Develop critical success factors along with adequate business measures, in addition aim at quality amelioration for individual business measure, over time,
- Outline indispensable business processes against objective and decide on processes requiring detailed mapping,

c) Understanding the big picture

It is of foremost importance to establish an overview of the key features of the whole process, prior to engaging in detailed mapping of the actual situations. The big picture can be drawn in five easy phases as follows:

- document service requirements,
- add information flows,
- add physical flows,
- link all three to construct the big picture map of all flows,
- add time line on the map to log service lead time and value adding time.

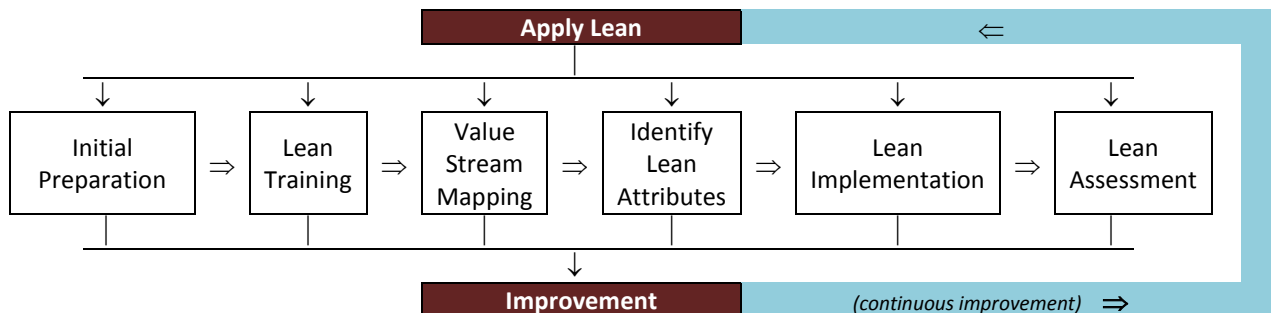
d) Detailed mapping

To complete the detailed mapping, the entire workforce has to be involved. This is to ensure that the entire system is captured by the map, and get every individual understand the action plans for waste removal to gradually optimize power consumption.

e) Checking the plan fits the direction

This stage is to question whether the projected means for improvement will meet the embedded target.

FIGURE V-2215: LEAN CYCLE AND PHASES



Source: (Anvari, Zulkifli, & Rosnah, 2012)

V-222. Lean implementation model for port of Toamasina

Since becoming lean requires some training and employees empowerment at all levels to spot and eliminate waste, port's employees will be invested in lean training for key management, then draw prominent level strategy to accommodate lean enterprise training and realization into the activities of the port business. The following step is, for each department or division, to establish value stream mapping to lodge a convenient implementation road map before exercising effective lean tools to port organization. Last but not least, lean tools are to be depicted for use to fulfil

the set goal. Moreover, each department or division is advised to institute a Lean Steering Committee to supervise the administration of the continuous improvement scheme. The committees set goal, direct and ensure greater propagation of lean perception via both training and employee participation initiatives. In addition, the committees' roles are to institute, apply and follow up pertinent key performance indicators to steer behaviour in view to keep lean improvement success. They are also important partakers in value streams mapping besides assigning preferences to improvement activities.

Thorough lean concepts are offered throughout training along with peculiar lean tools including Lean Office Principles, Total Productive Maintenance, Kaizen and Leadership.

There are almost 25 tools for lean concept. But not all these tools are suitable to be integrated to any company. Instead specific set of goals of a particular company can only be achieved via appropriate lean tools. The seaport lean implementation model can be illustrated in form of multi-layered architecture where workplace organization tools constitute the foundation. The subsequent two upper layers consist of workplace analysis and workplace optimization tools. The overall lean tools should be carried out under the unique umbrella of a continuous improvement culture. In addition, value stream map is seen as an instrument leading into the lean tools of the architecture. Furthermore, value stream map enjoys the role of rendering a plan incorporating foremost approach of lean tools application to reduce or deplete wastes.

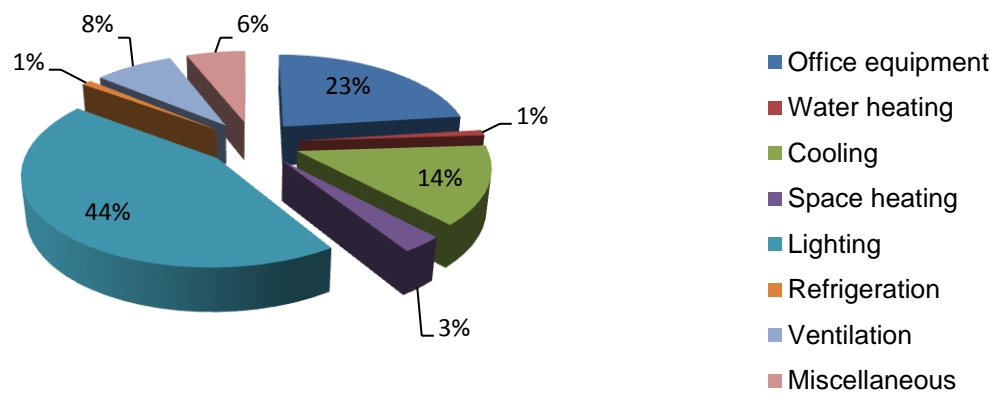
FIGURE V-2221: LEAN IMPLEMENTATION MODEL FOR PORT

Continuous Improvement Culture	Kaizen			<i>Value Stream Mapping</i>
	Teamwork			
	Customer Focus (TAKT)			
Workplace Optimization	Quality at source		TPM	
Workplace Analysis	Layout	SMED Principles	Standardized Work	
Workplace Organization	5S System	POUS	Visual Workplace	

Source: (Loyd, et al., 2009)

To fully enjoy the benefits of lean enterprise, the lean concept and thinking implementation for port should be extended to support functions such as office building and workshop, which generally seen as auxiliary to operations in port. Office power consumption has lately displayed augmentation, generally due to the proliferation of information technology, air-conditioning, and density of use. A typical breakdown of office power demand is shown in the Figure V-2222.

FIGURE V-2222: TYPICAL POWER DEMAND BREAKDOWN FOR OFFICE



Data source: Schneider Electric

a) Continuous improvement culture

Kaizen, teamwork and customer focus make the continuous improvement culture. Each and every improvement element or project should correspond to a course of action described on the value stream implementation plan. The ultimate goal of the project plan is to support and meet customer demand.

i. Teamwork

Teamwork includes cross-training of employees that will ensure quality personnel of extensive flexibility. Cross-training displays enormous gap at port, and has to be instigated to address the gap.

ii. Kaizen

Kaizen describes a continuous improvement process orchestrated by small team achieving significant wastes removal effort on targeted process. Kaizen possesses dual nature of being part action and part philosophy. As an action plan, kaizen consists of organizing events involving team of employees at all level to tackle improvement on very specific process within the company. On the other hand, as a philosophy, kaizen deals with founding a culture for all employees to commit to advising and implementing improvements. Thus, Kaizen is about developing a culture of continuous improvement of all employees by organizing events to improve specific areas of the company. Kaizen is exercised in parallel with the Standardized Work. The latter articulates the actual best practice for a process whereas Kaizen is devoted for improvements for those processes. A typical Kaizen event cycle is often referred to as PDCA (Plan, Do, Check, Act) which is a scientific approach for improvement.

b) Workplace Organization Lean Tools

Workplace organization focuses on ensuring a safe, clean, neat work space to basically get rid of unnecessary items, and arrange the rest in a specific location. This initial phase, known as foundation layer of lean port, comprises of 5S system, visual workplace and point-of-use storage (POUS).

i. 5S system

5S system builds an efficient and well-organized workplace where all needed resources are placed in clearly identified, designated locations. Properly organized workplace not only ameliorates productivity and improves employee moral but also enhance quality. Work space organization is of vital importance.

Having employees engaged in the process leads to fruitful enriched workplace, thus ensure quality at work as well as increase productivity, and cut substantial wastes. The 2008 study of Echo Research, conducted in United States, revealed that 62% of employees would be more motivated and would yield up to 30% more productive in attractive and organized workplace that is preferably the outcome of the employees' involvement. In addition if such workplace organization were involving the workers themselves, the productivity rate would enhance of circa 30% (Knight, 2009). He concludes that employees spend relatively less time complete task and, with fewer errors in such organized enriched work environment. This certainly drives down energy consumption of the company. 5S stands for sort, shine, set-in-order, standardize and sustain.

- Sort means to get rid of all unnecessary components from the workplace
- Shine implies removal of dirt origin and cleaning of the workplace
- Set-In-Order refers to proper location for supplies, tool and materials
- Standardize signifies that all locations in the workplace are labelled identically
- Sustain denotes training, audits and checklists are performed to keep 5S

A 5S score sheet should be established to create a standard for scoring the level of organization between each work area within the entire port. The scores range from 0 to 100 to depict worst and best respectively. This gives each value stream manager a performance metric to enable to track the sustainability of the workplace organization. The score sheet is utilized to grade the work area, not only before the initial workplace organization kaizen event, but also subsequent to the kaizen event, and then regularly.

FIGURE V-2223: WORK SPACE AFTER WORKPLACE ORGANIZATION



Photo courtesy: University of Alabama Huntsville



Photo courtesy: Montana State UNiversity

ii. Visual Workplace

The lean concept Visual Workplace, also known as Visual Management post critical information at the point of use including on the equipment, floors, shelves, walls, and anywhere employees can spot it at a glance for “just-in-time” communication. Visual system is of greater importance because they convey to the employees what to do precisely at all circumstance. Moreover, visual systems and devices hold crucial role in other lean tools, for instance, 5S, Standard Work, Total Productive Maintenance, Kanban and Changeover.

FIGURE V-2224: VISUAL WORKPLACE

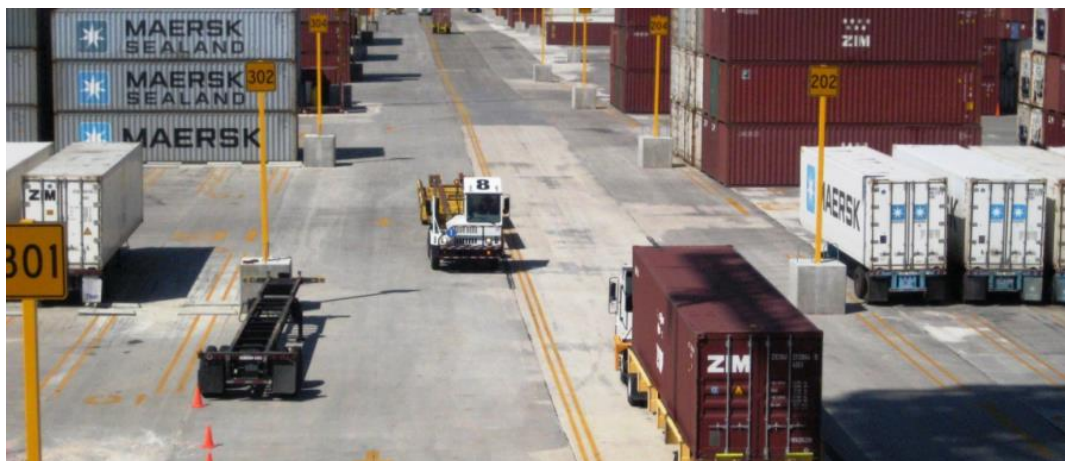


Photo courtesy: University of Alabama Huntsville

iii. Point-Of-Use Storage (POUS)

The point-of-use storage suggests that materials or items are to be delivered directly to its point of use in a proper quantity. It opposes the usual concept of delivering materials to a receiving location or a warehouse and, then transported to a work center where the materials are needed. One of the major wastes, in the conventional non-lean process, is excess movement of materials. The lean POUS concept removes these intermediate moves.

c) Workplace Analysis Tools

The workplace analysis tools include layout analysis, single minute exchange of die (SMED) principles, and standardized work. These tools represent means to critically studying existing processes and spotting opportunities to truncate wastes by depleting needless steps.

i. Layout Analysis

The work area layout assessment would be the first kaizen event triggered following value stream mapping process. Layout analysis and planning allows removal of wastes. Excess space utilization should be minimized or indeed optimized because space represents costs. In addition space minimization or optimization engenders reduced movement for both employees and material which, in turn, cut time absorbed during non-adding value activities such as additional transportation and/or movement of employees. Furthermore, needless materials are likely built up in the extra space.

ii. Principles of Single Minute Exchange of Die (SMED)

Activities performed for a process should be thoroughly analyzed to assess internal and external components to trim time interval between performing value-added activities. Internal elements consist of activities achieved within interval when the value-added step has ended and when it starts again; whereas external elements includes activities which are carried out alongside the value-added activities. SMED Principles prevent these activities to amalgamate; hence avoid consequent inefficiency. SMED principles upgrade opportunity for improvement. Checklists should be established for activities which are to be performed as external elements. This eliminates waiting period and speeds up processes.

iii. Standardized Work

In the last tools of workplace analysis, improved process is documented to serve to train personnel. This initiates the establishment of standardized work, or standard operating procedures (SOPs). Obviously SOPs lead to the institutionalization of knowledge, in addition to creating visual, simple, and effective training for employees engaging into new responsibilities.

d) Workplace Optimization Tools

The top layer of seaport lean implementation model comprises tools to optimize processes previously organized and analysed. Quality at the Source and total productive maintenance constitute the optimization tools (TPM).

i. Quality at the Source

The essence of the quality at the source concept is the state of being proactive regarding quality concerns by getting processes to capture defects as they occur, or hinder them from taking place, at all.

ii. Total Productive Maintenance (TPM)

TPM is a productive equipment maintenance applied to the entire organization embracing every personnel. The aim of TPM is to reach zero unplanned downtime at a port. At glance, cargo handling equipment represents the backbone of port operations. Being proactive in the care of the equipment, and systematic implementation of a TPM are crucial. A thorough executed TPM program can lower unplanned equipment downtime, breakdown cost, and spare part cost up to 60%, 80%, and 30% respectively (Loyd, et al., 2009).

iii. Value stream map

This tool is to map physical and information flows in order to exhibit waste in the current state value stream map and feature opportunities embodied in roadmap for improvement via future state value stream map. A value stream map comprises of three deliverables including a current state map, a future/ideal state map, and a detailed implementation plan. Appropriate value stream management represent element to a successful lean transformation. A team of key personnel assigned the responsibility to map the value stream which lead to drafting of an implementation plan and designation of a value stream manager. The latter bears the accountability to follow through and update the plan towards fulfilment.

iv. Current state value stream map

The current state map is a visual representation of materials and information flow of actual operations process. This phase presents the opportunity to depict wastes residing within the current system. The current state and wastes are assessed and analysed in order to generate countermeasures to address these wastes, and be the foundation to draft the future state map.

v. Future state value stream map

The future state value stream map is the visual representation of the ideal value stream process after removal of wastes depicted in the current state, as scheduled in the plan. A typical future value stream maps are developed on one year timeframe, and show expected changes starting from execution of improvements.

vi. Value stream implementation plan

The implementation plan contains details related to shift from current state to future state. It is a detailed roadmap. Countermeasures are transformed into course of actions displayed along the timeline and allotted to employees who will carry out the actions. But it is the tasks of the value stream manager to undertake adjustments and loads updates to value stream plan properly.

List of References

- Afanasyeva, S. (2011). *Optimization of Wind Farm installations*.
- Alves, A. C., Carvalho, J. D., Sousa, R. M., Moreira, F., & Lima, R. M. (2011). *Benefits of Lean Management: results from some industrial cases in Portugal*.
- Anvari, A., Zulkifli, N., & Rosnah, Y. M. (2012). A dynamic modeling to measure lean performance within lean attributes. *International Journal of Advanced Manufacturing Technology*.
- Asariotis, F., Benamara, H., Hoffmann, J., Jaimurzina, A., Premti, A., Rubiato, J. M., . . . Youssef, F. (2013). *Review of Maritime Transport 2013*. UNCTAD.
- Bartholomew, P., Bates, K. V., Bury, D., Cawein, J., Coyle, A., Currie, R., . . . Wlodarczyk, J. (2007). *The Lean and Environment toolkit*. EPA.
- Bassi, S., Bowen, A., & Fankhauser, S. (2012). *The case for and against onshore wind energy in UK*.
- Bergmiller, G. G., & McCright, P. R. (2009). *Parallel Models for Lean and Green Operations*.
- Beylot, A., Payet, J., Puech, C., Nadine, A., Jacquin, P., Blanc, I., & Beloin-Saint-Pierre, D. (2011). *Environmental impacts of large-scale grid-connected ground-mounted PV installations*. World Renewable Energy Congress.
- BiGGAR Economics. (2012). *Onshore Wind, Direct & wider Economic Impacts*. BiGGAR Economics.
- Boone, S., Breeze, J., Cawein, J., Church, G., Currie, B., Gaither, M., . . . Wolfsberger, J. (2011). *Lean, Energy & Climate Toolkit*. EPA.
- Boyle, G. (2012). *Renewable Energy*. Oxford University Press.
- Bradbury, K. (2010). *Energy storage Technology Review*.
- Budhischak, C., Sewel, D., Thomson, H., Mach, L., Veron, D. E., & Kempton, W. (2013). *Cost-minimized combinations of wind power, solar power and electrochemical storage, powering the grid up to 99% of the time*. Elsevier.
- Carbon Trust. (2009). *Offshore wind power: big challenge, big opportunity*. The Carbon Trust.

- Carbon Trust. (2013). *CO₂ conversion factors: Energy and carbon conversions 2103 update*. London: Carbon Trust.
- Carnegie, R., Gotham, D., Nderitu, D., & Preckel, P. V. (2013). *Utility Scale Energy Storage Systems*. State Utility Forecasting Group.
- Chawla, K., Lins, C., McCrone, A., Musolino, E., Riahi, L., Sawin, J. L., . . . Sverrisson, F. (2014). *Renewables 2014, Global status report*. REN21.
- Chu, Y., & Meiesen, P. (2011). *Review and Comparison of Different Solar Energy Technologies*. Global Energy Network Institute (GENI).
- Clarkson. (2014). *Sub-Panamax 2750 teu gls 6-12 Month Time Charter Rate*. Clarkson. Récupéré sur www.clarksons.net/sin2010/ts/
- Delft University of Technology. (2013). *Eco-costs of emissions*. TUDelft.
- Denholm, P., Jorgenson, J., Hummon, M., Jenkin, T., Palchak, D., Kirby, B., . . . O'Malley, M. (2013). *The Value of energy Storage for Grid Applications*. NREL.
- Eminoglu, U., & Ayasun, S. (2013). *Modeling and Design Optimization of Variable-Speed Wind Turbine Systems*. Energies.
- Engin, M. (2012). *Sizing and simulation of PV-Wind Hybrid Power System*. International Journal of Photoenergy.
- EPRI. (2010). *Addressing Solar Photovoltaic Operations and Maintenance Challenges*. EPRI.
- Feldman, D., Barbose, G., Margolis, R., Wyser, R., Darghouth, N., & Goodrich, A. (2012). *Photovoltaic (PV) Pricing Trends: Historical, Recent, and Near-Term Projections*. SunShot U.S. Department Of Energy.
- Fingersh, L., Hand, M., & Laxson, A. (2006). *Wind Turbine Design Cost and Scaling Model*. National Renewable Energy Laboratory (NREL).
- Gaffney, M. (2012). Improving Energy and Emission efficiency in port terminals. *Port Technology International*, 10.
- Goodrich, A., James, T., & Woodhouse, M. (2012). *Residential, Commercial, and Utility-Scale Photovoltaic (PV) system Prices in the United States: Current Drivers and Cost-Reduction Opportunities*. NREL.
- Gyuk, I., Johnson, M., Vetrano, J., Lynn, K., Parks, W., Handa, R., & Kannberg, L. (2013). *Grid Energy Storage*. U.S. Department of Energy.

- Hansen, U. E., Nygaard, I., & Pedersen, M. B. (2014). *Prospects for investment in large-scale, grid-connected solar power in Africa*. UNEP.
- IEA. (2010). *Solar photovoltaic energy*. International Energy Agency -IEA.
- IEA. (2013). *Technology Roadmap, Solar photovoltaic energy*. IEA.
- IPCC. (2011). *Special report on renewable energy sources and climate change mitigation (SRREN)*. Geneva: IPCC.
- IRENA. (2012). *RENEWABLE ENERGY TECHNOLOGIES: COST ANALYSIS SERIES - Wind Power*. IRENA.
- IRENA. (2012). *RENEWABLE ENERGY TECHNOLOGIES: COST ANALYSIS SERIES, Solar Photovoltaics (Vol. 1)*. Bonn: International Renewable Energy Agency - IRENA.
- Japan International Cooperation Agency -JICA. (2009). *The Feasibility Study on Toamasina Port Development in Republic of Madagascar*. Japan International Cooperation Agency -JICA.
- JIRAMA. (2013). *Statistique Production Electricité 2013*. Antananarivo: JIRAMA.
- Knight, C. (2009). *Enrich the office and engage your staff: why lean is mean*.
- Komor, P., & Glassmire, J. (2012). *Electricity Storage and Renewable for Island Power*. IRENA.
- Koussa, S. D., Koussa, M., Haddadi, M., & Belhamel, M. (2011). *Hybrid Options Analysis for Power Systems for Rural Electrification in Algeria*. Elsevier.
- Krohn, S., Morthorst, P.-E., & Awerbuch, S. (2009). *The Economics of wind Energy*. EWEA.
- Lago, C., Prades, A., Lechon, Y., Oltra, C., Pullen, A., & Auer, H. (2009). Environmental Issues. Dans EWEA, *Wind Energy* (pp. 309 - 411). EWEA.
- Lambert, T., Gilman, P., & Lilienthal, P. (2006). Micropower system modeling with homer. Dans F. A. Farret, & M. G. Simoes, *Integration of Alternative Sources of Energy*.
- Lantz, E., Wiser, R., & Hand, M. (2012). *The past and Future Cost of Wind Energy*. IEA.
- Lean Enterprise Research Center. (2000). *Going Lean*. Crdiff: Lean Enterprise Research Center.
- Liqun, L., & Chunxia, L. (2013). *Feasibility Analysis of hybrid wind-PV-battery power system in Dongwangsha, Shanghai*. Przegląd Elektrotechniczny.

- Lisell, L., & Mosey, G. (2010). *Feasibility Study of Economics and Performance of Solar Photovoltaics at the Former St. Marks Refinery in St. Marks, Florida*. NREL.
- Loyd, N., Jennings, L. J., Siniard, J., Spayd, M. L., Holden, A., & Rittenhouse, G. (2009). *The Application of Lean Enterprise to improve Seaport Operations*. Huntsville: The University of Alabama.
- Ma, T., Yang, H., & Lu, L. (2014). A feasibility study of a stand-alone hybrid solar-wind-battery system for a remote island. *Elsevier*.
- Montana State University. (2009). *Lean Office Overview*. Montana: Kalispell Chamber of Commerce.
- Mueller, P. (2014). *UK Energy Security Myth and Reality*. The Global Warming Policy Foundation - GWPF.
- Mukasa, A. D., Mutambatsere, E., Arvanitis, Y., & Triki, T. (2013). *Development of Wind Energy in Africa*. African Development Bank Group.
- Notton, G., Diaf, S., & Stoyanov, L. (2011). *Hybrid Photovoltaic/Wind Energy System for Remote Locations*. Elsevier.
- NOVACES. (2014). How Lean sigma improves Port & Ship Operations. New Orleans, Los Angeles, USA. Récupéré sur www.novaces.com/port-shipping.php
- NREL. (2013). *Distributed Generation Renewable energy Estimate of Costs*. NREL.
- Pawel, I. (2013). *The cost of storage - how to calculate the levelized cost of stored energy (LCOE) and applications to renewable energy generation*. Elsevier.
- Philibert, C., & Holttinen, H. (2013). *Technology Roadmap: Wind energy*. IEA.
- Poullikis, A. (2013). *A comparative overview of large-scale systems for electricity storage*. Elsevier.
- Pozo, J. G. (2011). *Electric Energy storage in the stockholm Royal Seaport*. Stockholm.
- Puglia, G. (2013). *Life cycle cost analysis on wind turbines*. Gothenburg.
- Red Mountain Insights, LLC. (2012). *Utility Energy Storage: Profiles Batteries, Compressed Air Storage, Flywheels, Hydrogen, Superconducting Magnetic Energy Storage, Thermal Energy Storage, Ultracapacitors, and Vehicle-to-grid*. Red Mountain Insights.
- REN21. (2014). *Renewables 2014 Global Status Report*. Paris: REN21.

- Salam, M. A., Aziz, A., Alwaeli, A. H., & Kazem, H. A. (2013). *Optimal sizing of photovoltaic systems using HOMER for Sohar, Oman*. International Journal of Renewable Energy Research.
- Schlogl, R. (2013). *Chemical Energy Storage*. EBSCO.
- Schmiegel, A. U., & Kleine, A. (2014). *Optimized Operation Strategies for PV Storage Systems Yield Limitations, optimized battery configuration and the benefit of a perfect forecast*. ScienceDirect.
- Shafiee, M., & Dinmohammadi, F. (2013). *An FMEA-Based Risk Assessment Approach for Wind Turbine Systems: A Comparative Study of Onshore and Offshore*. Energies.
- Snyder, B., & Kaiser, M. J. (2008). *Ecological and economic cost-benefit analysis of offshore wind energy*. Elsevier.
- SunShot. (2012). *SunShot Vision Study*. SunShot, U.S. Department of Energy.
- Tegen, S., Lantz, E., Hand, M., Maples, B., Smith, A., & Schwabe, P. (2013). *2011 Cost of Wind Energy Review*. Colorado: National Renewable energy Laboratory.
- Vandeligt, K. (2012). *Assessment of the Environmental Performance of Solar Photovoltaic Technologies*. Environment Canada.
- Wilkes, J., & Moccia, J. (2012). *Wind in power: 2012 European statistics*. EWEA.
- Wind & Sun Ltd. (2014). Hoppecke OPzS Sereis. UK. Récupéré sur www.windandsun.co.uk/products/Batteries/Hoppecke-#6078
- Wiser, R., & Bolinger, M. (2012). *2011 Wind Technologies Market Report*. U.S. Department of Energy.
- Wiser, R., & Bolinger, M. (2013). *2012 Wind Technologies Market Report*. US Department of Energy.
- Yaqub, M., Sarkni, S. P., & Mazzuchi, T. (2012). *Feasibility Analysis of Solar Photovoltaic Commercial Power Generation in California*. Engineering Management Journal.