

Technical University of Denmark



## Isolated systems with wind power. Main report

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# **Isolated Systems with Wind Power**

## **Main Report**

**Per Lundsager, Henrik Bindner, Niels-Erik Clausen, Sten Frandsen, Lars Henrik Hansen and Jens Carsten Hansen**

**Abstract** It is generally expected that wind power could contribute significantly to the electricity supply in power systems of small and medium sized isolated communities, but the market for such applications of wind power has not yet materialised in any substantial scale. Wind power in isolated power systems have the main market potentials in developing countries, but the money available world-wide for this technological development is limited and the necessary R&D and pilot programmes have difficult conditions. Consequently, technology developed exclusively for developing countries rarely becomes attractive for consumers, investors and funding agencies.

The overall objective of this research project is to study the development of methods and guidelines rather than "universal solutions" for the use of wind energy in isolated communities. Presently, studies of isolated systems with wind power have mostly been case-oriented and thus it has been difficult to extend results from one project to another, not least due to the strong individuality that has so far characterised such systems and their implementation.

Therefore, the main objective of the present project is to develop and present a more unified and generally applicable approach for assessing the technical and economical feasibility of isolated power supply systems with wind energy. As a part of the project the following tasks were carried out: Review of literature, field measurements in Egypt, development of an inventory of small isolated systems, overview of end-user demands, analysis of findings and development of proposed guidelines.

The project is reported in one main report and four topical reports, all of them issued as Risø reports. This is the Main Report Risø-R-1256, summing up the activities and findings of the project and outlining an Implementation Strategy for Isolated Systems with Wind Power, applicable for international organisations such as donor agencies and development banks.

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# Preface

*The project has been financed by the Danish Ministry of Energy under the energy research programme (EFP97), jour. no. 1363/0022.*

*Presently, studies of isolated systems with wind power have mostly been case-oriented. Thus it has been difficult to extend results from one project to another, not least due to the strong individuality that has so far characterised such systems and their implementation. Therefore, a main objective of the present project is to develop and present a more unified and generally applicable approach for assessing the technical and economical feasibility of isolated power supply systems with wind energy. As a part of the project the following tasks were carried out: Review of literature, field measurements in Egypt, development of an inventory of small isolated systems, overview of end-user demands, analysis of findings and development of proposed guidelines.*

*The project is reported in one main report and four topical reports, all of them issued as Risø reports:*

## *Isolated Systems with Wind Power*

- *Main Project Report (Risø R-1256)*
- *Implementation Guideline Report (Risø R-1257)*
- *Review of Relevant Studies of Isolated Systems (Risø R-1109)*
- *Results of Measurements from Egypt (Risø R-1240)*
- *Inventory of Isolated Systems in Egypt (Risø, I-1703)*

*This is the Main Report Risø-R-1256, summing up the activities and findings of the project and outlining an Implementation Strategy for Isolated Systems with Wind Power, applicable for international organisations such as donor agencies and development banks.*

# Glossary

BOO	Build - Own - Operate
BOOT	Build - Own – Operate - Transfer
CENELEC	Comité Européen de Normalisation Electrotechnique
COE	Cost of energy
DGS	Diesel Generator Set
DRE	Decentralised Renewable Electrification
EDF	Electricité de France
EMS	Energy Management System
ESMAP	WB Energy Sector Management Assistance Programme
ETDE	Energy Technology Data Exchange
EWDS	European Wind Diesel Software Package
GEF	Global Environmental Facility
GUI	Graphical User Interface
IGBT	Isolated Gate Bi-polar Transistor
IEA	International Energy Agency
IEC	International Electro-technical Commission
IHRE	Integrated Hybrid Renewable Energy
IRES	Integrated Renewable Energy System
IRR	Internal Rate of Return
LAC	Levelised annual costs
LPC	Levelised production cost
LOLE	Loss of load expectancy
LOLF	Loss of load fraction
LOLP	Loss of load probability
LTMC	Long term marginal cost
NPV	Net present value
NREA	New and Renewable Energy Authority (Egypt)
NREL	National Renewable Energy Laboratory (USA)
PAS	Publicly Available Specification
PCF	Prototype Carbon Fund
PV	Photovoltaics
O&M	Operation and Maintenance
QPW	Quattro Pro for Windows
PPA	Power Purchase Agreement
RAPS	Remote Area Power–supply System
RE	Renewable Energy
ROE	Return on Equity
SHS	Solar home system(s)
SQI	Service Quality Index
STMC	Short term marginal cost
UNDP	United Nations Development Programme
VOE	Value of Energy
WB	World Bank
WD	Wind-diesel
WECS	Wind Energy Conversion System
WMO	World Meteorological Organisation
WTG	Wind Turbine Generator

# 1 Introduction and Overview

This report presents an overview of the results of a study relating to integration of wind energy in isolated power supply systems, Isolated Systems with Wind Power, supported by the Energy Research Programme of the Danish Ministry of Energy, file no 1363/97-0007, EFP97.

The study was carried out in collaboration between Risø National Laboratory, Denmark, and National Renewable Energy Authority NREA, Egypt, with the main purpose of developing and presenting a unified and generally applicable approach for assessing the technical and economical feasibility of isolated power supply systems with wind energy

The study intends to base the proposed methodology on the methods and techniques already established by Risø in collaboration and/or interaction with other Danish consultants in the course of a number of Danish wind energy projects (grid connected as well as isolated) carried out world wide during the last two decades.

The study is carried out around a number of actions, including:

- Review of literature
- Field measurements in Egypt with an overview of end-user demands
- Development of an inventory of small isolated systems
- Analysis of findings and development of proposed guidelines.

Furthermore an Implementation Strategy for Isolated Systems with Wind Power has been outlined, applicable for international organisations such as donor agencies and development banks.

## 1.1 Background and Purpose

During the last two decades there has been considerable efforts on both national and international levels to implement wind energy in connection with local and regional electric power supply by integrating wind energy into small and medium sized isolated distribution systems world wide. These systems are often, but not necessarily always, powered by diesel power plants, and a fairly recent review made for the Danish International Development Agency DANIDA, ref. 1, identified about 100 reported and documented wind-diesel installations world wide.

In addition to these and other actually implemented systems a great deal of preparatory and investigative studies have been made in the framework of national and international R&D institutions and programmes, development agencies and financing bodies. Thus, even though internationally approved methods for layout, design and evaluation of such systems have so far not been established, a considerable body of experience exists based on the tools and approaches developed for and applied in each specific case.



Much of this work has been reported in the open literature, but studies of isolated systems with wind power have mostly been case-oriented. Thus it has been difficult to extend results from one project to another, not least due to the strong individuality that has so far characterised such systems and their implementation.

Therefore, a main objective of the present project has been to develop and present a more unified and generally applicable approach for assessing the technical and economical feasibility of isolated power supply systems with wind energy.

## **1.2 Outline of Risø's Methodology**

The study intends to base the proposed methodology on the methods and techniques already established by Risø in collaboration and/or interaction with other Danish consultants in the course of a number of Danish wind energy projects (grid connected as well as isolated) carried out world wide during the last two decades.

This experience may at the present stage be summarised in a philosophy combining the following three components:

- Site evaluation based on resource assessment modelling
- Technical assessments based logistic modelling techniques
- Economic evaluations based on life cycle costing principles.

The WAsP model for site resource assessment as described in ref. 2. has become the world standard for wind site assessment based on flow modelling for given terrain specifications. The WAsP model and the associated methodology has been verified extensively during two decades.

The WINSYS model for system performance as described in ref. 3. represents the philosophy in a form where the development of both technical and economical performance throughout the project life time is accounted for. The WINSYS model and the associated methodology has been verified for the type of cases it is designed for.

## **1.3 Outline of the Report**

The project is reported in one main report and four topical reports, all of them issued as Risø reports. This is the Main Report Risø-R-1256, summing up the activities and findings of the project.

Chapter 2 presents a survey of the activities of the study. Chapters 3 to 7 present the outcome of the study with respect to the following key issues:

- Status for Isolated Systems with Wind Energy
- Guidelines for the Implementation of Isolated Systems with Wind Power
- Results from Measurements in Egypt
- An Inventory of Isolated Systems in Egypt
- An Implementation Strategy for Isolated Systems with Wind Power

Details of these topics are given in the associated topic reports.

## 2 Survey of Main Activities

During the project, the main activities have been carried out according to the project plan. The project has collaborated with the New and Renewable Energy Authority (NREA) of Egypt on measurements and analysis of isolated systems. An overview of activities is given in this Chapter, more details are given in the following chapters and in the associated topical reports.

### 2.1 Review of Relevant Studies of Isolated Systems

A review of studies relating to integration of wind energy in isolated power supply systems was carried out, based on a systematic literature search in the ETDE Energy Database with a main search covering the period 7/88 to 6/97 and supplemented by partial update periods. A few newer references have been included in the review, most notably the IEC/PAS 62111 specification

The purpose of the review was to identify areas where the already established philosophy needs to be changed or supplemented. By screening the literature the intention was to get an overview of the previous experience to be utilised in the methodology to be established by the study. A number of key issues were selected as focal points for the review:

1. Methodologies
2. Guidelines
3. Economic principles
4. Concepts of application
5. Systems solutions
6. Case studies
7. Programmes
8. Models
9. Software tools

In addition to the references found by the structured searching principles a number of additional literature references were included, and in the end a few hundred references were selected for review. The bibliography contains 67 entries that were read and evaluated

The review was mainly concerned with isolated or remote electricity supply systems with wind power. The size of the installed power in the considered energy producing system is within the range of 10 kW to 500 kW, which covers both small and large remote systems. More details on the review is given in Section 3 of this report and in the review report Risø-R-1109.

### 2.2 Implementation Guidelines for Isolated Systems with Wind Power

The overall objective of the guideline report is to assist the dissemination of the use of wind energy in isolated communities by contributing to the development of operational engineering design- and assessment methods for isolated electricity supply systems with a large contribution of wind energy by

presenting an outline of a functional set of guidelines based on practical experience. The main issues dealt with in the guideline report are:

1. State of the Art, Technology and Economics
2. Fact Finding – Information Required for a WD Project
3. Project Feasibility Analysis
4. Environmental Impact Analysis
5. Institutional and Legal Framework
6. Project Financing
7. Project Implementation

The guideline report concludes in a summary with an overview of the main issues identified for achieving successful wind power projects in an isolated power systems, Risø-R-1257.

### **2.3 Measurements on Isolated Systems in Egypt**

The part of the project described in this Chapter covers measurements carried out in Egypt on various types of power systems. The main objectives of the measurements were to obtain information on the actual power quality of real power systems of different types and sizes and to establish load profiles to be used in future design of power systems with wind power. Details of this part of the project are given in the Report Risø-R-1240.

The collected data has been analysed for each of the systems and have been compared in order to generalise the results (as far as possible). The load profiles have also been used to assess the influence of load patterns on the predicted performance of power systems with a large amount of wind power capacity.

The objectives for executing the measurements were to establish a foundation for the description of the loads of an isolated system in order to be able to design an isolated power system with wind power in terms of sizing of components (diesel generators and wind turbines) and determination of operating strategy, and to predict the performance in terms of e.g. fuel consumption and utilisation of wind power.

Another objective has been to measure the actual power quality of such systems in order to be able to have a documented base case for the performance requirements when installing wind power in isolated systems.

The approach has been to measure different types of loads and to measure on different types of power systems. The load has been divided in several categories on the thought that it should then be possible based on these types of loads to aggregate the total load of a system based on the demographic data like number of inhabitants, number of shops etc.

The impact of the size of the power system is also very important to establish. This includes knowledge of the steps in load and of actual power quality (frequency and voltage quality).

The sites has been selected in order to meet the above mentioned objectives. This has resulted in the selection of three sites in Hurghada for the illustration of different types of load and selection of two sites in Sinai to investigate the behaviour in small and medium sized power systems.

The five locations were:

- Particular Load in Large System 1: Hotel
- Particular Load in Large System 2: Shopping Mall
- Particular Load in Large System 3: Residential Area
- Small System: Wadi Tal, Sinai
- Medium System: Ras Sudr, Sinai

For each location the measurement period was 1-2 months. Data were sampled at 0.1Hz. The signals measured included active and reactive power, voltage and current, and harmonic distortion.

For each of the five measurement sites data showing the power quality and characterising the load is presented. The main focus is on the voltage quality and on the active power demand, but also the frequency and the reactive load is analysed. The analysis has been performed with the objective of characterising the load type in order to be able to use it in the analysis of future systems. The original data is sampled with 10 sec intervals. The samples are then averaged using a 10 min averaging period.

A comparison between the different sites has been done in order to highlight similarities and differences. The comparison is done for both load and power quality key characteristics, and details of the analysis are given in Section 5 of this report and in Risø-R-1240.

## **2.4 Inventory of Isolated Systems in Egypt**

It is generally perceived that there is a large potential world wide for energy supply to remote and isolated villages with local power supply systems characterised by large wind resources and high energy production costs.

In order for this potential market to develop, a simple approach should preferably be found, which can be applied at low cost and at a risk comparable to the risk involved when deciding and designing a diesel powered system.

In view of this need and the fact that economics of scale apply, it was decided to try to acquire a general overview of the potential types of systems in which wind power could be an option. It was furthermore decided to use Egypt as an example, and therefore this part of the work was done in collaboration with New and Renewable Energy Authority (NREA) of Egypt.

The intention was that this overview will be applicable in a simplified but reliable approach to define consumer needs and system specifications. The typical size of small system electrification projects cannot justify very detailed and therefore costly analyses, unless they are bundled in a programmatic approach.

More details are given in Section 6 of this report and in the Report Risø-I-1703, which presents an overview of the inventory of isolated power systems in Egypt. It also outlines the main issues related to an implementation of wind energy in such isolated systems in the framework of an Energy Sector Development Component for Egypt.

## 2.5 Exchange of Scientists, Publications

In 1998 and 1999 several visits to Egypt were made by scientists from Risø with the purpose to identify sites for measurements, install measurement equipment and initiate measurements. Furthermore, during the visits the tables for the inventory of isolated systems were devised, and the analysis of data was initiated.

In 1999 a visit to Risø was made by scientists from NREA to undertake data analysis of the measurement results together with Risø scientists.

## 2.6 Workshop in Denmark

In January 2001 representatives from NREA visited Risø to finalise the joint work and to discuss possible follow up and application of the findings of the project. Representatives from Risø participated in a meeting at Danida, where the NREA representatives discussed the possible application of wind energy in isolated power systems in Egypt, based on the measurements and the inventory of isolated power systems in Egypt.

Subsequently an outline was made of the main issues related to an implementation of wind energy in such isolated systems in the framework of an Energy Sector Development Component for Egypt. The outline is summarised in Section 6 of this report and included in the Inventory Report Risø-I-1703.

## 2.7 Publications

In the course of the project two papers, refs. 4 and 5, were made and presented at international conferences:

***Keys to success for wind power in isolated power systems***

Jens Carsten Hansen, Per Lundsager, Henrik Bindner, Lars Hansen, Sten Frandsen. Wind Energy and Atmospheric Physics Department. Risø National Laboratory. European Wind Energy Conference EWEC'99, Nice, France, March 1999

***Wind power and small islands: ideas, theories and practical realities***

Jens Carsten Hansen, Wind Energy and Atmospheric Physics Department, Risø National Laboratory. International Conference on Renewable Energy Islands, Bermuda, September 1999.

The papers are included in Appendix 1 and 2, respectively, of this report.

## 2.8 Drafting of an Implementation Strategy for Isolated Systems with Wind Power

The “Danish approach” to the implementation of wind energy in the Danish energy policy during the last two decades has been very successful, and based on this approach an outline of a strategy and an associated action plan was

drafted for the implementation of wind power in wind diesel systems and other isolated systems for electricity supply

The outline is based on a previous study made for Danida, ref. 1, but it is equally relevant and applicable for other development agencies, development banks and private investors / developers for the implementation on a global level of wind energy in isolated systems for electricity supply, with special emphasis on implementation in 2<sup>nd</sup> and 3<sup>rd</sup> world countries.

### **The Technology**

Internationally the technology is presently characterised by wind diesel systems using wind turbines that are small compared to the current industry standard of MW size machines. The best experiences are obtained from systems using the very simple concepts, but the institutional framework for a given project clearly plays an important role as well.

Even so there is a tendency towards application of more complex configurations including energy storage and power electronics, which at the present state of development may make it more difficult to establish a positive track record for the technology. However, there is an ongoing development in power electronics and the ability of developing countries to handle power electronics, and there is an increased attention to the use of surplus energy for applications such as water processing, heating and cooling, and freezing / ice production.

Cost of Energy (COE) from the simple systems is less in real life than COE from the more complex systems, and depending on the specific local conditions isolated systems with wind energy may be competitive compared to the alternative, pure diesel power production.

### **The Products**

The Danish and International wind power industry, in particular the large companies, is capable of participating as qualified partners in large scale projects in contexts where the standard products of the industry are applicable.

In the context of developing countries this means simple configurations, where standard wind turbines are connected directly to (existing or new) diesel grids. For small grids the power penetration can be of the order 50 to 100% using simple control strategies, possibly in combination with alternative application of excess energy. For larger, island type diesel grids, the power penetration can be of the order 25 to 35%.

Such systems, in sizes from a few hundred kW up to a few MW, can today be implemented also in large scale both as retrofit to existing grids and as part of electrification projects.

### **The Industry**

Today a number of solid and experienced companies exist in Denmark and internationally as potential suppliers in the market for wind diesel and other isolated systems with wind energy. They act alone or together with suppliers of equipment including controllers and products such as water processing plants that can increase the efficiency of the systems and provide more than just electricity to the consumers.

Most of the wind turbine manufacturers have one way or the other been involved in wind energy for isolated systems, and generally the experience have been better the simpler the system. They do not consider the technology to be the problem, the organisational problems and other "soft" issues such as training and capacity building are seen to be the most critical issues.

The large wind turbine manufacturers have the strength and experience to operate in developing countries, and in a healthy market they would be the main Contractors, but they are unlikely to bid on projects on isolated systems with wind energy in developing countries unless they can see sufficient volume and continuity in the market.

These companies today have annual turnovers of the order of several hundred millions of Dollars. They operate in a market of hundreds of MW for their standard products, which is where they earn their money, and therefore it takes many MW of wind turbine capacity every year to make a significant volume for these companies. This indicates the size of the market it takes to involve the large manufacturers with their own strategy and product development, which is a necessary precondition for success.

### **Strategy and Action Plan**

Persistence is seen by the manufacturers as the key word for a long term market strategy. The application of reliable technology is also considered an essential part of a successful strategy, and even if this technology is not clearly defined the manufacturers consider themselves able to provide such technology.

An action plan for isolated systems with wind power should in the short run promote the application of wind energy in decentralised power supply in developing countries in a dedicated and suitable way by using the standard electricity producing wind turbines that constitute the industry's standard product. In the long run it should ensure a substantial contribution from wind energy in decentralised power supply in developing countries in combination with other renewable energy technologies.

The plan of action should build on the "Danish strategy" for implementation of wind power, adapted to the implementation of isolated systems with wind power in developing countries. This would require a framework that includes at least the following components:

- A market that includes mechanisms and subsidies that makes good projects financially attractive and avoids less promising projects.
- Tying of subsidies to project quality requirements for e.g. the wind energy system and for the project review system including Environmental Impact Assessment as well as the application of (adapted) international standards. The subsidy system should also be tied to continued cost reductions
- Connection of projects to international resource base and know-how development e.g. by requirements to involve international consultants in project design, review and assessment.
- Regular implementation in a bundling and programmatic approach of demonstration projects in a sufficient scale, where projects are prepared together with international teams of consultants and sustainability is ensured by updating of technology and capacity building.

This development would be supported and promoted by establishing a 'market' of a size in terms of money and time, which makes it attractive for the Danish

and International Renewable Energy resource base to apply strategic thinking with respect to investments in product and market development.

## **3 Review of Isolated Systems with Wind Power**

### **3.1 Overview**

A review of studies relating to integration of wind energy in isolated power supply systems was carried out, based on a systematic literature search in the ETDE Energy Database with a main search covering the period 7/88 to 6/97 and supplemented by partial update periods. A few newer references have been included in the review, most notably the IEC/PAS 62111 specification.

The review was done as part of the project by searching library data bases using search profiles with suitable key words and key word combinations, and the resulting references are grouped according to their relevance for a number of main issues in the methodology. More details on the review is given in the topical report Risø-R-1109.

The principles applied in the review were developed in an iterative process where search profiles and main topics were gradually refined to give an operational basis for the review. The report includes statistics for a number of searches with various search profiles.

A number of key issues were selected as focal points for the review:

1. Methodologies
2. Guidelines
3. Economic principles
4. Concepts of application
5. Systems solutions
6. Case studies
7. Programmes
8. Models
9. Software tools

For each key issue the statistics of the search for that particular issue was compiled, and a limited number of key references are listed and reviewed briefly.

Potentially a very large number of references indeed would result from a search unless the search profiles are carefully designed in order to restrict the outcome to operational levels.

Using “wind” as keyword in a search resulted in 20,978 hits (for the period 7/88 to 6/97). Using “renewable” as keyword in a search resulted in 29,015 hits (for the period 7/88 to 6/97). Therefore the search profiles were refined in order to get a manageable amount of hits.



In addition to the references found by the structured searching principles described in the previous sections, a number of additional literature references were included, and in the end a few hundred references were selected for review. The bibliography contains 67 entries that were read and evaluated

## 3.2 Summary

The purpose of this review is to identify areas where the already established philosophy needs to be changed or supplemented. By screening the literature the intention is to get an overview of the previous experience to be utilised in the methodology to be established by the present study.

With emphasis on experience, the review – of Danish as well as international studies – is made concerning integration of hybrid power sources in isolated or remote systems. Special importance is attached to descriptions of regional conditions with respect to economy, methodology, power quality and sustainability.

The Energy Technology Data Exchange (ETDE) Energy Database is selected to serve as the main Literature source, due to its comprehensive coverage of energy research and technology (more than 3.5 million bibliographic citations). Refer to <http://www.etde.org/> for further information.

### Preconditions for the Review

This review is mainly concerned with isolated or remote electricity supply systems with wind power. The size of the installed power in the considered energy producing system is expected within the range of 10 kW to 500 kW, which covers both small and large remote systems.

Characterisation and demands to small versus large remote systems are expected to be quite different a fact which of course influences the studies, which are considered relevant for this review of isolated or remote electricity supply system.

At the same time the review is not limited to consider systems with wind power as add-on, i.e. the review is also concerned with studies of new planned systems for sites with no power supply at all or studies of other hybrid system solutions, such as solar cells, biogas etc.

### Searching Principles and Results

Using “wind” as keyword in a search resulted in 20,978 hits for the period 7/88 to 6/97. Thus, the search had to be refined in order to get a manageable amount of hits, and therefore the searching was divided in two search directions related to “wind” and to “renewable”, respectively.

The keyword combination *wind and (energy or power) and (system or systems)* formed a suitable base for a wind related search when combined with other keyword groups as shown in table 1 on the next page.

Using these groups, the search result for the “wind” related search can be presented as in Table 1, where the search results are listed for three periods. The first period is the present available time period in the ETDE Energy Database, while the second and third period are partial update periods.

Concatenating groups 1, 5, 6 and 8 of Table 1 resulted in 242 hits, and from these 242 literature references 19 were selected based on their relevance for the review.

Using “renewable” as keyword in a search resulted in 29,015 hits for the period 7/88 to 6/97. Combining key word groups into a search profile consisting of *renewable and (rural or remote)* in a process similar to that described above resulted in 148 hits, and from these literature references 25 were found relevant for the review.

*Table 1. Keyword (wind) and (energy or power) and (system or systems).*

Group combinations		Number of hits		
Group	Period	7/88 - 6/97	1/95 - 9/96	10/96 - 6/97
--	base	6810	1511	701
1	autonomous, isolated or rural	488	99	53
2	battery, hydraulic, hydro or storage	1547	289	205
3	diesel, hybrid or renewable	2943	692	403
4	domestic	1540	309	216
5	economic or economy	101	12	14
6	guidelines or methodology	219	54	29
7	model, modelling or simulation	1789	420	204
8	review and study	1910	404	179
9	software	170	43	27

Interestingly enough the two selected groups of references had only one reference in common.

In addition to the references found by the structured searching principles described above a number of additional literature references were included.

### 3.3 Software Tools

The technical and economical performance of prospective systems is analysed by computer simulation of the systems, and several types of models are used depending on the characteristics on which the simulation is focused. The main parameter characterising the models is the time scale of the simulation, and we usually distinguish between the following types:

- Screening models give an overall assessment of the performance of the system, without going into very much detail of the specifics in the operation of the system.
- Logistic models focus on predicting the annual power productions, fuel savings and power flows in the system. Logistic models are usually the basis in screening models, and they may be deterministic time series models or probabilistic models that produce probability distributions.
- Dispatch models focus on the dispatch of the various power producing components of the system, i.e. start/stop of diesels etc. Time scale typically minutes to an hour.

- Dynamic models focus on the electromechanical behaviour of the system, i.e. machine dynamics but not electrical switching may be represented. Time scale typical a few seconds to half an hour.
- Transient models focus on electrical transients including switching. Time scale typically seconds to minutes.

System control models focus on a representation of control strategies of the system, or parts of the system. Dispatch type models are usually the basis for system control models.

A number of numerical modelling techniques and models are available for the assessment of technical-economic performance the system. Risø R-1109 presents a review of models, and selected models from the review are briefly described below:

*Table 2: Overview of models for analysis of isolated systems*

<b>Model</b>	<b>Description</b>
HOMER	A fast & comprehensive village power systems screening model, in 1998 supplemented with the VIPOR model for optimal layout of a supply area into grid connected vs. independently supplied consumers. State of the art in this category, publicly available.
INSEL	Offers almost unlimited flexibility in specifying system configurations by allowing the user to specify the connectivity on a component level. Intended as an out-of-house-model.
HYBRID2	The state-of-the-art (1998) time series model for prediction of technical-economical performance of hybrid wind/PV systems. Offers a very high flexibility in specifying the connectivity of systems. Publicly available and quite widely used.
SIMENERG	The only model so far with a very high degree of flexibility in the control / dispatch strategy, using a “market square” approach, where the economically optimal subset of power sources that satisfy the power demand is dispatched in each time step.
WINSYS	A spreadsheet (QPW, MS Excel) based model implementing probabilistic representations of resources and demands. WINSYS incorporates the anticipated technical expansions during its lifetime in the technical performance measures, combined with a traditional economic life cycle cost assessment. Thus WINSYS represents a more real life cycle cost analysis than most other models. It is not commercially available.
WDLTools	ENGINEERING DESIGN TOOLS FOR WIND DIESEL SYSTEMS, This package contains seven European logistic models: SOMES (NL), VINDEC (N), WDIALOG (DK), RALMOD (UK) and TKKMOD (FIN). It also includes the modular electromechanical model JODYMOD.
PROLOAD	A probabilistic load flow analysis code, using Monte Carlo techniques, developed in co-operation with an electrical utility for dimensioning of distribution systems with wind turbines.
RETScreen	is a spreadsheet (Microsoft Excel) based analysis and evaluation tool for assessment of the cost-effectiveness of potential projects with renewable energy technologies. The software package consists of a series of worksheets with a standardised layout as well as an online manual and a weather and cost database. The tool is developed by the CANMET Energy Diversification Research Laboratory (CEDRL) and is available from the Website of CEDRL.

It appears that practically any theoretical modelling for isolated power system projects can be handled by available numerical models. Availability of models is not a limiting factor for development, but efforts involved in applying a complete set of modelling tools for a given isolated community situation may be considerable.

### **3.4 Conclusions and Recommendations**

The amount of wind energy literature related to the subject is excessively large, and a complete review in which every relevant abstract is identified and examined is not feasible within the framework of this (or probably any other) study.

By applying more detailed search criteria the amount of literature was reduced to a few subsets that were operational in extension and believed to be representative. Thus the literature review is based on systematic spot checks of the entire literature supplemented with random searches in “known” literature.

A great deal of work has been published conveying useful experiences within each of the topics to be covered by the methodology of the present study. This includes methods and tools for a number of specific issues, but no significant reference presents methods or tools that contradict the philosophy of Risø’s methodology such as is implemented in the WINSYS model, ref. 3.

It is therefore concluded that since Risø’s methodology is in agreement with all significant references, it makes a good platform for further development.

#### **Methodology & Guidelines**

The most significant development in this respect is the appearance of the IEC/PAS 62111, ref. 6. Specifications for the use of RE in rural decentralised electrification, and the decision that such guidelines in the future should be structured as follows:

- Part A: Project specific guidelines or specifications for project implementation for e.g. rural electrification, large wind diesel grids or other specific applications, to be issued by main actors in the respective fields.
- Part B: Technology specific standards for Photovoltaics, Wind energy and other technologies, to be issued within the IEC standards framework. Only one part B will be issued, to be referenced by all Parts A.

It is concluded that with the exception of the IEC/PAS 62111 no work with the scope of the present study has been carried out before for the design and evaluation of isolated electric power systems with high wind energy penetration, i.e. no comprehensive and consistent methodology, operational on an engineering level, exists for those systems.

It is therefore recommended, that for the type of isolated systems relevant for Denmark’s/Risø’s field of experience, i.e. medium to large scale isolated electric power systems with high wind energy penetration, more specific guidelines should be developed in the form of checklists for relevant issues.

For each item on the checklist engineering operational methods & tools should be indicated, and the guidelines should be issued as a Part A guidelines as described above.

### **Economic principles**

It is concluded that the development of guidelines should continue with the economic principles already applied, i.e. levelised production costs based on life cycle cost analyses.

It is recommended that externalities should be quantified by methods like the Environmental Manual, ref. 7, and that other benefits like optional or deferrable loads, uninterrupted power supply etc. should be included as well. Furthermore the diversification of economic risks should be introduced.

### **Models and software**

It is concluded that the WINSYS model ref. 3 and similar models will be the workhorse in the technical-economical analyses of isolated systems with high wind energy penetration.

It is recommended that in addition to WINSYS extensions and similar models the needs for versatile screening models (spreadsheet based) and for system optimisation models should be considered as well as the need for genuine time history models. Furthermore, the models should be prepared for extension to (multiple) RE integration.

## **4 Guidelines for the Implementation of Isolated Systems with Wind Power**

### **4.1 Introduction and Background**

The project is based on the assumptions that isolated systems with a high degree of wind energy penetration constitute technically reliable options and can be made cost-competitive in the near future. In addition, it is assumed that such systems have their major potential markets both as distributed generation in large utility grids in the developed world and as local power supply in 1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> world countries.

In both applications such systems are subgroups of systems that are often referred to as Decentralised Renewable Electrification (DRE) systems. In the basic form, where wind turbines are connected to local diesel power stations, the systems are referred to as Wind Diesel (WD) systems. In the more general form, where several renewable energy sources and support technologies may be included, the systems are frequently referred to as Integrated Hybrid Renewable Energy (IHRE) Systems

The background for the project is the perception that there is a large potential world wide for energy supply to remote and isolated villages with local power supply systems characterised by large wind resources and high energy production costs.

This Chapter is a summary of the report on functional guidelines for isolated systems with a high proportion of wind energy, Risø-R-1257

## 4.2 Objectives and Overview

The overall objective of the guideline report is to assist the dissemination of the use of wind energy in isolated communities by contributing to the development of operational engineering design- and assessment methods for isolated electricity supply systems with a large contribution of wind energy by presenting an outline of a functional set of guidelines based on practical experience.

The main issues dealt with in the guideline report are:

1. State of the Art, Technology and Economics
2. Fact Finding – Information Required for a WD Project
3. Project Feasibility Analysis
4. Environmental Impact Analysis
5. Institutional and Legal Framework
6. Project Financing
7. Project Implementation

The guideline report concludes in a summary with an overview of the main issues identified for achieving successful wind power projects in an isolated power systems.

## 4.3 The Technology

The main purpose of the first part of this section is to uncover “state of the art” from a technical point of view. The second part sets up a framework on how to characterise power systems with wind energy.

Wind turbines can be divided into five groups with respect to the range of the nominal power as listed in Table 3. The power limits presented below are approximate and should be seen as a guideline only.

*Table 3. Categorisation of wind turbines.*

<b>Nominal power</b>	<b>Typical application</b>
< 1kW	Micro's
1-10kW	Wind home
10-200kW	Hybrid/Isolated systems
200-1MW	Grid connected – single or in cluster
> 1MW	Offshore (or onshore) wind farms

The present state of the art on wind turbines has been analysed in ref. 8. The main results are listed in Table 4, outlining the applied concept of the two largest turbines from each manufacturer of the top-8 suppliers world wide.

*Table 4. Applied concept of the two largest (i.e. newest) wind turbines from each manufacture of the top 10 suppliers world wide. Source ref. 8.*

<b>Manufacturer (top 8 supp.)</b>	<b>Wind turbine</b>	<b>Configuration</b>	<b>Power control features</b>	<b>Comments</b>
NEG Micon (Denmark)	NM 2000/72	a	Active stall	Two speed
	NM 1500C/64	a	Stall	Two speed
Vestas (Denmark)	V80 – 2 MW	c	Pitch and variable speed	Range: 905 rpm. to 1915 rpm.
	V66 – 1.65 MW	b	Pitch and OptiSlip	Range: 1500 rpm. to 1650 rpm.
Gamesa (Spain)	G52 – 850 kW	c	Pitch and variable speed	Range: 900 rpm. to 1650 rpm.
	G47 – 660 kW	c	Pitch and variable speed	Range: 1200 rpm. to 1626 rpm.
Enercon (Germany)	E-66 – 1.8 MW	d	Pitch and variable speed	Gearless. Range: 10 to 22 rpm.
	E-58 – 1 MW	d	Pitch and variable speed	Gearless. Range: 10 to 24 rpm.
Enron Wind (USA)	1.5s – 1.5 MW	c	Pitch and variable speed	Range: 989 rpm. to 1798 rpm.
	900s – 900 kW	c	Pitch and variable speed	Range: 1000 rpm. to 2000 rpm.
Bonus (Denmark)	2 MW	a	Active stall	Two speed
	1.3 MW	a	Active stall	Two speed
Nordex (Germany)	N80/2500 kW	c	Pitch and variable speed	Range: 700 rpm. to 1303 rpm.
	N60/1300 kW	a	Stall	Two speed
Dewind (Germany)	D4 – 600 kW	c	Pitch and variable speed	Range: 680 rpm. to 1327 rpm.
	D6 – 1.25 MW	c	Pitch and variable speed	Range: 700 rpm. to 1350 rpm.

The letter concerning the configuration in Table 4 denotes:

- a) a fixed speed wind turbine using an asynchronous generator with cage rotor, a soft starter and a battery bank for reactive power compensation.
- b) a variable speed wind turbine using a doubly fed asynchronous generator implemented in a setup known as OptiSlip (used by Vestas since the mid 1990's).
- c) a variable speed wind turbine using a doubly fed asynchronous generator where the rotor is connected to the grid through a frequency converter.
- d) a gearless variable speed wind turbine using a multipole wound synchronous generator, where the stator is connected to the grid through a frequency converter and the rotor through a rectifier.

Based on the findings in ref. 8, the present “state-of-the-art” large wind turbine is a 3 bladed upstream machine with tubular tower using:

- active stall with a two speed asynchronous generator, or
- pitch control combined with variable speed, mostly using configuration “c” with a rotor connected IGBT based frequency converter.
- only one of the top-10 manufactures is building a gearless (variable speed) wind turbine.

The above characteristics are for a typical main-stream wind turbine. In addition to this design a number of alternative wind turbine designs exist as described in Risø-R-1257.

In Table 5 below an overview of hybrid power systems at research facilities throughout the world are listed,

Table 5. Selected list of hybrid power systems at research facilities, ref. 9.

Lab. / Country Installation year	Die-sel (kW)	WTG (kW)	Dump load	Con-sumer load	Storage (kWh)	Features
NREL / USA 1996	2 x 60	1 x 20 <sup>a</sup> 1 x 75 <sup>a</sup> 1 x 20 <sup>c</sup> 1 x 10 <sup>e</sup> 1 x 50 <sup>f</sup>	–	100kW	16 (24V) 180 (120V)	3 AC buses 3 DC buses PC based control system Advanced data acquisition system
CRES /Greece 1995	1 x 45	1 x 30 <sup>a</sup>	45	20kVA	–	PC based control system
DEWI /Germany 1992	1 x 30	1 x 50 <sup>a</sup> 1 x 30 <sup>b</sup>	?	75kVA 127 x 1kW	?	?
RAL /England 1991	1 x 85	1 x 45 <sup>b</sup>	72kW	48kW	45 (flywheel)	Dedicated microcomputer controller PC data-logging system
EFI /Norway 1989	1 x 50	1 x 55 <sup>a</sup> 1 x 55 <sup>b</sup>	55kW	40kW 20kVA <sub>r</sub>	27	Dedicated microcomputer controller Data acquisition w/ transient recorder
RERL–UMass / USA 1989	1 x 15	1 x 15 <sup>a</sup>	16kW (1994)	16kW (1994)	–	PC based control system 4 operating strategies Advanced data acquisition system (1994) Rotary converter AC-DC-AC
IREQ /Canada 1986	1 x 35	1 x 50 <sup>c</sup>	17kW	50kW	–	–
AWTS /Canada 1985	2 x 50	1 x 40 <sup>b</sup> 1 x 35 <sup>c</sup> 1 x 65 <sup>d</sup> 1 x 80 <sup>e</sup> 1 x 50 <sup>f</sup>	190k W	115	–	–
RISØ /Denmark 1984	1 x 30	1 x 55 <sup>b</sup>	75kW	–	30 (400V) (1997)	PC based control system Sophisticated data acquisition system
(a) wind turbine simulator; (b) fixed speed induction generator; (c) VAWT, fixed speed induction generator; (d) two speed induction generator; (e) variable speed synchronous generator; (f) downwind fixed speed induction generator.						



Table 6 below presents an overview of hybrid power systems installed throughout the world during the last decade.

*Table 6. Selected list of relevant hybrid power systems installed throughout the world in the last decade, ref. 9.*

Site / Country Operation period	Diesel (kW)	WTG (kW)	Dump load	Other loads (kW)	PV (kW)	Storage (kWh)	Wind penetration
Sal / Cape Verde 1994–2001	2 x 500 1 x 800 1 x 620 1 x 400	2 x 300	–	2 x 250 (RO desalination) 1 x 60	–	–	22% (month) 14% (3 years)
Mindelo / Cape Verde 1994–2001	2 x 2300 2 x 3300	3 x 300	–	1 x 250 (RO) 1 x 500 (RO) 2 x 400-750	–	–	17% (month) 14% (3 years)
Dachen Island / China 1989–2001	1 x 280 1 x 256 2 x 100 1 x 560	3 x 55 2 x 20	127	–	–	–	26% (month) 15% (years)
Fuerteventura / Canary Island 1992–2001	2 x 75	225	100	16.5 (RO) 8 (Ice) 70 (Lights)	–	–	?
Foula Island / Shetland Islands 1990–2001	1 x 28 1 x 18 (hydro)	1 x 60	90 25	96 (heating)	–	1400 (hydro)	70% (3 months)
La Desirade / Guadeloupe 1993–2001	1 x 160 3 x 240	12 x 12	–	–	–	–	40% (peak)
Marsabit / Kenya 1988–2001	1 x 100 1 x 200	150	–	–	–	–	46% (3 years)
Cape Clear / 1987–1990	1 x 72	2 x 30	–	–	–	100	70% (peak)
Rathlin Island / Northern Ireland 1992–2001	1 x 48 1 x 80 1 x 132	3 x 33	–	–	–	73	100% (peak) 70% (year)
Kythnos Island / Greece 1995–2001	3 x 125 2 x 250 3 x 633	5 x 33 1 x 150	–	–	100	330	?
Frøya Island / Norway 1992–1996	1 x 50	1 x 55	72	–	–	27	100% (peak) 94% (8 months)
Denham / Australia 1998–	2 x 288 2 x 580	1 x 230	–	–	–	–	70% (peak) 23% (6 months)
Lemnos Island / Greece 1995–	2 x 1200 2 x 2700 1 x 2600	8 x 55 7 x 100	–	–	–	–	?

## 4.4 Categorisation of Power Systems

In the following a categorisation of power systems is suggested. Some design characteristics and performance conditions of e.g. a wind turbine in an isolated system in Egypt and a wind turbine situated in an offshore wind farm in Denmark are similar, while others are quite different. Thus it is useful to introduce a division of the power systems into a number of groups or categories according to the installed power capacity.

We will consider four groups as listed in Table 7 below using the installed power as the main key.

*Table 7. Categorisation of power systems.*

<b>Installed Power</b>	<b>Category</b>
< 1kW	Micro systems
1-100kW	Wind home systems
100 kW -10MW	Island/Isolated systems
> 10MW	Wind Power Plant systems

The installed power presented in Table 7 should be seen as indicative of the order of magnitude. Thus a micro system is typically a small wind turbine with a capacity less than 1kW; a wind home system has a typical a capacity between 1 and 100 kW with a wind turbine of 1-50 kW; an isolated power system is typically from 100 kW to 10 MW installed power and with wind turbines in the range from 100 kW to 1 MW, while a wind power plant or wind farm typically is larger than 10 MW with several wind turbines larger than 500 kW.

The wind penetration level of the power systems presented in Table 6 are plotted in Figure 1 as a function of the installed capacity. The situation in Denmark in 1998 and as planned for the year 2030, respectively, have been used as an indication of the very large power systems. The dashed trend line shows the degree to which the level of wind energy penetration of actual power systems with successful track records decreases as the power system size increases. The dotted line indicates a possible future development towards higher penetration levels, which may be achieved in the coming 20-30 years. The benchmark points assumed for the dotted line are

- Frøya Island - a Norwegian research system aiming at maximum penetration
- Denmark in 2030 according to the official Danish energy plan

The feasibility of very high wind energy penetration is seen to change dramatically in the 100kW-10MW system size range. In this range conventional electricity generation is still diesel based and cost of energy rather high, but not necessarily varying a lot through this range. The main reason for the dramatic drop in penetration is rather that energy storage is needed to reach the very high penetration levels and that managers of larger systems will prefer a cautious approach, fearing negative consequences for the existing equipment due to wind power fluctuations.

As indicated by the dotted line in Figure 1, the level of wind energy can be developed to increase significantly in the future. Thus the challenges of national (and Trans-national) systems will be to increase penetration to levels already existing in smaller isolated systems, which themselves seem to be well placed to

increase their wind energy penetration to levels typical for just slightly smaller systems. Obviously great care has to be taken in this process, where many failures have occurred due to over-ambitious system designs with too high degree of complexity and too little experience as a background for the project development. Gradual increase starting at the dashed line and moving towards the dotted step-by-step applying simple, robust, reliable and well tested concepts seems to be the recommendable approach.

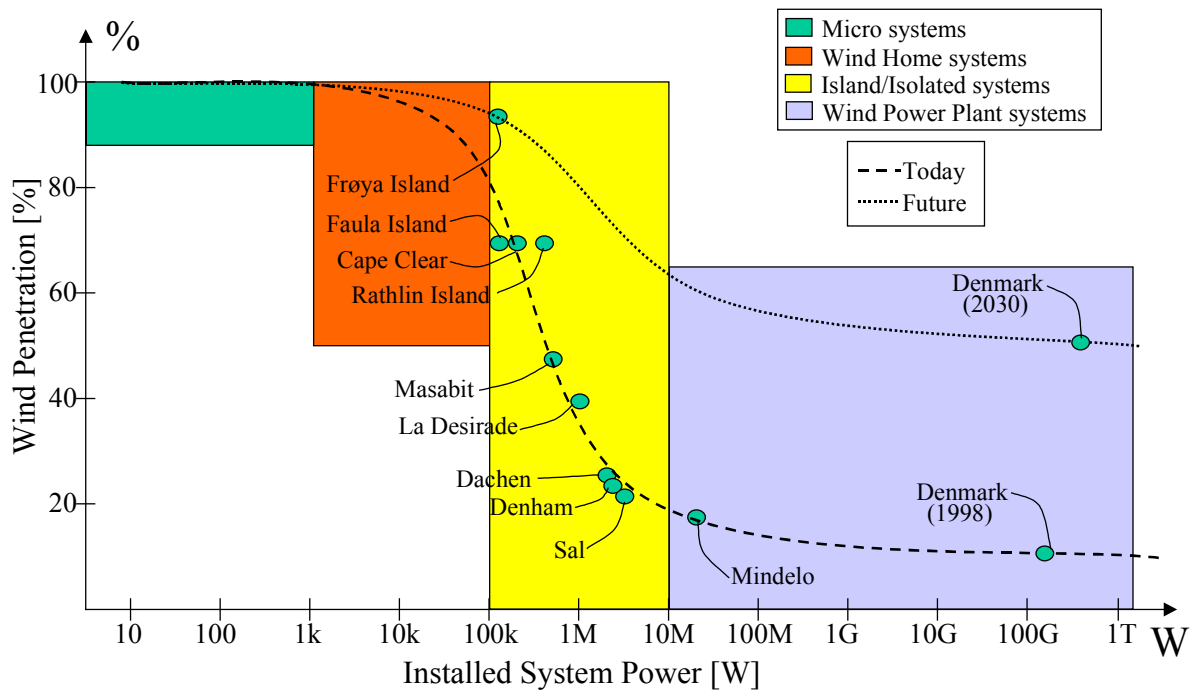


Figure 1. Present and expected future development of the wind energy penetration vs. the installed system capacity.

## 4.5 Conclusions and Recommendations

The difference between guidelines and standards is illustrated by the two types of documents, that are now being developed in the framework of IEC:

Guidelines deal with project implementation related elements of DRE systems and may include guidelines for system selection, bid and contract, quality assurance, operation, maintenance and overall system classification. Several versions of project implementation guidelines may be envisaged for various types and classes of systems

Standards deal with the specific technical elements of DRE systems and is the responsibility of individual technical committees in the national and international standardisation framework, that include IEC, CENELEC and other bodies. The standards are unique, and all project implementation guidelines should refer to one and the same set of RE systems standards

This setup is adopted in the development of IEC/PAS 62111 guidelines ref. 6. for small DRE systems for rural electrification in 3<sup>rd</sup> world countries.

## **Barriers**

Barrier identification is a key. Basically, it is about eliminating the deadlock situation that the market for wind power in isolated power systems has not developed because the product is not there and the product has not developed because the market is not there.

Some of the main barriers that may be mentioned are:

- lack of positive track records due to failures in too complex system designs applied in early pilot projects
- lack of institutional sustainability at the recipient in small remote communities with limited human resources
- lack of detailed knowledge of user demands and priorities and their development in time
- lack of project preparation and implementation models adapted to remote community conditions and capacities
- lack of financial sustainability and commercial markets
- lack of availability of cost-efficient wind turbines with a long positive track-record in the appropriate size range (10-300kW) – old types are out of production from large suppliers
- lack of funding for technological development
- lack of engineering tools for customising systems
- lack of generalised reported experience and guidelines

## **Recommendations**

A number of issues have been identified which should be considered when developing a wind power project in an isolated power system. The main characteristics of a successful project may be summarised as follows:

- The use of updated versions of relevant international standards – including the one for decentralised power systems with renewable energies now in progress within the IEC.
- That best practice guidelines for project implementation are applied including common references and relevant experience from recent projects.
- That the wind power project in the isolated system in question is part of a concerted action in a national and international programme rather than an individual project.
- That the wind power technology applied in a small to medium size system follow simple and proven approaches, e.g. by repeating and/or downscaling pilot and demonstration systems with positive track records, which may have been developed from filtering down from large-scale systems any technological achievements adaptable to smaller systems.
- That small systems are developed and specified to apply rugged technology suitable for remote communities.
- That no experimental systems are installed at rural remote communities unless previously thoroughly tested and documented at test benches dedicated to serve as experimental facilities
- That ownership is well defined with a built-in interest identified to ensure long-term interest and funding of operation, maintenance and re-investments when needed.

- That an organisation is established with the necessary capacity and capability for implementation, operation and maintenance, preferably including the back-up from a relevant national or regional knowledge centre.
- That a sufficiently detailed feasibility study has been performed.
- That modelling assumptions, input data and methodology applied for the feasibility study and system design reflect the true hardware reality for the types of systems in question

The technical capacity to design, build and operate isolated power systems with a high penetration of wind power exists, but the mature product and the market have not yet met. Nevertheless, there is today an industry offering small wind turbines (10 - 300kW) for hybrid system applications with a long-term commitment in this business. This indicates their belief that a market is emerging so that interest also from some of the large wind turbine manufacturers can be expected.

The above recommendations are seen as moves that would all lead in the direction of a development of the use of wind power in isolated power systems. This will open up and extend access to electricity for the benefit of the development of small rural communities.

## 5 Results from Measurements in Egypt

This Chapter covers measurements carried out as part of the project in Egypt on various types of power systems. The main objectives of the measurements were to obtain information on the actual power quality of real power systems of different types and sizes and to establish load profiles to be used in future design of power systems with wind power. Details of this part of the project are given in the Report Risø-R-1240.

The collected data has been analysed for each of the systems and have been compared in order to generalise the results (as far as possible). The load profiles have also been used to assess the influence of load patterns on the predicted performance of power systems with a large amount of wind power capacity.

### 5.1 General overview

The objectives for executing the measurements were to establish a foundation for the description of the loads of an isolated system in order to be able to design an isolated power system with wind power in terms of sizing of components (diesel generators and wind turbines) and determination of operating strategy, and to predict the performance in terms of e.g. fuel consumption and utilisation of wind power.

Another objective has been to measure the actual power quality of such systems in order to be able to have a documented base case for the performance requirements when installing wind power in isolated systems.

The approach has been to measure different types of loads and to measure on different types of power systems. The load has been divided in several categories. These include domestic, shopping/office, light industry, hotels etc. The reasoning behind this is that it then should be possible based on these types of loads to aggregate the total load of a system based on the demographic data like number of inhabitants, number of shops etc.

The impact of the size of the power system is also very important to establish. This includes knowledge of the steps in load, actual power quality (frequency and voltage quality).

## 5.2 Selection of sites

The sites has been selected in order to meet the above mentioned objectives. This has resulted in the selection of three sites in Hurghada for the illustration of different types of load and selection of two sites in Sinai to investigate the behaviour in small and medium sized power systems. The five locations were:

- Particular Load in Large System 1: Hotel
- Particular Load in Large System 2: Shopping Mall
- Particular Load in Large System 3: Residential Area
- Small System: Wadi Tal, Sinai
- Medium System: Ras Sudr, Sinai

For each location the measurement period was 1-2 months. Data were sampled at 0.1 Hz. The signals measured included active and reactive power, voltage and current, and harmonic distortion.

The power system at Hurghada on the West Coast of the Red Sea has rather recently been connected to the national grid. It can therefore not serve as an example of an independent grid.

The measurement of the characteristics of such independent grids has been done at two sites in Sinai. The first site, Ras Sudr, represents a medium sized system (approx. 4 MW and 8,000 inhabitants). The other site, Wadi Tal, is a small village (75 kW and 200 inhabitants).

These sites were selected based on inspection of several sites. The criteria for selecting the sites were several including size, collaboration of local utility/operator and location/infrastructure.

The measurements executed as part of the project does not give an exhaustive picture of the various types of loads and system behaviour but they give indications of the real life situation in terms of load shapes load changes and power quality. They can be seen as a step in the direction of establishing a more general foundation for the design of isolated hybrid systems.

In each case the measurements were done by measuring at the outgoing cable of a transformer. The measurement system consisted of a Voltech PM300 power analyser, three current clamps, direct measurement of voltage and a data-logger in the form of a laptop computer with dedicated software.

### **Hurghada System 1: Hotel**

The hotel has approx. 150 rooms, some with air-condition and TV, and it has its own 500kVA transformer for power supply. The measurement system was connected directly at the terminators at the secondary side of the transformer.

### **Hurghada System 2: Shopping Mall**

The Shopping Mall is close to the hotel, and it is a small mall with approx. 15 shops and with air-conditioned office space in the floors above. The building is rather new, and it has its own 500kVA transformer. The measurement system was connected and set up in the same way as at the hotel.

### **Hurghada System 3: Residential Area**

The residential area is located in the city centre of Hurghada. The area is dominated by houses but there are also a few small shops. The measurement system was connected to a 500KVA transformer. The installation and setup was identical to the previous ones.

### **Town System: Ras Sudr**

Ras Sudr is a small town situated on the Red Sea Coast of Sinai approx. 100km South of Suez. It has 8000 households, and several hotels are located along the coast line, and there is some industrial activity related to oil handling.

The power system is an autonomous isolated grid with a single power station situated in the town. The power is distributed using a 11 kV and 22 kV overhead lines. The power station has several gensets due to the rapid growth of the load, but currently they are only using two rather new MAN diesel gensets of 2 MWe each. The power station is connected to the distribution company through two 11 kV cables. The bus bar for distributing the power is situated at the distribution company.

### **Village System: Wadi Tal**

Wadi Tal is a small Bedouin village situated on Sinai approx. 50 km south of Ras Sudr and a few kilometres inland. The village has approx. 400 inhabitants living in 50 households. There is a primary school and a small hospital. The main need for power is for lighting. There is power available from ca. 16.00h to 22.00h every day.

Power is generated at the local power station, and each house is connected to the power station through a 400 V grid line of only a few hundred meters extension. Two gensets are available, however, only one at the time can be connected. Fuel is delivered in barrels and is paid for by the villagers.

## **5.3 Data screening**

For each of the five measurement sites data showing the power quality and characterising the load is presented. The main focus is on the voltage quality and on the active power demand, but also the frequency and the reactive load is analysed. The analysis has been performed with the objective of characterising the load type in order to be able to use it in the analysis of future systems. The

original data is sampled with 10 sec intervals. The samples are then averaged using a 10 min averaging period.

The measurement period and the procedure for each sites is slightly different from site to site and it is therefore indicated in the section for each site.

*Table 8 Key data for measurements in Hurghada*

Item	Hotel	Shopping Mall	Residential area
Load type	Hotel	Shop/office	Residential
Grid type	Interconnected	Interconnected	Interconnected
Start date	98.03.06	98.07.11	98.05.24
Stop date	98.05.22	98.08.15	98.07.06
Average load	89 kW	161 kW	82 kW
Standard deviation	34 kW	38 kW	45 kW
Min 10 min load	28 kW	76 kW	28 kW
Max 10 min load	236 kW	286 kW	204 kW

*Table 9 Key data for measurements in villages in Sinai*

Item	Ras Sudr Village	Wadi Tal village
Load type	Medium sized town	Small village
Grid type	Isolated	Isolated
Start date	98.11.16	98.11.18
Stop date	98.12.16	98.12.18
Average load	1471 kW	20 kW
Standard deviation	315 kW	1 kW
Min 10 min load	530 kW	16 kW
Max 10 min load	2221 kW	23 kW

## 5.4 Analysis of data

A comparison between the different sites has been done on order to highlight similarities and differences. The comparison is done for both load and power quality key characteristics, and details of the analysis are given in Risø-R-1240. Key figures for the five sites are listed in Table 10.

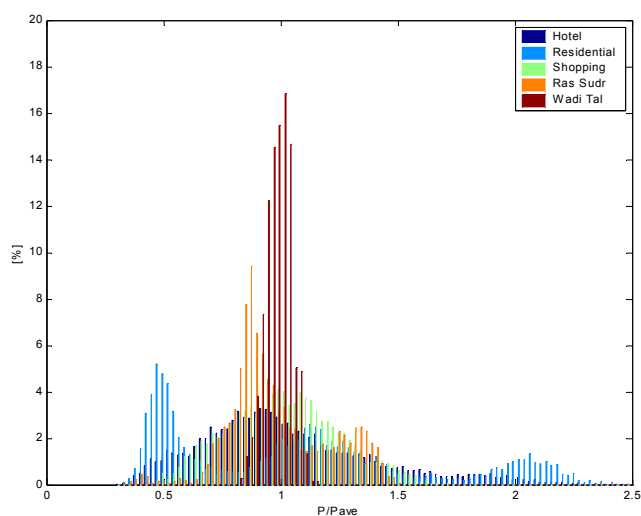
*Table 10 Measured key figures (based on 10 min average values)*

	Hotel	Residential	Shopping	Ras Sudr	Wadi Tal
<b>Pave [W]</b>	88981	82385	161362	1470882	19678
<b>Pmax/Pave</b>	2.65	2.49	1.78	1.51	1.16
<b>Pmin/Pave</b>	0.31	0.34	0.47	0.36	0.84
<b>Pstd/Pave</b>	0.3811	0.5465	0.2373	0.2143	0.054
<b>Umin/Un</b>	0.9516	0.9998	0.9207	0.9928	1.0009
<b>Umax/Un</b>	1.0437	1.0992	1.0598	1.0016	1.0083
<b>Uave/Un</b>	1.0151	1.0625	0.9929	0.9966	1.0052
<b>Ustd/Un</b>	0.0151	0.0188	0.0253	0.002	0.0013
<b>fmin/fn</b>	0.9986	0.9988	0.9958	0.995	0.982
<b>fmax/fn</b>	1.0004	1.0004	1.0048	1.017	1.049
<b>fave/fn</b>	0.9994	0.9995	1.0004	1.0013	1.0227
<b>fstd/fn</b>	0.0002	0.0002	0.0009	0.0011	0.011



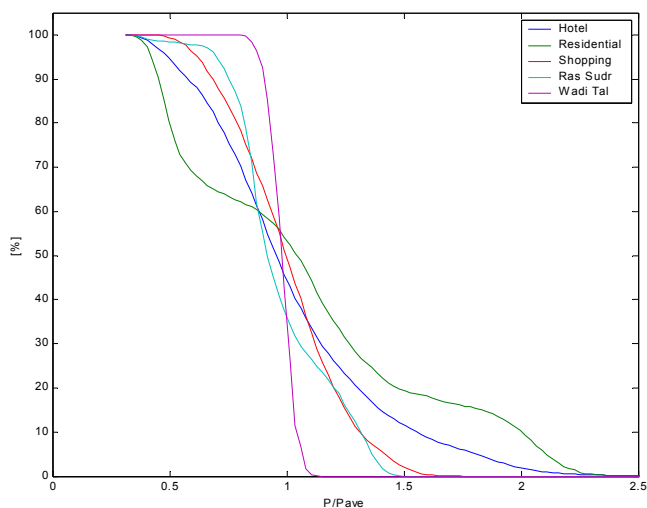
## Loads

To compare the load characteristics of the different sites the load distribution, load, duration curve, daily load profile with standard deviation and the reactive vs. active power figures have been prepared.



*Figure 2 distribution of loads*

The distribution of the loads is in Figure 2, and on the figure it is very clearly seen that the shape of the distribution is very different for the different sites. The same data are presented as duration curves of the loads in Figure 3. The same features are therefore seen in this figure.



*Figure 3 Load duration curves*

The load profiles for each of the five sites are shown in Figure 4. It is clearly seen that the profiles are very different. The hotel load is characterised by a rather high standard deviation for each of the 10 min bins, and this is of course due to the changing number of hotel guests staying at the hotel. For the residential load the night time load is very low and the evening peak is very high, and thus it is quite well determined since the standard deviation is low. This is also the case for the Wadi Tal load with an extremely low standard deviation confirming the almost constant load there.

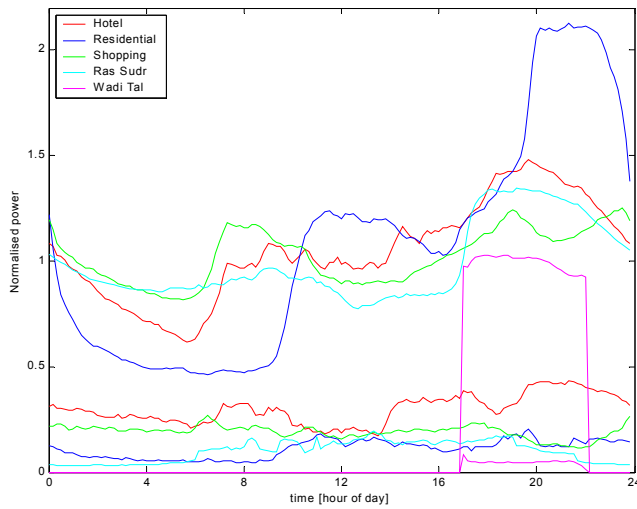


Figure 4 Load profiles for the five sites. Also included are the standard deviations for each 10 min bin

The load data collected as part of the project can be used to illustrate different load shapes. However, since the measurement periods for all the cases are limited to approx. one month the results should be used with care when applying the shapes for system studies. The load profiles should be reasonable well determined for the measurement period but seasonal variations as well as variations between weekdays are not well determined.

### Power quality

Power quality is an issue of increasing importance, due to increasing demands from the customers with respect security and quality of power supply.

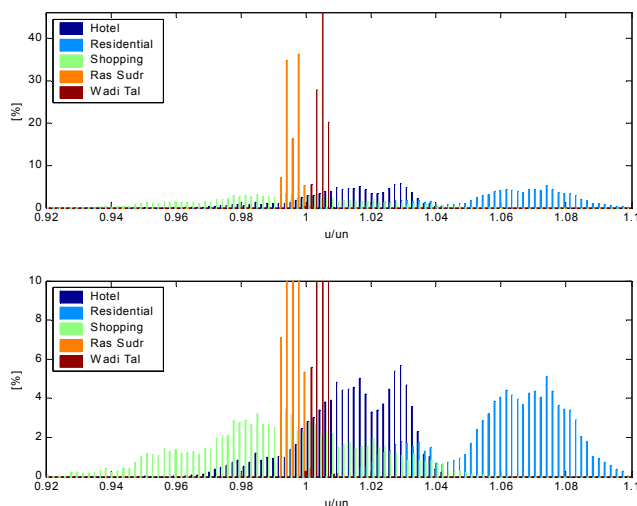


Figure 5 distribution of voltage

Figure 5 shows the distribution of the grid voltage at the measurements points for the five sites. The voltage ranges at the main bus bars at Ras Sudr and Wadi

Tal are quite narrow, depending of the impedance between the bus bar and the generators, the voltage controller of the generators and the variation of the load . For the three cases in Hurghada the voltage variations are larger, as the measurements are carried out on the secondary side of a distribution transformer and the impedance for these sites is therefore significantly higher.

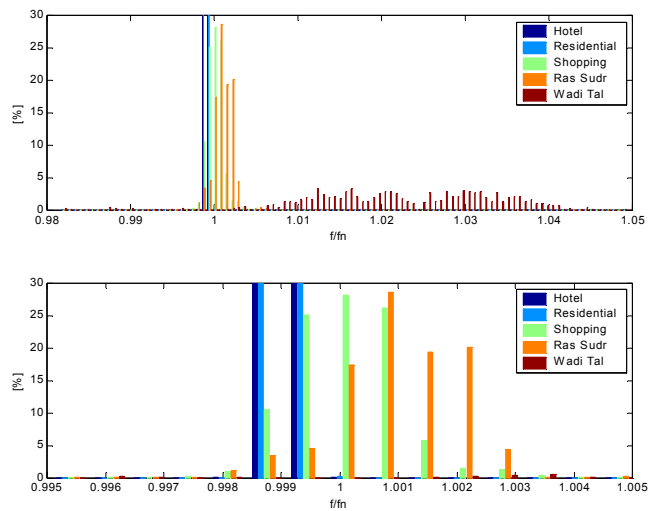


Figure 6 Distribution of frequency

The range for the frequency variations is mainly determined by the size of the generating capacity. For the cases in Hurghada the frequency range is very narrow, and for the Ras Sudr case the variations are larger but still small since the generating capacity is quite large compared to the load and especially to the load changes. For Wadi Tal it is clear that the system is small. Even the small changes in the load is causing changes in the frequency almost exceeding the standards for frequency limits.

In general it is noticed that the power quality as measured is quite acceptable also for the smaller systems. They all exhibit good voltage control with a narrow variation range. The frequency control is also good, however, it is seen that the quality experienced at Wadi Tal will degrade if more changes in the load were introduced e.g. if more appliances were installed.

## 5.5 Application of the Results for System Performance Analysis

This section deals with the impact of different load profiles as measured at the five different sites, as compared with the impact of other important parameters in a System Performance Analysis.

### The System Performance Analysis Method

When assessing system performance during the feasibility stage of a project the amount of data of the future system is often not complete and the forecasts are often not based on detailed analysis. There is therefore uncertainty on the data on which the feasibility analysis is performed. Part of the uncertainty also includes the load profile. In order to conduct the feasibility analysis it is important to have a good impression on the impact of some of the uncertainties. The impact of the load profile is compared to the impact of the load

development. The systems performance is here taken as the fuel saving, the utilised and dissipated wind energy and the profit. In order to investigate these issues a range of scenarios is defined and the performance parameters are calculated based on a simulation of each scenario using a dedicated simulation model.

The simulation model used is a technical/economic model that simulates the total behaviour of the system with respect to energy flow and based on the results of the technical simulation calculates the economic performance.

The important issues are the scenario definitions and specification of the base system. This is described in the next section.

## Scenarios, Assumptions and Tools

*Table 11 Key parameters common to all scenarios*

<b>Item</b>	<b>Description</b>
Full load fuel consumption	385.8kg/h
No load full consumption	23.8kg/h
Technical minimum load of Diesel	25%
1 <sup>st</sup> year energy consumption	12,900MWh/y
Weibull scale parameter	8.0
Weibull shape parameter	2.0
Fuel cost	2,500 DKK per ton
Wind turbine	Nordtank 300kW
Systems technical lifetime	20 years
Discount Rate	8%

The simulated system is based on the situation in Ras Sudr. The power system is assumed to consist of two 2.5 MW MAN B&W diesel generator sets feeding a load which in all the scenarios' first year is the average load as measured during the measuring campaign. The diesel gensets are characterised by the fuel consumption curve and their allowed minimum load. In all the scenarios no energy storage is included, and the genset capacity on line is therefore always large enough to cover demand including some spinning reserve.

The wind speed is specified by Weibull scale and shape parameters. They are assumed to be the same through the year. The wind turbines are assumed to be 300 kW stall controlled. For all the scenarios the simulation of the system performance is repeated for 1 to 10 installed wind turbines i.e. installed capacity in the range 300-3000 kW.

The scenarios are defined by three different energy consumption forecasts and by five load profiles. The system is simulated for a 20-year period. The energy consumption forecasts are: constant load throughout the analysis period, 3% load increase each year throughout the analysis period and a load forecast with a 10% load increase the first five years followed by a five year period with 3% load increase per year and a constant load thereafter. The load profiles are the four load profiles measured (Wadi Tal is not used since 24h power supply is assumed) and a constant load.

The tool used for the analysis is WINSYS, ref. 3. WINSYS is a power system analysis model designed for technical and economic analysis of primarily power

systems with diesel power combined with wind power. A unique feature of WINSYS is that it can simulate scenarios where the annual power consumption patterns develop throughout the years.

## Results

For all the scenarios the system is simulated for 20 years lifetime and with 1 to 10 wind turbines of 300 kW rated power installed. The main output from the simulations are the net profit, the fuel consumption and dissipated wind energy. The net profit is of course the key parameter in the evaluation of different system solution options and the fuel saving and dissipated wind energy are very good indicators for explaining the behaviour of the system.

The Report Risø-R-1240 presents the results from the analysis of this wide range of scenarios. In this section examples of results for system profit, fuel consumption and net dissipated wind energy are shown for systems with 3% annual increase of the load. The consumption pattern of all 5 measured sites are represented.

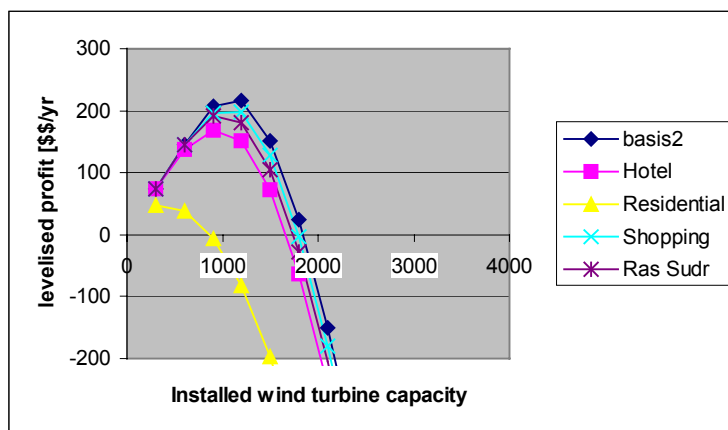


Figure 7 Profit of systems with 3% annual load increase

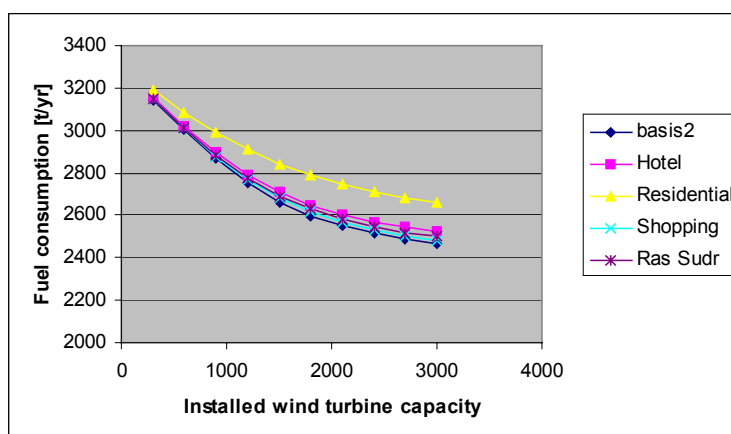


Figure 8 Fuel consumption of systems with 3% annual load increase

The scenarios with a 3% annual increase are at a higher level than in the case with a constant annual energy consumption. This is mainly due to the increase in the minimum load giving more room for the wind energy. It is also seen that

all curves except residential load profile are close to each other. This trend is even more pronounced in the case with high load increase in the initial years, where the impact of the different load profiles is much lower than in the case with constant energy consumption.

Regarding the fuel consumption of the different scenarios it is again evident that cases with the residential load profiles are significant different from the other cases, and again the differences are reduced as the energy consumption rate is increased. The reduction in fuel consumption is reduced as the amount of installed wind turbine capacity is increased since the fraction of the potential wind energy that is actually utilised decreases and the amount of wind energy that has to be dissipated in order to maintain the operating limits of the system given a particular load profile increases.

At the very high penetration level most of the potential wind energy of the last added wind turbine has to be dissipated. It does therefore not contribute significantly to the reduction of the fuel consumption. It is therefore very expensive to add this wind turbine to the as very little fuel is saved at the same specific investment. The cost of utilised wind energy is therefore high. These observations are confirmed by the figure below with the dissipated wind energy,

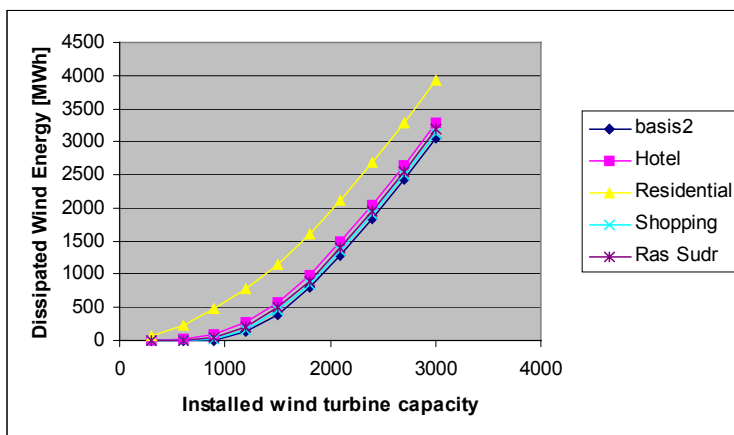


Figure 9 Dissipated wind energy of systems with 3% annual load increase

The analysis shows how the shape of the load profile that is used to analyse a given system may have an impact on the predicted technical and economic performance. However, this impact has to be considered together with the impact of other parameters that are important in the assessment of wind diesel systems. Some of the particular important parameters in this cases are the minimum load of the diesel gensets and the development of the energy consumption during the life time of the system.

When assessing systems it is important to determine if the system load profile will have a very low minimum value, and if this is the case to be very careful in the determination of the load profile. If the initial investigation indicates the minimum value of the load is not particularly low other issues are more important especially the energy consumption development.

After the feasibility analysis there is a phase of actual system design. During this phase the actual operating strategy is developed. In this phase the load profile can have an important impact. This has to be investigated by models suitable for operating strategy development.

## 5.6 Conclusions

Measurements have been carried out at five different location in Egypt. The objective of the measurements were to establish knowledge of the behaviour of different types of load in order to use that information in the feasibility analysis phase of a project. From a load perspective it is clear that the load profiles are very different at the different sites.

It can be concluded that a one month measuring period is too short for a good statistical description of the load. Loads should be measured for longer periods in order to include seasonal variations and other long-term variations. The actual load profile is however reasonably well determined for the different sites.

The power quality is quite satisfactory at the measurement sites. Voltage and frequency fall within the ranges required by international standards as far as slow variations are concerned. The total harmonic distortion of the voltage is also within standards. The voltage fluctuations are smaller when the voltage is measured at the power station bus bar, but this is mainly due to the small impedance between the generator and measurement point and is not at result of better voltage control. The voltage fluctuations at the customers can very well be equal or even worse.

The measured load profiles have been used to investigate the impact of different load profiles when executing a feasibility study. The results indicate that the shape of load profiles can indeed have a significant impact on the technical and economic performance of a system. However, this will only be the case when the load profile has a low value for a rather long time each day and no or a low increase in the load.

For load profiles with less salient extreme values the impact of the load profile on the system performance is not so strong and other parameters are at least as much or more important. The energy consumption and minimum load of the diesel gensets are also a very important parameters in the assessment of systems with a large amount of wind energy and in most cases more important than the load profiles.

# 6 An Inventory of Isolated Systems in Egypt

## 6.1 Overview

It is generally perceived that there is a large potential world wide for energy supply to remote and isolated villages with local power supply systems characterised by large wind resources and high energy production costs.

In order for this potential market to develop, a simple approach should preferably be found, which can be applied at low cost and at a risk comparable to the risk involved when deciding and designing a diesel powered system.

In view of this need and the fact that economics of scale apply, it was decided to try to acquire a general overview of the potential types of systems in which wind power could be an option. It was furthermore decided to use Egypt as an example, and therefore this part of the work was done in collaboration with New and Renewable Energy Authority (NREA) of Egypt.

The intention was that this overview will be applicable in a simplified but reliable approach to define consumer needs and system specifications. The typical size of small system electrification projects cannot justify very detailed and therefore costly analyses, unless they are bundled in a programmatic approach.

More details are given in the Report Risø-I-1703, which presents an overview of the inventory of isolated power systems in Egypt. It also outlines the main issues related to an implementation of wind energy in such isolated systems in the framework of an Energy Sector Development Component for Egypt.

## **6.2 An Inventory of Isolated Power Systems**

### **Background**

Methods and guidelines rather than "universal solutions" for the use of wind energy in isolated communities should include the ability to describe consumer needs and requirements in isolated communities with independent power systems, e.g. in mini-grids. Such requirements should serve as input to operational engineering design and assessment methods. Descriptions of consumer needs and requirements should to the degree possible address some of the questions identified as main barriers:

- lack of institutional sustainability at the recipient in small remote communities with limited human resources
- lack of detailed knowledge of user demands and priorities and their development in time
- lack of project implementation models other than turnkey
- lack of financial sustainability and commercial market

In order for wind power in isolated power systems to develop, a simple approach to the description of consumer needs and thereby system specification requirements should preferably be found. It should be possible to apply this approach at low cost and at a risk comparable to the risk involved when deciding and designing a diesel powered system.

In search for keys to success for wind power in isolated power systems, the project has attempted to investigate consumer demands and priorities through an actual case in Egypt.

### **Consumer Demands in Isolated Communities**

It was decided to try to acquire a general overview of the potential types of systems in which wind power could be an option, using Egypt as an example. A set of questionnaire forms were developed for collection of all relevant information, characteristics and conditions for those isolated communities in



Egypt that were not connected to the National Grid. The questionnaire forms are shown in Risø-I-1703, and the main focus of the questionnaire forms was to identify:

- Community location – geographically and relative to other power systems
- Community size and development plans
- Consumer types and numbers by type
- Power system loads – daily and seasonal variations as well as forecasts
- Power system specification and expansion plans
- Wind and climate descriptions

### Overview of results

An overview where the communities are divided into 3 categories is shown in Table 12 below.

Table 12: Overview of isolated power systems in Egypt

Category	Isolated power systems - brief description	Estimated No. in Egypt
1	very small - not electrified or non-grid communities – which get electricity from buying or charging batteries or individual household systems	more than 100
2	small – micro or mini grids, p.t. power by diesel systems of sizes 50-1000 kW	50
3	medium size – isolated or end-of-line grids with 1-150MW installed capacity of diesel or gas-turbines fuelled by oil or natural gas	5-10

An inventory of information of Category 2 communities in Egypt was made by NREA. An overview of such systems is shown in Table 13 below.

Table 13: Selected key information for 50 Category 2 communities of in Egypt

Item	Average	std. dev.*
Installed diesel capacity (kW)	165	170
Distance to grid (km)	41	30
No. of households	145	235
Persons per household	8	2
Consumption per year (MWh/y)	450	750
Estimated annual growth rate (%)	4	
Hours per day supply	7.5	3
Tariff (USD/kWh)	~0.05	0.00
Load factor on diesels	0.87	0.45

\*distributions are not necessarily symmetric

An overview like the one provided in Table 13 documents the availability, conditions and similarities of the “market”, and it offers a possibility to assess whether the “market” could be developed as a common programme, enabling a reduction of effects of the economics of scale. Although such an overview of data should be treated carefully, the finding of most immediate impact is that electricity in Category 2 communities is typically offered only part of the day and night, which is a major problem if wind power is to become economically competitive to other options.

A similar study providing an overview of the power supply situation and expected development could be made for Category 1 communities as well. With such overviews in hand, load patterns for different key types of load can be used in the design phase for estimation of the total load, and the implications of providing 24 hours power supply can be compared to the present situation.

### **Recommendations for Further Development**

It is concluded that the technical capacity to design, build and run isolated power systems with high penetration of wind power exists, but the mature product and the market have not met. It is recommended based on the case study exercise in Egypt that specification of community characteristics and conditions should use a simple approach characterised by items such as

- 2-5 main consumer types for each community and isolated power systems studied.
- Mapping of precise location and distance to other power systems with well-defined criteria for deciding whether to interconnect to larger grid or to implement isolated mini-grid solutions
- Bundling of project studies to enable common and efficient assessments of issues such as load forecasts, power system expansion planning, wind resources and site assessment including technical and institutional issues
- Preparing for modular system expansion depending on actual community and load development

A programmatic approach should be pursued for the development of isolated power systems with wind power in a regional or national framework

## **6.3 An outline of the Implementation of Wind Energy in Isolated Systems in Egypt**

In January 2001 representatives from NREA visited Risø to finalise the joint work in the project and to discuss possible follow up and application of the findings of the project. Representatives from Risø participated in a meeting at Danida, where the NREA representatives and Danida discussed the possible application of wind energy in isolated power systems in Egypt, based on the measurements and the inventory of isolated power systems in Egypt.

Subsequently an outline was made of the main issues related to an implementation of wind energy in such isolated systems, for possible consideration in the framework of the Renewable Energy Component of the Danida Energy SPS for Egypt. The outline is summarised below.

The application of wind energy in isolated communities is in accordance with Danida's energy sector policy in general and the country strategy for Egypt in particular. Such applications are in line with the rationale for Danish assistance regarding poverty alleviation in combination with rural development issues, with a strong focus on environmental issues and renewable energy.

On this background an area of activities dealing with support to the implementation of wind energy (and eventually other renewable energy technologies) in isolated power systems could be a relevant part of any

component dealing with the promotion of renewable energy presently (2001) being considered in the continuation of the Danida Energy SPS.

Such Support to the implementation of wind energy (and eventually other renewable energy technologies) in isolated power systems could include:

- i. Technical Assistance (TA) to further screening of potential sites with category 2 power supply systems, as defined in the inventory in the previous Section of this report, and to identify 5 – 10 sites with potential for similar systems, suitable for bundling in a programmatic approach<sup>1)</sup>.
- ii. TA to develop concepts for and assess the feasibility of implementing wind energy in such communities with isolated category 2 power systems. Concepts should include optional loads such as water processing (pumping/purification/desalination) and the possibility to combine with other renewable energy technologies
- iii. Support to the implementation of a few pilot (hybrid) wind energy systems in category 2 communities, if found feasible.
- iv. Provided a positive outcome of the pilot projects to implement wind energy in category 2 systems in a bundled and programmatic approach.
- v. In the process capacity building of local O&M infrastructure businesses as well as private financing mechanisms should be developed and supported as much as possible.

The technology risks associated with the proposed area of activities are perceived to be limited. The present project documents in this main report and the associated topical reports that today (2001) the situation with respect to implementation of wind energy in isolated systems for power supply is characterised by:

1. Simple, robust and reliable system concepts and technology exists, with provisions for optional loads such as water processing including pumping, purification and desalination.
2. An industry exists that can supply such systems on a commercial basis and is capable of participating as qualified partners in projects in developing countries. Especially for the large manufacturers this is true also for large scale applications.
3. Enough experience has been acquired to provide for qualified TA in relation to international development projects. The documentation of this includes the review report Risø-R-1109 and the Implementation Guideline Report Risø-R-1257.
4. There is a need for contributions to a positive track record for the technology based on well designed and closely monitored pilot and demonstration plants implemented in a capable institutional framework on suitable locations. The sites identified in the Measurement Report Risø-R-1240 and the Inventory Report Risø-I-1703 would provide such project opportunities.

The proposed area of activities on support to the implementation of wind energy (and possibly other renewable energy technologies) in isolated power systems is in accordance with the implementation strategy outlined in the following Section of this report. The strategy is in agreement with the wind energy

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1 In this approach a number of similar system solutions are implemented in a scale that is large enough for synergy effects to be utilised and local support business such as O&M service companies to be established

industry's perception of the international development market, and the proposed area of activities would be a model activity in such a strategy.

The rationale, justification and approach outlined above is formulated with reference to Danida's Energy SPS in Egypt. However, this concept for the implementation of wind energy in isolated power system is believed to be equally applicable to other international development assistance programmes

## **6.4 Conclusions and Recommendations**

The main recommendations in general for further development of the use of wind power in isolated power systems are

- to join forces in development of international standards for decentralised power systems with renewable energies as now initiated within IEC
- to develop best practice guidelines as living documents with common references and based on updated experience from recent projects
- to develop the use of wind power in isolated systems as concerted actions in national and international programmes rather than as individual projects
- to develop wind power in small to medium size systems following simple and proven approaches, e.g. by repeating and/or downscaling pilot and demonstration systems with positive track records
- to filter down from the large-scale systems any technological achievements adaptable to smaller systems
- to invest research and development in small systems to support development of rugged technology applicable for remote communities
- to use modelling assumptions from the hardware reality for the types of systems that will be applied
- to install experimental systems only at test benches prepared to serve as experimental facilities
- to encourage the industry to offer small wind turbines (10 - 300kW) for hybrid system applications – large wind turbine manufacturers need to give priority to allocation of production line capacity for small machines

# **7 An Implementation Strategy for Isolated Systems with Wind Power**

This Chapter presents an outline of a strategy and an associated action plan for the implementation of wind power in isolated systems for electricity supply. The outline is based on an extrapolation of "the Danish strategy", developed for the implementation of wind energy in the Danish energy policy, so that it can be applied for the implementation on a global level of wind energy in isolated systems for electricity supply, with special emphasis on implementation in 2<sup>nd</sup> and 3<sup>rd</sup> world countries.

This outline of a strategy is based on the report ref. 1. in which a proposed strategy & plan of action was developed under contract with the Danish International Development Agency (Danida). The report represents the opinions

of the authors, and Danida is not in any way responsible for or obligated by the proposed strategy & plan of action.

Although originally developed for possible use by Danida, the proposed strategy & plan of action is considered to be equally applicable for other Danish and International Organisations such as donor agencies and development banks.

## 7.1 Background

With respect to renewable energy, Danida's Energy Sector Policy is based on the following principles

- "The application of renewable energy provides the possibility for developing countries to decentralise the energy supply system and to save fossil fuels."
- "Based on environmental perspectives on both local and global level, renewable energy sources preferable compared to fossil fuels".

Fundamental issues of Danida's Energy Sector Policy includes the following items:

- "Contributions to the use of well established renewable energy technologies within e.g. wind energy and solar energy".
- "Contributions to pilot projects with the purpose to adapt well established technologies to local conditions".

Since 1981 Danida has supported the application of wind energy in a number of projects in developing countries. The projects include wind farms connected to national grids, wind turbines connected to regional diesel powered grids and a project with a wind diesel system connected to a local grid.

All projects have been based on the application of commercially available electricity producing wind turbines in sizes that in each particular application was best suited with respect to economy and maturity of technology. In addition to these a number of Danish projects in developing countries have had a Danish main contractor using Danish wind turbine technology, even if the project was not financed by Danida.

Conditions are good for the application of Danish wind turbines in the context of isolated power supply in developing countries. Danish standard wind turbines, developed for grid connected operation, have been widely proven in a strongly competitive international market where Danish wind turbine industry has a market share of the order 50%, thus building a solid 'track record' for themselves. The needs in the recipient countries are often such that the standard products of the industry intended for grid connected electricity production are directly applicable.

In the context of isolated systems (wind diesel and high penetration systems) the main aim of applying standard electricity producing wind turbines is to save fossil fuel by operating in parallel with coal or oil fired units. This can be done

by 'retrofit' in connection with existing electricity supply or as part of electrification of areas and communities with no previous electricity supply.

Projects in developing countries have experienced problems of both technical and institutional nature:

- Technical problems have most often occurred as a consequence of applying technical solutions that have been too complicated for the local capabilities. Frequently the choice of these solutions has been caused by the requirement that the solution (on paper, in the appraisal phase) should be economically competitive with fossil fuel based technologies, which do not offer the same environmental benefits.
- Institutional problems have most often occurred because the project could not be / had not been incorporated into the existing institutional framework. As an example the local electricity supply may operate under authority of the local municipality, while the capabilities necessary to operate and maintain the systems of the project may only be available on a regional or national level.

Simple, robust and reliable system concepts are commercially available, and when applied in suitable institutional frameworks in developing countries and elsewhere they have most often performed satisfactorily. It has been demonstrated in the context of a number of Danida financed projects, that Danish wind energy industry - in particular of course the large manufacturers – have the capability to fulfil the requirements of projects in developing countries on both technical and institutional levels.

The industry's standard products can be applied directly and in large scale in several contexts:

- Simple configurations (island systems/isolated systems) where standard wind turbines are connected directly to an existing or new local diesel powered grid, with power penetrations of up to 50 - 100 % and with the simplest possible (modular) supervisory control strategy.

Such systems could include the application of excess wind energy to satisfy optional or deferrable loads, and systems sizes from 150 kW (the smallest standard turbine on the market today) to a few MW are considered to be ready for large scale implementation today, in the context of retrofits as well as electrification.

Simple configurations where standard wind turbines or their grid connections are modified, e.g. using power electronics possibly together with battery storage systems, should be proven in smaller scale before being implemented in large scale.

- Isolated wind power plant system configurations, where standard wind turbines are connected directly to an existing large, independent diesel powered grid possibly with several power plants, with a power penetration of max. 25 - 50 %. They will always be installed on existing grids, and the wind turbines (or wind turbine clusters) will have their own control functions ensuring that the stability and other control functions of the grid are not disturbed.

Such systems, typically from 1 to 10 MW, are considered ready for large scale implementation today.

Danish manufacturers are presently developing systems for isolated power supply for markets in developed countries and 2<sup>nd</sup> world countries with a well developed technical infrastructure. Lately concepts have been developed, in which the excess energy at high proportions of wind power are utilised for alternative (optional or deferrable) applications such as fresh water production, heating, cooling/freezing etc.

The adaptation of these systems for developing countries, as well as the further development of more complex and optimised systems, relies on the willingness to accept a certain level of innovation and associated risks in a limited number of pilot projects.

## **7.2 Present Situation**

A couple of hundred isolated systems with wind energy have been installed world wide, but a great deal of these are not properly referenced or documented. The majority are located in developed countries and 2<sup>nd</sup> world countries, typically in remote locations or islands, and they are frequently installed as part of development or research projects. R&D in isolated systems with wind energy, with associated experimental facilities, is being undertaken in a dozen national wind energy centres world wide.

Internationally based projects have mostly focused on remote locations or islands in developed countries and 2<sup>nd</sup> world countries. With support from EU Programmes there are ongoing activities in the Mediterranean, and especially in a number of high penetration systems on Greek Islands there is a large proportion of Danish wind turbines. With support from North American Programmes a wind diesel market is developing for electricity supply of local communities in the North American/Canadian Arctic, and this development has been positively influenced by a number of systems with Danish wind turbines adapted for the very difficult operating conditions frequently found in these regions.

With basis in a vigorous village power program conducted by National Renewable Energy Laboratory (NREL) in USA a number of wind diesel projects for isolated communities is being started these years in South America and in the North American/Canadian Arctic. The programme will also include projects in developing countries, and an openly declared part of the strategy is to promote the development and application of North American RE technology for decentralised electricity supply.

With starting point in the Danish resource base projects have been carried out in Denmark, in Greenland and in several developing countries. The projects in Denmark are predominantly development and demonstration projects of various kind and scale, aiming at general electricity supply, and most of the projects have been supported by the Energy Research Programme (EFP) and the Development Programme for Renewable Energy (UVE) of the Danish Ministry of Energy. In Greenland the aim is a proper power supply of remote tele-stations with difficult access conditions, installed and operated by Greenland's

Telecom who participated in the development of the systems and is very satisfied with the performance of the systems.

The projects in developing countries have mostly been small scale pilot plants in a variety of system concepts. However, several high penetration island systems in the Republic of Cape Verde with up to 20 % wind energy penetration has performed well, and recently it was decided to expand the systems with wind energy penetrations up to 30-40%.

Objectives for a strategy and action plan for isolated systems with wind energy would be the following:

- Firstly, in the short run, to promote the application of wind energy in developing countries in a targeted and appropriate way so that well proven Danish products are adapted and implemented in an operational way and the existing Renewable Energy resource base is activated optimally. As a starting point the wind turbines should be the electricity producing wind turbine designs that are the standard products of the wind turbine industry.
- Secondly, in the long run, to ensure a substantial contribution from wind energy to decentralised electricity production in developing countries, probably in combination with other renewable technologies for electricity production such as Photovoltaics (PV), micro-hydro etc., by engaging the Danish RE resource base actively in the development and implementation of improved systems and technologies.

This development would be supported and promoted by establishing a 'market' of a size in terms of money and time, which makes it attractive for the RE resource base in Denmark to apply strategic thinking with respect to investments in product development and to market cultivation e.g. by ensuring a suitable development of costs and prices.

The plan of action should build on the "Danish strategy" for implementation of wind power, adapted to the implementation of isolated systems with wind power in developing countries.

### **7.3 Outline of a Strategy**

The strategy behind the action plan should build on the experience with the successful Danish strategy for the development and application of wind energy in Denmark. Important elements of the strategy has been:

- Clear long term energy policy goals combined with economic incentives
- Economic incentives were given on the condition that increasingly strict technical-economical requirements were fulfilled, linked to a decrease with time of the incentives.

In order to ensure a widespread application of isolated wind power systems in developing countries, the objectives of the recipient countries should be dictated by energy and environment policy related objectives in combination with goals for a general improvement in living conditions in rural districts and local communities.



Main points in the strategy should be:

1. *Identification of the Danish resource base by company name, product specification and other qualifications,* including the financial and organisational strengths of the companies to undertake long term wind energy projects in developing countries. In addition to the wind energy industry as such, the resource base should be taken to include technologies that could be part of isolated wind energy systems in relation to storage, conditioning and alternative utilisation of excess energy.

2. *Establishing of a positive technical track record by strict emphasis on simple, robust and reliable system layouts, to be implemented with a correspondingly strict priority of realistic, appropriate and reliable organisational conditions.*

If necessary the economic performance may initially be given lower priority than the above mentioned issues, e.g. by including environmental and other externalities with a realistic weight, but also if necessary with reference to the strategy.

*These priorities should be currently updated in the light of the technological development.*

What is today considered complicated technology in the context of developing countries may very well in the future come across as simple and robust technology. Power electronics and energy storage are examples on technologies that could be expected to experience such development.

4. *Significant annual funding should be secured for an extended period of time, allocated for projects dealing with isolated systems with wind power, provided a number of criteria are fulfilled.*

The funding should be available for projects which fulfil strict criteria as outlined above, but the funding should only be applied to the extent that such projects can be defined in a credible way. An engagement by Danida or other donors should only be continued as describes as long as the industry and the other players in the field can deliver projects and products that are up to requirements and can add positively to the track record of the technology. This way it is made attractive for the industry to engage in the field in a long term strategic manner.

In order for the strategy to have a significant influence on the decisions of the industry, the annual funding should be visible in comparison with the annual turnover of the industry.

5. *Clear and realistic acceptance criteria should be established for projects dealing with isolated systems with wind energy.*

This is a necessity for the sake of both Danida (or other donors) and the Danish resource base, as well as the recipient countries for the projects.

*At the same time a continuous, coherent and consistent monitoring of the projects should be undertaken* so that the projects and their technical, institutional and organisational solutions are assessed while at the same time one keeps abreast of the technical developments in the field.

## 7.4 Elements of an Action Plan

The main points in the action plan are:

1. *Minimum requirements to technology and players should be clearly defined, and the long term objectives should be clearly stated.*

This could be done as part of a strategy or position paper, signalling the intentions of the donor regarding isolated systems with wind power, and describing the strategy and action plan to be implemented by the donor. The aim is to state as clearly as possible the intentions and commitments of the donor within this area in terms of

- “The product”, aiming at the recipients
- “The market”, aiming at the RE resource base

At the same time the concrete technical and organisational requirements to be fulfilled should be clearly defined.

2. *It should be clearly identified and described, what is to be understood as simple, robust and reliable technology for isolated systems with wind energy.*

With the present days (2001) state of development the following concepts can be considered simple, robust and reliable technology for isolated systems with wind energy:

- Simple, robust and reliable wind diesel systems without energy storage, based on the standard products of the wind turbine industry.
- High penetration island systems

Alternative applications of excess energy could be included, such as pumping, heating, cooling, fresh water treatment and production.

3. *The definitions should be updated on a regular basis* in order to avoid stagnation and to ensure, that technological achievements are transferred to 2<sup>nd</sup> and 3<sup>rd</sup> world applications when they are developed and matured.

4. *Technical/economical/organisational acceptance criteria should be developed, which ensure the application of simple, robust & reliable technology* rather than systems that are too complex.

- Technology: Functions, operational parameters, power quality and security of supply.
- Economy: Probably necessary to include externalities, alternatively acceptance with reference to strategic goals.
- Organisation: Transparent and functional requirements for responsibilities and competencies.
- Implementation: Requirements to O&M, training.

*The criteria should be updated on a regular basis* to ensure/supervise that the technical requirements are currently sharpened and that the necessary economic preferential treatment/subsidy is currently reduced.

5. *'The market' should be identified according to types of application & need, compared to the functional and reliable system solutions available at any given time.*

The market identification should probably be carried out in two steps, the first step being desk top analyses based on available material in combination with questionnaires and other contacts, the second step being proper 'government rounds' which could be a regular item on the agenda whenever there is contact/visits to a potential recipient country.

6. *Early in the course of events a few concrete pilot projects should be implemented, communicated to the industry through a bidding process.*

The projects should serve as vehicles for the development as it is described above, and eventually projects should be bundled together into programme type activities in order to provide enough volume for the development of a self-contained infrastructure.

*The time frame to implementation of the entire action plan in a scale large enough for the objectives of the strategy to be obtained is estimated to be of the order 10 years.*

It is estimated that items 1 to 5 of the action plan could be implemented during the first 2 – 3 years, leading up to the implementation of a few concrete pilot projects, item 6 of the action plan. During the remaining part of the 10 year period large scale implementation and monitoring could be done in programme frameworks.

## **7.5 Expected Outputs from the Strategy**

*The implementation of the action plan in accordance with the proposed strategy will pave the way for a positive development,*

which in a longer perspective will result in Danida and other donors being able to rely on the large scale application of wind diesel systems and other isolated systems with wind power in both regional and (centralised) and local (decentralised) energy supply in developing countries.

*The present "chicken and egg" situation, where the market awaits the right product and vice versa, will be resolved.*

A serious market will be established with a well defined demand of a significant extent and duration, and therefore serious and competent industry will want to enter the market with products meeting the requirements of this market.

*In the beginning isolated systems based on wind diesel and high penetration system architecture will be based on the standard products of the industry, implemented in a simple, robust and reliable way*

operating in parallel with diesel power plants and with options for alternative application such as fresh water production, heating, cooling etc.

*Firstly, this will lead to a positive track record being established, which again will lead to an increased credibility of wind diesel, high penetration and other technologies for isolated systems with wind power.*

*Secondly, in the long run, the industry will eventually involve new technologies in optimised system designs and layouts, and adapt them for application in developing countries.*

Provided the strategy is implemented as described, this will happen on the initiative of the industry itself as part of its own development strategy, based on a desire to serve the long term and consistent development market that is a consequence of the proposed strategy. This will lead to better and increasingly competitive products being available.

*As was the case with the Danish strategy for wind energy, a positive synergy will eventually be generated between buyers (donors and developing countries) and sellers (the Danish and international RE resource base).*

*The end result will be that wind diesel systems, high penetration island systems and other isolated systems with wind power (and other renewables in more integrated systems) will contribute very significantly to the solution of energy and environment related problems in developing countries.*

## **7.6 Risks**

The proposed action plan takes its starting point in minimising the risks. Therefore, if the action plan is implemented with the proposed priorities and follow-up, the risks are reduced as much as possible.

If the action plan and its requirements are adhered to, there is no reason to expect any significant problems caused by technical issues. The donor itself will have a high degree of control in this area, so a realistic assessment of the technical risks should be that they are small.

The same goes for the risk that the Danish and International wind power resource base cannot deliver. The Danish and International wind energy industry and its related industry today have a size and experience that ensures sufficient strength and resources for a competent follow-up of its supplies in the field of wind diesel, high penetration and other technologies for isolated systems with wind energy in terms of warranties, service, training etc. Therefore the risk for deficiencies in this area should be considered small.

The Danish and International resource base today also have know-how and experience sufficient for a contribution to the formulation and implementation of workable projects. Therefore, provided that sufficiently realistic (which does not necessarily mean only restrictive) requirements and priorities are applied in the administration of the Donor, the risk for non workable projects is limited.

Thus there is no reason to expect any significant risk for deficiencies caused by factors under the control of the Donor or the Danish and International wind energy resource base.

However, like projects in general in developing countries these projects will be vulnerable to deficiencies in the ability of the recipient country to meet the technical and institutional needs of the projects. The risk for such deficiencies, which are outside the control of the Donor and the Resource Base, can be minimised by suitable project designs in accordance with the requirements and priorities of the action plan, but it cannot be entirely eliminated.

However, there is no reason to expect a higher risk for deficiencies in this area for isolated systems with wind power than for other technologies in relation to developing countries.

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# **Appendix 1: Keys to Success for Wind Power in Isolated Power Systems**

## *Keys to success for wind power in isolated power systems*

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## KEYS TO SUCCESS FOR WIND POWER IN ISOLATED POWER SYSTEMS

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**ABSTRACT:** It is generally expected that wind power could contribute significantly to the electricity supply in power systems of small and medium sized isolated communities. The market for such applications of wind power has not yet materialized. Wind power in isolated power systems have the main market potentials in developing countries. The money available world-wide for this technological development is limited and the necessary R&D and pilot programmes have difficult conditions. Consequently, technology developed exclusively for developing countries rarely becomes attractive for consumers, investors and funding agencies. A Danish research project is aimed at studying development of methods and guidelines rather than "universal solutions" for the use of wind energy in isolated communities.

This paper reports on the findings of the project regarding barriers removal and engineering methods development, with a focus on analysis and specification of user demands and priorities, numerical modeling requirements as well as wind power impact on power quality and power system operation. Input will be provided on these subjects for establishing of common guidelines on relevant technical issues, and thereby enabling the making of trustworthy project preparation studies.

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Keywords: Wind power, isolated power systems, high wind energy penetration, power system modeling, power quality

### 1 INTRODUCTION

The market for wind power applications in small and medium sized isolated communities has not yet materialized. Few pilot projects have been made and even fewer have been successful. A Danish research project is aiming at development of methods and guidelines rather than "universal solutions" for the use of wind energy in isolated communities. The main activities of this project, which forms the basis for this paper, are

- review of projects done, relevant literature on the subject and available computational methods and tools
- identification of barriers for use of wind power in isolated power systems
- user demands to isolated power systems
- development regarding operational engineering design and assessment methods
- application and verification of methods on sites in Egypt
- formulation of a guideline for project preparation

Wind power in isolated power systems have the main market potentials in developing countries. The amount of R&D and pilot projects world-wide for this technological development exclusively for the developing countries market is limited compared to large scale applications. Consequently, the technology offered has not yet reached the same level of maturity, and it has difficulties convincing consumers, investors and funding agencies that it offers commercially attractive solutions. The main barriers identified are

- lack of positive track records due to failures in too complex system designs applied in early pilot projects
- lack of institutional sustainability at the recipient in small remote communities with limited human resources
- lack of detailed knowledge of user demands and priorities and their development in time
- lack of project implementation models other than turnkey
- lack of financial sustainability and commercial market

- lack of funding for technological development
- lack of engineering tools for customizing systems
- lack of generalized reported experience and guidelines

In search for keys to success for wind power in isolated power systems, the focus of this paper is on the three selected issues

- consumer demands and priorities, e.g. in Egypt
- review of models availability and modeling requirements
- wind power impact on power quality and power system operation - some results from a measurement programme

Inputs are provided on these three subjects for establishing of common guidelines on relevant technical issues, and thereby enabling the making of trustworthy project preparation studies. For documentation, data on power supply conditions in Egypt are analysed. Some actions and methods to facilitate introduction on the markets in the developing countries are presented.

### 2 CONSUMER DEMANDS IN ISOLATED COMMUNITIES

Small isolated power systems with wind power should from a consumer's point of view meet demands exactly as is the case for conventional power system solutions. Wind power should as such be treated as just another option in accordance with priorities of relevant policies and plans. However, in order to be able to assess wind power in comparison with conventional options such as diesel, a supplementary set of information describing the community may be necessary.

Regarding consumer demands and community development, wind power feasibility in small isolated power systems may be particularly sensitive to

- variations in land use
- village/town expansions
- site availability – distance to grid



- grid interconnection costs
- electricity demand development
- diurnal consumer pattern – especially whether the power system offers electricity supply 24 hours a day or less

Furthermore, costs for consultants for special studies or power system design add to the investment, which may be unacceptable for such small communities.

In order for this potential market to develop, a simple approach should preferably be found, which can be applied at low cost and at a risk comparable to the risk involved when deciding and designing a diesel powered system.

Realizing this need and the fact that economics of scale apply, it was decided to try to acquire a general overview of the potential types of systems in which wind power could be an option in Egypt as an example. An overview splitting the communities in 3 categories is done in Table 1.

*Table 1 Overview of isolated power systems in Egypt*

Category	isolated power systems – brief description	estimated No. in Egypt
1	very small - not electrified or non-grid communities – which get electricity from buying or charging batteries or individual household systems	more than 100
2	small – micro or mini grids, p.t. power by diesel systems of sizes 50-1000 kW	50
3	medium size – isolated or end-of-line grids with 1-150MW installed capacity of diesel or gas-turbines fueled by oil or natural gas	5-10

Hurghada, which is studied more closely below, is Category 3 with about 100 MW installed gas turbines and already a 5 MW wind farm at Hurghada Wind Energy Technology Center (WETC). Hurghada has operated as a high-wind-energy-penetration system, and it has provided demonstration for Egypt of this technology, ref [11] and [12]. This technology may in certain cases be applied in Category 2 systems, for which reason an inventory of information of such systems was made by NREA. Some statistics are shown in Table 2.

*Table 2 Selected key information - 50 communities of Category 2 in Egypt*

	Average	st. dev. <sup>†</sup>
installed diesel capacity (kW)	165	170
distance to grid (km)	41	30
No. of households	145	235
persons/household	8	2
consumption/year (MWh/y)	450	750
Estimated annual growth rate (%)	4	
hours/day supply	7.5	3
tariff (USD/kWh)	~0.05	0.00
load factor on diesels	0.87	0.45

<sup>†</sup> distributions are not necessarily symmetric

Embarking on an approach with individual feasibility studies for each community, e.g. with demand-forecasting techniques similar to those used for urban systems of Category 3 or larger, rarely apply to remote rural isolated communities. An overview such as the one provided in Table 2, documents availability, conditions and similarities of the “market”, on the other hand offers a possibility to assess, whether it could be developed as a common programme, enabling a reduction of effects of the economics of scale. Doing so, Table 2 also shows that such overview data should be treated carefully. E.g. systems

appear, according to the first draft of the data, which have load factors higher than 1, and distance to grid is in this context the distance to the existing substation of the national grid, which may be different from the actual future potential grid connection location. The finding of most immediate impact is that electricity in Category 2 communities is offered only part of the day and night, which is a major problem if wind power is to become economically competitive to other options.

A similar study providing an overview of the power supply situation and expected development could be made for Category 1 communities as well.

With such overviews in hand, consumer demands may be studied more thoroughly for selected types of communities. Load patterns for different key types of load can be used in the design phase for estimation of the total load and consequences of offering 24 hours power can be compared to the present situation.

### 3 NUMERICAL MODELING REQUIREMENTS – A REVIEW OF ISSUES AND MODELS

Numerical modeling is an important part of the design, assessment, implementation and evaluation of isolated power systems with wind power. Usually the performance of such systems are predicted in terms of

- technical performance (power and energy production)
- economical performance (COE or IRR)

Performance measures may also include

- power quality measures
- load flow criteria
- grid stability issues
- scheduling and dispatch of generating units, in particular diesel generators

Thus a large variety of features are needed to cover the numerical modeling needs for all contexts. No single numerical model is able to provide all features, as they often are in conflict with each other in terms of modeling requirements. This survey of modeling requirements is based on a review of relevant studies that was carried out as part of the present project, see [1].

#### 3.1 Requirements & Applications

The requirements to the numerical models depend on the actual application of the modeling. Many factors influence the layout of a numerical model, and the main factors include

- The objectives of the simulations
- Time scale of the modeling
- Modeling principle (deterministic or probabilistic)
- Representation of the technical & economic scenarios
- System configurations, including dispersed vs. single system configurations

The objectives of the simulations depend on whether the simulations are done in a feasibility study as part of the decision process or by a manufacturer as part of the design process:

- Screening or optimization of possible system / grid configurations

- Overall annual performance of selected configurations
- Supervisory control including scheduling / dispatch of generating units
- Grid modeling, stability or load flow

Several time scales of modeling are used, depending on the context and purpose of the simulation

- Transient analysis of electrical transients due to switching, or certain power quality measures. Typically a few seconds at time step  $< 0.001$  sec.
- Dynamic analysis of machine dynamics, power quality or grid stability. Typically around 1 minute at time steps around 0.01 sec.
- Dispatch analysis of supervisory control, including diesel dispatch. Typically a few minutes to 1 hour at time steps of 0.1 to 1 sec.
- Logistic analysis of power flows and seasonal / annual energy production. Days, weeks, months, seasons or one year at time steps 10 minutes to one hour

Probabilistic modeling, based on probability distributions such as load duration curves or wind speed probability curves, can work directly with the outputs of typical utility statistics and WASP analyses. Time series simulation can represent “memory” effects such as energy storage, diesel dispatch strategies and deferrable loads, but to obtain the same statistical significance as probabilistic models, ideally Monte Carlo techniques should be applied.

Most models represent technical performance by one year’s performance measures (fuel savings etc), and use an economic life cycle analysis to establish the economic indicators. This way the technical developments/extensions of the system during its lifetime are neglected. This is in fact inadequate to give a realistic representation of the rapid development of isolated systems during their entire technical/economic project life.

A realistic representation of both system configuration and control strategy in the modeling is essential for a reliable prediction of system performance. Several techniques have been applied to facilitate flexible modeling of system configuration/connectivity, while flexible modeling of supervisory control strategy appears to be even more challenging, cf. [2] and [3].

For dispersed systems the electric grid becomes part of the system. Deterministic load flow analysis is well established, but probabilistic load flow modeling is more in line with the stochastic nature of wind and loads in isolated systems, and the associated probabilistic power quality measures, [4].

Actual grid stability analysis requires real dynamic electromechanical models, and such analysis is frequently outside the scope of isolated system analysis.

### 3.2 A Review of Numerical Models

A number of numerical modeling techniques and models are reviewed in ref. 1, although the review does not claim to be complete. Selected models are briefly described below:

[5] HOMER is a fast & comprehensive village power systems screening model, now (1998) supplemented with the VIPOR model for optimal layout of a supply area into grid connected vs. independently supplied consumers. State of the art in this category, but not publicly available.

[6] INSEL Offers almost unlimited flexibility in specifying system configurations by allowing the user to specify the connectivity on a component level. Intended as an out-of-house-model.

[7] HYBRID2 The state-of-the-art (1998) time series model for prediction of technical-economical performance of hybrid wind/PV systems. Offers a very high flexibility in specifying the connectivity of systems. Publicly available and quite widely used.

[3] SIMENERG The only model so far with a very high degree of flexibility in the control / dispatch strategy, using a “market square” approach, where the economically optimal subset of power sources that satisfy the power demand is dispatched in each time step.

[8] WINSYS is a spreadsheet (QPW) based model implementing probabilistic representations of resources and demands. WINSYS incorporates the anticipated technical expansions during its lifetime in the technical performance measures, combined with a traditional economic life cycle cost assessment. Thus WINSYS represents a more real life cycle cost analysis than most other models.

[9] ENGINEERING DESIGN TOOLS FOR WIND DIESEL SYSTEMS, This package contains seven European logistic models: SOMES (NL), VINDEC (N), WDILOG (DK), RALMOD (UK) and TKKMOD (FIN). It also includes the modular electromechanical model JODYMOD.

[10] PROLOAD A probabilistic load flow analysis code, using Monte Carlo techniques, developed in co-operation with an electrical utility for dimensioning of distribution systems with wind turbines.

## 4 WIND POWER IMPACT ON POWER QUALITY AND POWER SYSTEM OPERATION – MEASUREMENTS AT HURGHADA

The varying of the power output from wind turbines has an impact on both the operation of the power system and on the power quality of the system. This impact increases as the level of penetration increases.

The influence on power quality is mainly on the level and fluctuations of voltage and frequency. The stability of voltage and frequency should not be degraded significantly as the controllers of systems are required to be able to prevent instability. Furthermore, the shape of the voltage should not be degraded by the inclusion of wind power in the system. If wind turbines or storage systems applying power electronics are included in the system, it should be ensured that the distortion of the voltage is within required limits.

### 4.1 Voltage levels

Isolated power systems considered in this context are usually characterised by having only one power station. The transmission and distribution network is usually quite simple and weak. When the wind turbines are connected to the grid, the situation will often be that they are connected at a point in the grid where consumers are also connected.

The voltage level at the point of common connection will depend on the output from the wind turbines and on the consumer load. Situations where the voltage becomes high due to a high wind power production and a low consumer load will quite often occur. Measurements illustrating the dependence of the voltage on the wind power production and the consumer load from Hurghada are shown in Figure 1, from [11]. It is clearly seen that the voltage level depends on the output from the wind farm, but also that the consumer load is important. In Figure 2, the estimated bus bar voltage as a function of the wind farm output for both the maximum and minimum consumer load is shown. The permitted voltage limit is 11kV+10%, and it is noticed that for the current size of the wind farm this limit is not reached. Care has to be taken that the voltage level at the wind turbines is not too high even when the voltage level at the bus bar is within limits.

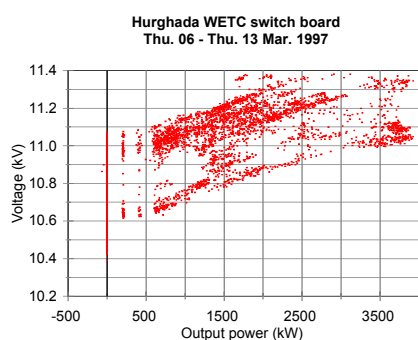


Figure 1 Measured instantaneous true RMS values of bus-bar voltage at WETC switch board versus measured instantaneous values of active power from the WETC.

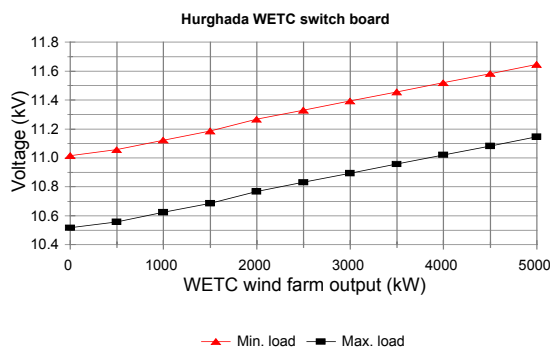


Figure 2 Estimated bus-bar voltage at the WETC switch board as a function of the output power from the WETC.

#### 4.2 Power fluctuations

Another important aspect is the power fluctuations. The power fluctuations create fluctuations in the voltage and they impose fluctuations in the diesel output. The voltage fluctuations have to be low to avoid disturbances e.g. in the light intensity. The power fluctuations do not only depend on the amount of installed wind power capacity, but whether the wind farm consists of a few large wind turbines or correspondingly more, but smaller wind turbines. The dependence of the power fluctuations on the number of wind turbines is shown in Figure 3. The wind farm is made up from 4\*300kW (NTK) + 20\*100kW (WC) stall controlled wind turbines and 10\*100kW (V) pitch

controlled wind turbines. The number of wind turbines in the figure is a calculated as the equivalent number of wind turbines, see Table 3. It is noticed from Figure 3 that the relative power fluctuation level basically is decreasing as the number of wind turbines is increasing. Keeping power fluctuations small is a desirable feature in an isolated power system with a high penetration level. The decrease in power fluctuations is due to the stochastic nature of the turbulent wind. The power fluctuations from the individual wind turbines will to some extent be independent of each other and they will therefore even out some of the higher frequency fluctuations. The non-ideal decrease of the fluctuation levels for increasing number of wind turbines may be explained by the wind farm consisting of different types of wind turbines.

Table 3 Number of different types wind turbines, and the calculated equivalent number of wind turbines

No. NTK	No. WC	No. V	Neq
1	-	-	1
1	-	-	1
1	-	-	1
1	-	-	1
2	1	-	2.5
4	-	-	4
-	15	-	15
-	4	7	11.0
6	20	7	24.6

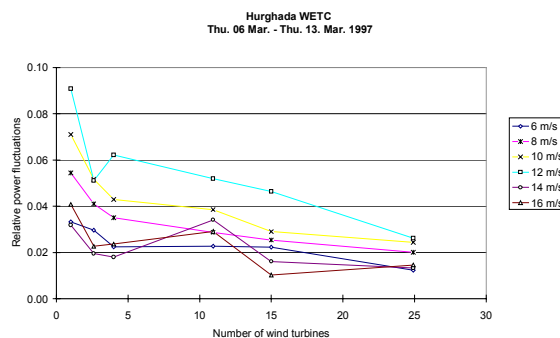


Figure 3 Measured relative power fluctuations.

#### 4.3 Operation

The operation and performance of an isolated system with wind power depends on the characteristics of the load. The load is the sum of many individual loads. The load can to some extent be categorized. In Figure 5 and Figure 6, the load patterns of a hotel load and a residential load are shown for illustration. Both of the loads are measured as the load of a 10/0.4kW transformer. The figures show the diurnal pattern. It is clearly seen that there is a distinct diurnal pattern for the residential load whereas the hotel load is quite constant over the day. It is also seen that the pattern for the reactive power is very similar to that of the active power. Day-to-day variations of loads shown by the minimum to maximum band are small in the residential load case. In the hotel load case the variation is larger. This is also seen in the standard deviation of loads in Figure 4.

Due to their impact on the operation strategy of the diesels, several aspects of the load are important. Briefly summarizing, the minimum load, together with the allowed technical minimum load of the diesel, determines the amount of wind power that can be absorbed by the system.

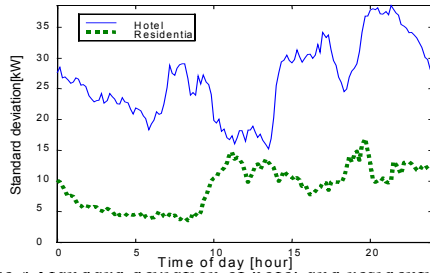


Figure 4 Standard deviation of hotel and residential load.

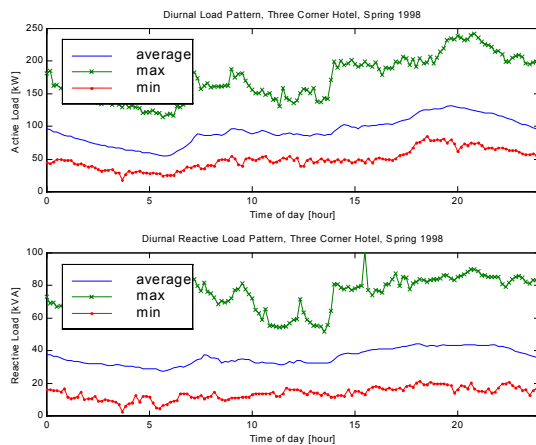


Figure 5 Diurnal load pattern for hotel load.

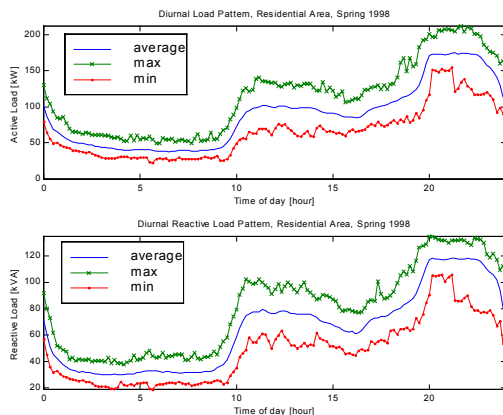


Figure 6 Diurnal load pattern for residential load.

The maximum load determines the necessary installed diesel capacity. The variations in loads and wind power – active and reactive - together with the rate of change of the load and the rate of change of the wind power, determine the necessary spinning capacity, in order to ensure adequate power quality and reliability in terms of loss of load probability.

## 5 CONCLUSIONS AND GUIDELINES

The main recommendations of this paper as keys to success for the further development of the use of wind power in isolated power systems are

- to develop the use of wind power in isolated systems as concerted actions in national and international programmes rather than as individual projects
- to develop wind power in small to medium size systems following the simple proven approaches, e.g. by repeating and/or downscaling pilot and demonstration systems with positive track records
- to invest research and development in very small and small systems to support development of rugged technology applicable for remote communities
- to use modeling assumptions from the hardware reality for the types of systems that will be applied
- to install experimental systems only at test benches prepared to serve as experimental facilities
- to develop a common best practice guideline as a living document, addressing at least key issues such as

Technology  
 Climate and wind resources  
 Site description  
 Consumer needs and community development  
 Scenario definitions  
 Technical performance  
 Economic performance and Finance  
 Institutional issues  
 Socioeconomic and sociological issues  
 Uncertainties and risk/sensitivity  
 Project implementation  
 Sustainability - operation and maintenance

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## **Appendix 2: Wind Power and Small Islands: Ideas, Theories and Realities**

*Wind power and small islands: ideas, theories and practical realities*

Jens Carsten Hansen, Wind Energy and Atmospheric Physics Department, Risø National Laboratory.

Invited paper presented at International Conference on Renewable Energy Islands, Bermuda, September 1999.



# WIND POWER AND SMALL ISLANDS: IDEAS, THEORIES AND PRACTICAL REALITIES

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**ABSTRACT:** Wind power can contribute to the electricity supply of isolated island communities in power systems of small and medium size. The market for such applications of wind power has not yet materialized. Wind power in isolated power systems have the main market potentials in developing countries. The money available worldwide for this technological development is limited and the necessary R&D and pilot programmes have difficult conditions. Consequently, this technology rarely becomes an attractive solution for consumers, investors and funding agencies.

Based on experience from actual projects and studies as well as the present state of the technological development, this paper gives some ideas and recommendations rather than "universal solutions" for development of the use of wind power in isolated communities. Practical realities, theoretical modeling and barrier removal will be addressed, with focus on selected essential technical issues. The ability to make trustworthy project preparation studies will be discussed.

## 1 INTRODUCTION

The market for wind power applications in small and medium sized isolated island communities has not yet materialized. Few pilot projects have been made and even fewer have been successful.

Wind power in isolated power systems have the main market potentials in developing countries. The amount of R&D and pilot projects worldwide for this technological development exclusively for the developing countries market is limited compared to large-scale applications. Consequently, the technology offered has not yet reached the same level of maturity as for large-scale applications, and it has difficulties convincing consumers, investors and funding agencies that it offers commercially attractive solutions.

In short, it is the chicken-and-egg problem: the market has not developed because the product is not there and the product has not developed because the market is not there.

This paper reports on experiences and recommendations from research and practical projects with wind power in isolated power systems.

The focus of this paper is on isolated island power systems with at least micro- or mini-grids and sizes of 100kW-10MW. The issues addressed are practical realities, theoretical modeling and barrier removal, in particular

- community needs and demands
- wind turbine technology
- wind climate, measurements and resource assessment
- power quality and power system operation
- power system modeling
- standards and guidelines

## 2 PRACTICAL REALITIES

### 2.1 Community needs and demands

Isolated grid power systems with wind power should from a consumer's point of view meet demands exactly as is the

case for alternative conventional options and at similar costs or cheaper. Wind power should as such be treated as just another option in accordance with priorities of relevant policies and plans. However, in order to be able to assess wind power in comparison with conventional options such as diesel, a supplementary set of information describing the community may be necessary.

Wind power feasibility in small isolated island power systems may be particularly sensitive to

- land availability and use
- village/town expansions
- electricity demand development
- power system size, distance and costs of grid interconnection
- diurnal consumer pattern – especially whether the power system offers electricity supply 24 hours a day or less

Furthermore, costs for consultants for special studies or power system design add to the investment, which may be unacceptable for such small communities.

In order for this potential market to develop, a simple approach should preferably be found, which can be applied at low cost and at a risk comparable to the risk involved when deciding and designing a diesel powered system.

Realizing this need and the fact that economics of scale apply, it seems obvious to

- establish regional wind power programmes for island communities
- categorize islands according to main characteristics determining
  - type of power system
  - size of power system
  - wind resource
- establish and carry out project preparation according to common agreed guidelines

Individual feasibility studies for each community rarely apply to remote rural isolated communities. Conditions and similarities of the "market" offer possibilities to assess, whether wind power could be developed as a common



programme, Overview data should, however, be treated carefully. Systems data may be unreliable, distance to potential sites need thorough siting assessment and future potential grid expansion study.

Finally, but not the least, many small communities are offered electricity only part of the day and night, which might be the major problem if wind power is to become economically competitive to other options. With sufficiently detailed overviews in hand, consumer demands may be studied more thoroughly for selected types of communities. Load patterns for different key types of load can be used in the design phase for estimation of the total load and consequences of offering 24 hours power must be compared to the present situation.

## 2.2 Wind turbine technology

Briefly, in a very simplified form, an attempt is made to summarize the state of the wind turbine technology in Table 1. The purpose is to illustrate some main differences between small and large wind turbines and some trends in the development with an impact on its application in small to medium size island power systems.

It appears that present successful wind power technology is due to an initial successful development of wind turbines in the 10-100 kW (1980-1990) range, up-scaled to the 100-1000kW range (1987-2000). The successful up-scaling technique is now again being pursued to create even larger wind turbines (particularly for off-shore applications), but limited track-records are available yet. Some different and new technological approaches have been found necessary. The main purposes of modifications are to

- Minimize costs
- Reduce structural loading by increased flexibility, more use of adaptive controls, pitch-regulation, and variable

speed regulation

- Improve safety
- Improve adaptability to grid integration, which will become necessary for reaching the planning goals of high wind energy penetration in large-scale power systems

The focus of the main players of the industry - with the extensive experience from the past 10-20 years successful development and with the considerable in-house know-how built - is now almost entirely on developing the new generation of large wind turbines (1-5MW).

Wind power for small island applications have always suffered from lack of funding for the technological development and have had to rely on relatively small company's limited capacity to undertake rather complex projects. Two potentially positive consequences of the new development in the industry manufacturing the large machines are, however, that

- development of wind turbine technology for high wind penetration is now being undertaken by "big" industry for large-scale application, and the knowledge thus built may filter down to small-scale application
- the industry is in a position to apply in-house expertise to developing new types of small wind turbines

This application of knowledge from large systems may not be given priority until a sufficiently large market emerges.

Today's small wind turbines are of very varying types and design. They are all significantly less cost-efficient than the large machines due to higher investment costs (up to 3 times higher per installed kW for 5-10 kW than for 500-1000 kW wind turbines) and less efficiency in terms of kWh/year per swept m<sup>2</sup>. Projects will therefore benefit from using the largest possible type of wind turbine.

In many cases, therefore, the study of the wind power options leads to suggesting the creation of a "large" common power system. In order to being able to

Table 1 A simple overview of some typical wind turbine characteristics for different size ranges of the technology

Size (kW)	<1	1-10	10-100	100-1000	1000-5000
Rotordiameter		• 3-10m	• 10-20m	• 20-55m	• 50-100m
Rotor	• More than 3 blades	• 2 or 3 blades • Up- or downwind • Furling (or pitch) • "Passive" variable speed	• Mostly 3 bladed • Upwind (or downwind) • Stall (or pitch) • Fixed speed (few as variable speed after 1990)	• Mostly 3 bladed • Upwind (or downwind) • Stall (or pitch) • Fixed speed (few as variable speed)	• 3 blades • Upwind / active yaw • Pitch, active stall (or stall) • Variable speed for the largest machines, but still fixed speed for some of the smallest in this range
Blades		• Several non-airfoil types • varying materials	• Airfoil-profiles • GRP	• Airfoil-profiles • GRP	• Airfoil-profiles • GRP
Towers		• Guyed steel pipes or lattice – pivot-base	• Lattice or tubular steel – pivot-base available	• Tubular steel	• Tubular steel
Controlsystem		• Mechanical or PLC	• Relays or PLC	• Microprocessor	• Microprocessors
AC/DC Generator	• DC for battery charging	• Mostly DC types for battery charging, but also some AC types for grid connection	• AC • Asynchronous	• AC • Asynchronous, Multipole	• AC • Asynchronous, Multipole, Optislip, ...
Track-record	• Many on ships and in remote locations	• Few for AC supply • Many for DC 1930-today	• Good track-record for many wind turbines 1980-1990	• Good track-record for many wind turbines 1987-2000	• Limited experience, but present main interest of main players in industry
Availability	• China main supplier	• Few makes for a small market	• Limited availability. Original makes as second-hand, but new types coming	• Limited availability for the smaller types in this range	• Present main market – many makes, types and models

accommodate a larger wind turbine, isolated villages could be interconnected, thus at the same time enabling larger and more cost-efficient conventional system solutions and changing the wind power contribution from being uneconomical into being technically and economically feasible.

### 2.3 Wind climate and resource assessment

#### *Climate*

General climatological descriptions will be available in the literature, but these descriptions rarely (or never) comprise what is necessary for wind resource assessment and wind power project design in general. Dedicated wind climate studies for wind power are being undertaken throughout the world, but sufficiently accurate knowledge for remote isolated islands is rarely available. This section will not even try to cover all relevant aspects, but just highlight a few relevant observations for the trade wind belt as an example.

Many islands with exploitable wind resources are located in the trade wind belt, known for its extreme constancy in speed and direction. Seasonal variations are largely dependent on the moving of the Inter Tropical Convergence Zone (ITCZ). Some of these islands may also be affected by tropical cyclones. Estimation of the extreme maximum wind speeds for design of the wind turbine structure according to international standards is important. Tropical Cyclones can reach hurricane strength in latitudes of 5-35°. Cyclones are classified as hurricanes when wind speeds exceed 64 knots (33 m/s). Wind turbines with hub-height of say 30 m or more installed on a mountain ridge may be exposed to higher speeds than those referred to at sea level in flat terrain and in lower heights above ground, and the air density may be different. The wind turbine design should take account for the wind loading occurring in the actual site of installation.

General statistics of barometric pressure, temperature, humidity and rainfall together with the wind data for the site location may give information relevant for design. E.g. in near-coast sites corrosion protection may be important. The corrosion gets less severe when moving inland some kilometres in the direction of the wind and further when moving to sites on hills and mountains, since the amount of salt in the air carried to such places will be less than at the coast at sea level.

Risk of soil erosion at heavy rainfalls at wind farm construction sites and access roads are typical environmental concerns in small mountainous islands.

#### *Data*

Meteorological data will most often be available from the local Meteorology Office, but data from these stations are rarely applicable for accurate wind resource estimation.

Other sources of data may be sought from dedicated wind monitoring programmes with special well-calibrated accurate instrumentation and automatic battery powered dataloggers logging 10 minutes or hourly average values. In addition to wind speed averages, wind direction as well

as standard deviation (turbulence level) and wind gust values should be recorded. Availability of records of simultaneous values of wind speed and direction is necessary for accurate wind resource assessment studies, and turbulence and gust information are being used for structural design of the wind turbines.

Measurement sites should be well exposed to prevailing wind sectors in locations with relatively limited flow distortion from obstacles and topography, i.e. gentle landscape features for distances up to a few kilometers and no nearby large houses or trees. An ideal site would be a small flat island with no vegetation or houses. Alternatively, measurements should be made on the candidate wind farm site itself. Wind speed measurements should be made in 2 or more levels above ground to determine the vertical profile for vertical extrapolation and with a top-anemometer in more than 20m above ground level or in wind turbine hub-height.

Data should represent the wind climate throughout the 24 hours of the day and night and throughout seasons of the year. The measurement period should preferably be 3-5 years with a data recovery close to 100%. Data from dedicated stations with just 1-year measurement period may be used, provided that correction to climatological averages can be made using long time series of data available from nearby stations.

Quality assurance is needed regarding:

- Calibration of anemometer and wind vane
- Data recovery of valid data (bad data due to malfunctioning, loss of power, icing, etc.)
- Completeness of time series
- Sufficiently long time series to be representative (> 1 year, >5 years is desirable, otherwise short-term to long-term correction must be applied)
- Obstacle effects < 5% (10% is the absolute max. limit)

#### *Wind resource assessment*

Estimation of the wind energy resource potential at a given site should be done using the Wind Atlas method<sup>1</sup>. This implies extrapolation of nearby representative wind statistics *from* a high quality wind measurement station taken at a topographically simple site for a climatologically long enough period *to* the potentially interesting wind farm site.

A calculation of the wind energy potentials at the candidate sites can be made using the WAsP<sup>2</sup> program, which is a computer software tool modeling wind in accordance with the Wind Atlas method.

Some key concepts and terms in a Wind Atlas Analysis:

- Local wind climate
  - measured wind statistics/rose in one point
- Regional wind climate
  - wind statistics/rose valid for region (~50 km)
- Wind atlas

<sup>1</sup> "European Wind Atlas", Risø National Laboratory, 1989, ISBN 87-550-1482-8

<sup>2</sup> "Wind Atlas Analysis and Application Program (WAsP)", Risø National Laboratory, 1993 – see [www.wasp.dk](http://www.wasp.dk)

- collection of regional wind climates, e.g. presented in map form
- Wind resource
  - actual, exploitable energy in the wind
- Wind resource atlas
  - collection of (many) wind resource estimates, e.g. presented in map form

A wind resource assessment involves determining a wind atlas based on which wind resources can be determined for selected wind turbine candidate sites or for a collection of sites – and possibly be presented in map form as shown in Figure 1.

Calculating a wind atlas requires:

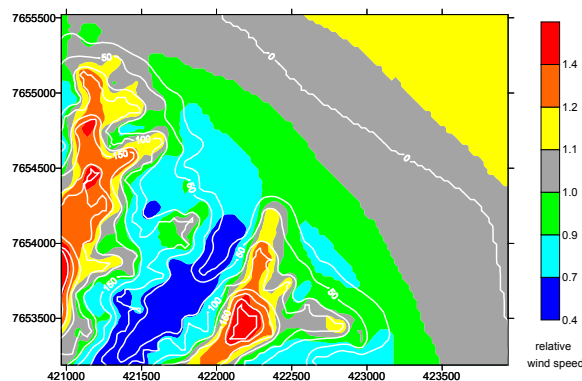
- Met-station position
- Topography description – digital orographic & terrain surface roughness map(s)
- Obstacle list
- Observed Wind Climate (histograms direction-sector by direction-sector)

The Observed Wind Climate will typically be generated from measured input wind data – time series of simultaneous values of wind speed and wind direction.

Map information should be quite accurate with high resolution near the location of measurement stations and wind turbine candidate sites.

The result of a wind atlas analysis for the Northeast part of the island of Rarotonga, Cook Islands, is shown in Figure 1 as an example. The expected annual average wind speed at 30 m above ground level is shown in colour codes on top of the height contour lines of the NE part of Rarotonga where the candidate wind turbine sites have been located. The colour codes are normalised values of wind speeds, where the common normalisation is done on an (in this connection) arbitrarily chosen value, which enables comparison between the sites.

Figure 1 Result of a wind atlas analysis for the north-east part of the island of Rarotonga, Cook Islands – relative annual average wind speed at 30 m above ground level plotted on top of the height contour lines



The estimated annual average wind speed distributions at a candidate site is shown in Table 2, which gives values of estimated annual average wind energy resources at 30 m height above ground level (agl) in terms of the annual

average wind speeds  $U_{mean}$  and the Weibull probability density distribution scale and shape parameters (A, k) sector-by-sector, energy density in the flow and potential annual energy production.

It should be noted that flow modeling in strongly complex

Table 2 Estimate of wind resources at candidate wind turbine site.

Ngatangia, 1995-96							
Height: 30.5 m a.g.l.							
Sect	Obstacle	Orography	A	k	%	P%	
0:	0.0%	35.6%	-9°	6.8	2.36	7.9	5.5
30:	0.0%	13.6%	-9°	6.1	2.78	5.2	2.3
60:	0.0%	4.0%	2°	6.4	2.79	8.1	4.3
90:	0.0%	18.9%	11°	8.5	2.89	14.7	17.4
120:	0.0%	44.4%	8°	9.8	3.24	23.1	38.6
150:	0.0%	52.7%	-3°	8.4	2.55	14.0	16.4
180:	0.0%	34.9%	-12°	5.8	2.48	4.4	1.7
210:	0.0%	6.9%	-10°	4.0	2.33	2.6	0.2
240:	0.0%	-1.1%	5°	3.3	1.75	3.2	0.2
270:	0.0%	22.7%	13°	4.9	2.20	6.1	1.4
300:	0.0%	42.3%	8°	6.7	1.30	4.6	4.1
330:	0.0%	48.9%	-1°	8.5	1.65	6.2	7.8
M= 6.8 m/s				E= 356. W/m <sup>2</sup>		7.7 2.11	

mountains terrain with steep slopes may be associated with large uncertainties.

## 2.4 Power system requirements

### Power quality

The varying of the power output from wind turbines has an impact on both the operation of the power system and on the power quality of the system. This impact increases as the level of penetration increases.

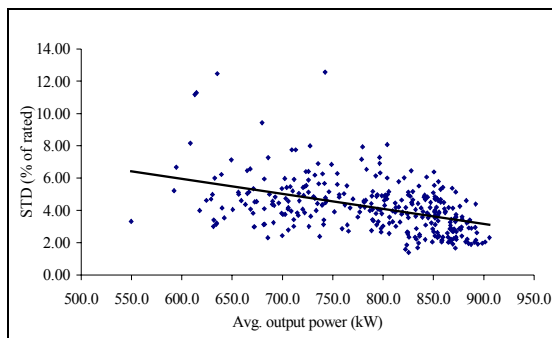
The influence on power quality is mainly on the level and fluctuations of voltage and frequency. The stability of voltage and frequency should not be degraded significantly as the controllers of systems are required to be able to prevent instability. Furthermore, the shape of the voltage should not be degraded by the inclusion of wind power in the system. If wind turbines or storage systems applying power electronics are included in the system, it should be ensured that the distortion of the voltage is within required limits.

The voltage level at the point of connection of the wind turbine to the grid will depend on the output from the wind turbines and on the consumer load. Situations where the voltage becomes high due to a high wind power production and a low consumer load will quite often occur. Design should limit maximum voltage to acceptable levels – normally nominal voltage+10%.

Another important aspect is the power fluctuations. The power fluctuations create fluctuations in the voltage and they impose fluctuations in the diesel output. The voltage fluctuations have to be low to avoid disturbances e.g. in the light intensity. The power fluctuations do not only depend on the amount of installed wind power capacity, but also on whether the wind farm consists of a few large wind turbines or correspondingly more, but smaller wind turbines. The relative power fluctuation level basically is decreasing as the number of wind turbines is increasing and as the power output from the wind turbines is increasing (see Figure 2). Keeping power fluctuations small is a

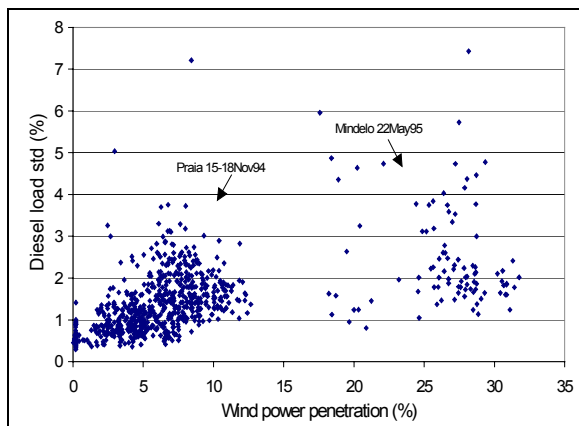
desirable feature in an isolated power system with a high penetration level. The decrease in power fluctuations is due to the stochastic nature of the turbulent wind. The power fluctuations from the individual wind turbines will to some extent be independent of each other and they will therefore even out some of the higher frequency fluctuations.

Figure 2 Measured and linear fit of standard deviation vs average output power from a 900 kW wind farm



Standard deviation of diesel power output will increase with increasing wind energy penetration – unless in certain hybrid systems, e.g. in systems with the facility to stop diesels completely, i.e. in relatively small systems with battery backup. The increase of the standard deviation is shown in Figure 3 for an example of 9 MW diesel power station with 900 kW standard grid connected wind farm.

Figure 3 Diesel load fluctuations measured as a function of wind power penetration at 9 MW diesel power stations with 900 kW wind farms



It may be noted that the actual diesel sets of the example shown in Figure 3 according to the diesel manufacturer will not suffer increased tear or wear and the specific fuel consumption will not be influenced by the fluctuations as long as the standard deviation is below 10% of rated power for the diesels.

### Operation

The operation and performance of an isolated system with wind power depends on the characteristics of the load. The

load is the sum of many individual loads. The load can to some extent be categorized.

The load most often clearly shows a distinct diurnal pattern over the day. Day-to-day variations of loads are mostly small.

Due to their impact on the operation strategy of the diesels, several aspects of the load are important. Briefly summarizing, the minimum consumption, together with the allowed technical minimum load of the diesel, determines the amount of wind power that can be absorbed by the system.

The maximum load determines the necessary installed diesel capacity. The variations in loads and wind power – active and reactive - together with the rate of change of the load and the rate of change of the wind power, determine the necessary spinning capacity, in order to ensure adequate power quality and reliability in terms of loss of load probability.

### 3 NUMERICAL MODELING

Numerical modeling is an important part of the project preparations – feasibility, design and assessment – as well as of implementation and evaluation of isolated island power systems with wind power.

Usually the performance of such systems are predicted in terms of

- technical performance (power and energy production)
- economical performance (Cost Of Energy or Internal Rate of Return)

Performance measures may also include

- power quality measures
- load flow criteria
- grid stability issues
- scheduling and dispatch of generating units, in particular diesel generators

Thus a large variety of features are needed to cover the numerical modeling needs for all contexts. No single model is able to provide all features, as they often are in conflict with each other in terms of modeling requirements. This survey of modeling requirements is based on a review of relevant studies that was carried out in [1].

### Requirements & Applications

The requirements to the numerical models depend on the actual application of the modeling. Main factors influencing the layout of a numerical model include

- The objectives of the simulations
- Time scale of the modeling
- Modeling principle (deterministic or probabilistic)
- Representation of the technical & economic scenarios
- System configurations - dispersed vs. single system

The objectives of the simulations depend on whether the simulations are done in a feasibility study as part of the decision process or by a manufacturer as part of the design process:

- Screening or optimisation of possible system / grid configurations
- Overall annual performance of selected configurations
- Supervisory control including scheduling / dispatch of generating units
- Grid modeling, stability or load flow

Several time scales occur, depending on the context and purpose of the simulation

- Transient analysis of electrical transients due to switching, or certain power quality measures. Typically a few seconds at time step  $< 0.001$  sec.
- Dynamic analysis of machine dynamics, power quality or grid stability. Typically around 1 minute at time steps around 0.01 sec.
- Dispatch analysis of supervisory control, including diesel dispatch. Typically a few minutes to 1 hour at time steps of 0.1 to 1 sec.
- Logistic analysis of power flows and seasonal / annual energy production. Days, weeks, months, seasons or one year at time steps 10 minutes to one hour

Probabilistic modeling, based on probability distributions such as load duration curves or wind speed probability curves, can work directly with the outputs of typical utility statistics and WASP analyses. Time series simulation can represent “memory” effects such as energy storage, diesel dispatch strategies and deferrable loads, but to obtain the same statistical significance as probabilistic models, ideally Monte Carlo techniques should be applied.

Most models represent technical performance by one year’s performance measures (fuel savings etc), and use an economic life cycle analysis to establish the economic indicators. This way the technical developments/extensions of the system during its lifetime are neglected. This is in fact inadequate to give a realistic representation of the rapid development of isolated systems during their entire technical/economic project life.

A realistic representation of both system configuration and control strategy in the modeling is essential for a reliable prediction of system performance.

For dispersed systems the electric grid becomes part of the system. Deterministic load flow analysis is well established, but probabilistic load flow modeling is more in line with the stochastic nature of wind and loads in isolated systems, and the associated probabilistic power quality measures.

Actual grid stability analysis requires real dynamic electromechanical models, and such analysis is frequently outside the scope of a study of an isolated power system.

#### *Availability of Numerical Models*

From [5], it appears that a variety of models are available, such as:

[5] HOMER: A fast & comprehensive village power systems screening model supplemented with the VIPOR model for optimal layout of a supply area into grid connected vs. independently supplied consumers (not publicly available).

[6] INSEL: Offering almost unlimited flexibility in specifying system configurations by allowing the user to specify the connectivity on a component level.

[7] HYBRID2: Time series model for prediction of technical-economical performance of hybrid wind/PV systems. Offers a very high flexibility in specifying the connectivity of systems.

[3] SIMENERG: The only model so far with a very high degree of flexibility in the control / dispatch strategy, using a “market square” approach, where the economically optimal subset of power sources that satisfy the power demand is dispatched in each time step.

[8] WINSYS: A spreadsheet (QPW) based model implementing probabilistic representations of resources and demands. WINSYS incorporates the anticipated technical expansions during its lifetime in the technical performance measures, combined with a traditional economic life cycle cost assessment.

[9] ENGINEERING DESIGN TOOLS FOR WIND DIESEL SYSTEMS, This package contains seven European logistic models: SOMES (NL), VINDEC (N), WDILOG (DK), RALMOD (UK) and TKKMOD (FIN). It also includes the modular electromechanical model JODYMOD.

[10] PROLOAD A probabilistic load flow analysis code, using Monte Carlo techniques, developed in co-operation with an electrical utility for dimensioning of distribution systems with wind turbines.

It appears that practically any theoretical modeling for isolated power system projects can be handled by available numerical models. Availability of models is not a limiting factor for development, but efforts involved in applying a complete set of modeling tools for a given isolated community situation may be considerable.

## 4 BARRIERS

Barrier identification is a key. Basically, it is about eliminating the deadlock situation that the market for wind power in isolated power systems has not developed because the product is not there and the product has not developed because the market is not there.

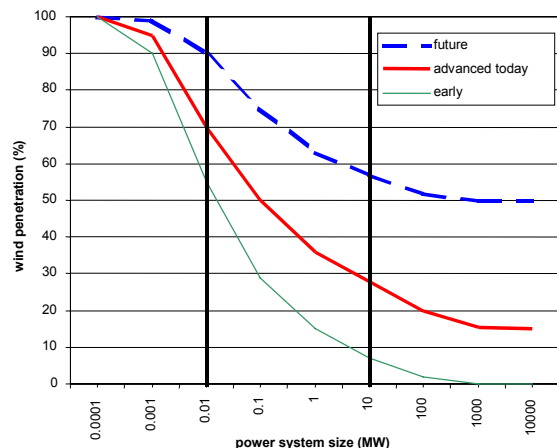
Some of the main barriers that may be mentioned are

- lack of positive track records due to failures in too complex system designs applied in early pilot projects
- lack of institutional sustainability at the recipient in small remote communities with limited human resources
- lack of detailed knowledge of user demands and priorities and their development in time
- lack of project preparation and implementation models adapted to remote community conditions and capacities
- lack of financial sustainability and commercial markets
- lack of availability of cost-efficient wind turbines with a long positive track-record in the appropriate size range (10-300kW) – old types are out of production from large suppliers
- lack of funding for technological development
- lack of engineering tools for customizing systems
- lack of generalized reported experience and guidelines

Another explanation why smaller (isolated) power systems have more difficulties to integrate wind power is also attempted through Figure 4, which shows wind energy

penetration levels as a function of power system size for different technological development levels.

Figure 4 Wind Energy Penetration vs. Power System Size for different development stages of the technology



Three levels are shown,

- the early stage illustrates the situation at the time of the first wind energy demonstration projects,
- the advanced stage is the highest penetration levels achieved today, and
- the future penetration levels reflect optimistic energy plans – e.g. the 50% goal for Denmark for year 2030.

Figure 4 illustrates the fact that the smaller the system, the higher the wind energy penetration necessary to justify having wind as a power source. For the very smallest systems, wind power is not interesting unless it is a stand alone wind system, but even in micro-grids up to MW-size, the penetration level must be high in order for wind to be financially interesting. The limited availability of small cost-efficient wind turbines is pushing this effect further.

The added complexity involved at the higher wind energy penetration levels is inherent and added risks and costs therefore unavoidable, until sufficient resources have been spent for the necessary technological development. The

coming technological development bringing the wind energy penetration of large systems from today's 10-15% up to planning goals of around 50% will surely bring solutions and technology that will be adaptable for smaller systems as well, but in the meantime simplicity should be the aim whenever possible and dedicated research should find solutions for the smaller systems.

## 5 INTERNATIONAL STANDARDS AND GUIDELINES

In 1988 the International Electrotechnical Committee (IEC) formed the Technical Committee TC88 for development of standards for Wind Turbine Generator Systems, chaired from Risø National Laboratory, Denmark. The different standards for Wind Turbine Generator Systems are developed in international Working Groups (WG), see Table 2 below.

Work on Danish wind turbine standardisation started 1982. The Danish standard DS 472 Loads and Safety for Wind Turbines was published in 1992. TC88 is still chaired by Risø, also chairing the committee BTF 83-2 in CENELEC, responsible for the European wind turbine standards.

Recently (early 2000), members of a joint IEC co-ordination group (JCG) on standards for decentralised power systems with renewable energies were appointed. The JCG is in the process of being formed with participation from the technical committees on solar energy (TC82), wind energy (TC88) and battery storage systems (TC21).

The JCG on standards for decentralised power systems with renewable energies is seen as a significant step forward in acknowledging the need for common references and guidelines setting standards for the renewable energy technologies applied in isolated/decentralised power systems in remote communities or islands.

This initiative of the IEC will build on efforts of national and international agencies to develop guidelines for projects involving isolated power systems with renewable

Table 3 List of IEC Working Groups (WG) in TC88 for standards on Wind Turbine Generator Systems

WG	Subject	Convenor	Status	Standard
	International Electrotechnical Vocabulary - Chapter 415: Wind turbine systems	DK (Risø)	CDV 1995-11	
1	Wind Turbine Generator Systems - Safety Philosophy	IT	1. ed. 1994-12	IEC 1400-1 ENV 61400-1
2	Wind Turbine Generator Systems - Engineering integrity	DK (Risø)	1. ed. 1994-12	IEC 1400-1 ENV 61400-1
3	Wind Turbine Generator Systems - Installation, maintenance and operation	US	1. ed. 1994-12	IEC 1400-1 ENV 61400-1
4	Wind Turbine Generator Systems - Safety of small wind turbines	EN	1 ed. 1996-04	IEC 1400-2 EN 61400-2
5	Wind Turbine Generator Systems - Acoustic Noise Measurement techniques	US	CDV 1995-01	IS medio 1998
6	Wind Turbine Generator Systems - Power performance measurement techniques	DK (Risø)	1. ed. 1998	IEC 61400-12
7	Revision of Wind Turbine Generator Systems - Part 1: Safety Requirements	DK (Risø)	CDV 1997-10	IS ultimo 1998
8	Wind Turbine Generator Systems - Testing Methods for rotor blades (Guideline)	NE	CD 1997-10	IS ultimo 1998
9	Wind Turbine Generator Systems - Certification procedures of wind turbines	DK (Risø)	CD 1998-02	DIS medio 2000
10	Power Quality Requirements for Grid Connected Wind Turbines	DK	CD 1998-02	IS medio 2000
11	Mechanical Load Measurements	NE	CD 1998-02	IS medio 2000

energy, and as such become a superstructure and a common reference. National projects and experiences, e.g. such as the work funded by the Danish Energy Research Programme or the PAS 62111 developed by EDF, will on the other hand get the opportunity to input results and recommendations to actual international standards, and thus join forces in attempts to build reliable electrification systems for isolated decentralised applications.

As an example, the Danish project to develop guidelines for isolated power systems with wind power will be addressing key issues such as

- Technology
- Climate and wind resources
- Site description
- Consumer needs and community development
- Scenario definitions
- Technical performance
- Economic performance and Financial issues
- Institutional issues
- Uncertainties and risk/sensitivity
- Project implementation
- Sustainability - operation and maintenance

## 6 CONCLUSIONS AND RECOMMENDATIONS

The main recommendations of this paper for further development of the use of wind power in isolated island power systems are

- to join forces in development of international standards for decentralised power systems with renewable energies as now initiated within IEC
- to develop best practice guidelines as living documents with common references and based on updated experience from recent projects
- to develop the use of wind power in isolated systems as concerted actions in national and international programmes rather than as individual projects
- to develop wind power in small to medium size systems following simple and proven approaches, e.g. by repeating and/or downscaling pilot and demonstration systems with positive track records
- to filter down from the large-scale systems any technological achievements adaptable to smaller systems
- to invest research and development in small systems to support development of rugged technology applicable for remote communities
- to use modeling assumptions from the hardware reality for the types of systems that will be applied
- to install experimental systems only at test benches prepared to serve as experimental facilities
- to encourage the industry to offer small wind turbines (10 - 300kW) for hybrid system applications – large wind turbine manufacturers need to give priority to allocation of production line capacity for small machines

In summary, the technical capacity to design, build and run isolated power systems with high penetration of wind power exists, but the mature product and the market have not met. The above recommendations are seen as moves that would lead to development of the use of wind power in isolated power systems, but as in any technological development process, financing is needed.

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Abstract (max. 2000 characters)

The overall objective of this research project is to study the development of methods and guidelines rather than "universal solutions" for the use of wind energy in isolated communities. The main specific objective of the project is to develop and present a more unified and generally applicable approach for assessing the technical and economical feasibility of isolated power supply systems with wind energy.

As a part of the project the following tasks were carried out: Review of literature, field measurements in Egypt, development of an inventory of small isolated systems, overview of end-user demands, analysis of findings and development of proposed guidelines.

The project is reported in one main report and four topical reports, all of them issued as Risø reports. This is the Main Report Risø-R-1256, summing up the activities and findings of the project and outlining an Implementation Strategy for Isolated Systems with Wind Power, applicable for international organisations such as donor agencies and development banks.

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