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Registration is a once-off requirement!

- Registration begins at 16:00 (desk closes at 19:00) on 22 Sept. 2009
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Small Wind Turbine Power Curve Comparison

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***Abstract*-- This paper focus is on the small wind turbines resource potential estimation. Assessment is done for seven selected small wind turbines and one measured set of wind speed data with the micropower optimization modeling tool HOMER. Goal was to investigate how estimated energy production and economical parameters are sensitive to the selection of small wind turbine. Selected turbines have similar rated power, but different blades diameter and aerodynamic characteristics. Energy production was quantified for one year with hourly resolution. Results from all different wind turbines were compared on the power production base, and on the economical base. Two sensitivity cases related to the wind speed and installation lifetime were also simulated. Results are showing significant importance of the small wind turbine selection for the both total energy production and economical feasibility. This makes small wind turbine characteristics such as reliability and power curves testing very important.**

***Index Terms*-- wind energy, wind power generation, power generation economics**

I. INTRODUCTION

IT is ever more interesting to assess utilization of small distributed renewable electrical energy sources. This was usually option to have self-sufficient independent electrical energy source for some remote off-grid load but with various regulatory incentives it is also potentially attractive for grid connected applications. Value of these sources might be beyond ecological and sustainable factors, primarily in increasing supply security and, in some cases, even in economical reasons.

Because there is a large number of factors involved in the thorough assessment of the distributed renewable electrical energy potential, this paper is discussing only some selected issues. Focus is on the small wind turbines resource potential estimation. Power generation and economy analysis is done for the seven selected small wind turbines and one measured set of data for the wind speed values. The assessment aimed to investigate how estimated energy production and economical parameters are sensitive on the selection of particular small wind turbine. Selected turbines have similar rated power, but different rotor diameter and aerodynamic characteristics.

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II. METHOD

Technical and economical evaluation of renewable energy utilization can be performed in the number of different ways with various levels of details. HOMER tool is used for numerous applications ([1], [2], and [3]). With hourly resolution HOMER seems to have accomplished compromise between need for complex simulation and limitation of available precise data about model (i.e., precise specification and resources estimate).

Simulation model was created for small wind turbine grid connected configuration which includes wind turbine, and converter. Results from this base model were compared for seven different wind turbines.

Wind resources (Fig. 1) were assessed in average hourly values for a one year period. This is considered sufficient in respect to the all other modeling uncertainties.

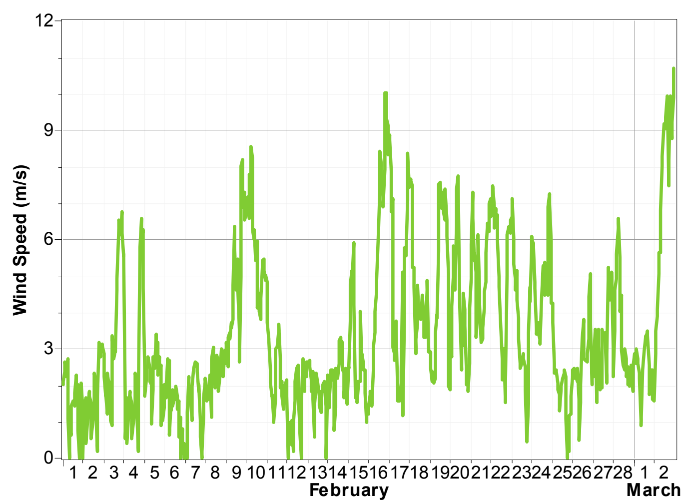

Fig. 1. Wind speed measured data – one month for illustration

Seven different small wind turbines have been modeled with two different model assumptions: A and B. This was done in order to test sensitivities of results on some important model parameters.

Comparison between different wind turbines was made according to the total electrical energy production and cost of energy.

III. Model and Data

Basic model is defined and then analysis is performed with different wind turbines for A and B model cases. Base model is varied with seven different small wind turbines power curves, and two different sets of assumptions. Differences between the A and B models are in system lifetime, tower height and average wind speed (keeping the same wind speed time series).

A. Model description

Base model is designed as in Fig. 2. Table I further describes certain most important data regarding the base system assumptions with, both A and B related model variations.

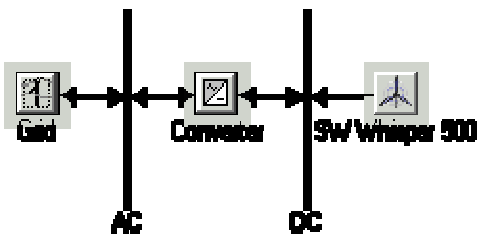

Fig. 2. Small wind turbine grid connected system

TABLE I
Basic Data for the Analyzed System

Parameter	Assumed values for model A/B
Electric nominal power (kW)	3
Capital Cost (US$)*	6500
Replacement Cost (US$)*	2000
O&M cost (US$)	200-250
Annual real interest rate	4 %
System life time (yr)	20 / 25
Tower height (m)	15 / 25
Average wind speed (m/s)	5 / 4

* Price is for the system without wind turbine: converter, tower and all required for the system installation.

Further details about particular components of system were left out of the paper. Only wind turbine is presented in more details because that is the major focus of the paper.

Figures 3 and 4 are showing significant power curve differences for selected small wind turbines. Figure 3 presents power curves as a function of the electrical power and wind speed. One would conclude that these seven small wind turbines are much more similar than it is fact. The first illustration of their difference is a normalized power curve shown in the Figure 4 where electrical power normalized to the rotor area is plotted, illustrating differences among the analyzed turbines, which will also be illustrated by the simulations results.
Wind turbines on both figures are referenced with sequential numbers related to the Table II. In Fig. 4, number 0 is given to the ideal wind turbine with 4 m rotor diameter and power curve following the Betz low, with efficiency equalling 0,593.

Table II shows numerical values for all small wind turbines related to the rotor diameter, normalized electrical power and assumed cost for the simulations. This cost is very complicated to estimate because not all wind turbines are available at the same market, and because in the life time of the project other factors have to be considered. Life cycle costs could be considered in different ways. For these simulations a simplified judgment about reliability and artificial price which will represent it has been selected, based on wind turbines warranty and general robustness (i.e., rotor size relative to nominal power, and other data). This is a very important question, and for this exercise we have managed that with the mentioned simplification. However, this issue requires further investigation, the most important being actual wind turbines testing.

TABLE II
Selected Small Wind Turbines Characteristics

WT#	Rotor diameter (m)	Normalized electrical power (kW/m^2)	Assumed cost (US$)
1	4,5	0,19	14,2
2	2,9	0,45	9,1
3	3,7	0,28	11,6
4	4,5	0,19	14,2
5	4,0	0,24	12,6
6	4,2	0,22	13.2
7	3,6	0,29	11.3

B. Wind resources data

Wind speed data were obtained from meteorological measurements. Input data are hourly average values, calculated from 10 minutes averages. This was done in order to have comparative results with some other assessments which have used the same data already, [8]. Figure 1 is presenting measured data for one month period as illustration. Probability distribution function which fits the data is Weibull with following parameters: k=1,42, c=4,36 m/s for simulation case A with 4 m/s average wind speed, and c=5,45 m/s for simulation case B with 5 m/s average speed.

Two average wind speed cases were used in the assessment by using HOMER capability to scale base input data for resources. In this way location wind characteristics are kept, and potential for advantage for micro location with better average wind speed is evaluated. This was done in order to estimate the influence of average wind speed value on the general results conclusions.

C. Modeling

Modeling was conducted with the micropower optimization modeling tool HOMER. Base model was created with simple on-grid configuration which includes wind turbine and converter. Economical consideration was based on the assumption that entire energy production was fed to the power grid. HOMER capability to handle sensitivity simulations for range of modeling parameters is used to analyze two different cases. Besides average wind difference two additional parameters were varied: tower height and system life time. In simulation case A. a 15 m tower height and 20 years project life time has been assumed. In simulation case B, a 25 m tower height and 25 years project life time has been assumed. This sensitivity cases were designed to estimate the effects of a higher average wind speed with a lower tower and life time compared to a lower average wind speed with a higher tower and longer life time.

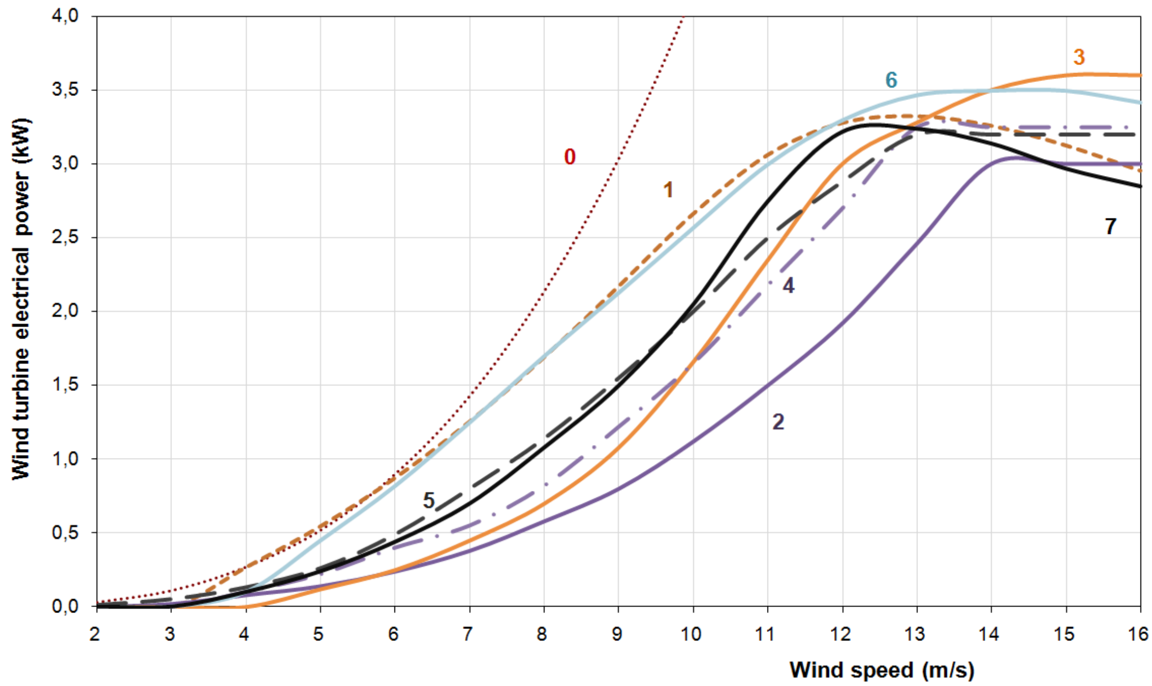

Fig. 3. Small wind turbine power curve comparison: seven selected wind turbines with 3 kW rated power, and "ideal" wind turbine

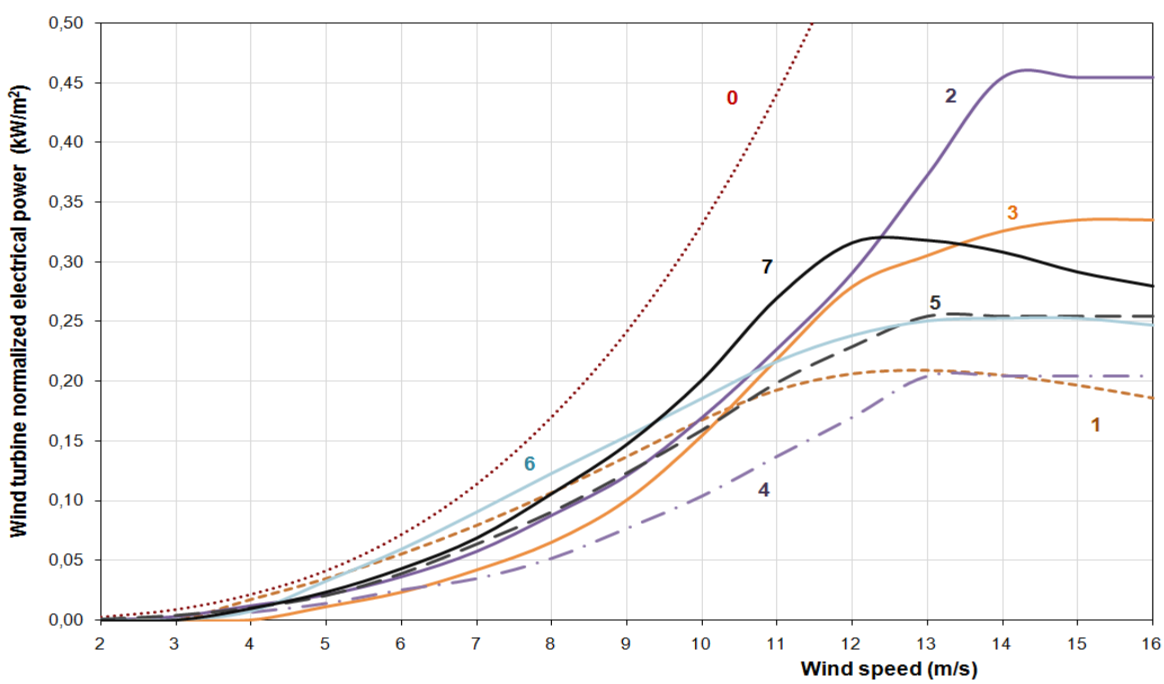

Fig. 4. Small wind turbine normalized power curve comparison: seven selected wind turbines with 3 kW rated power, and "ideal" wind turbine

IV. RESULTS

Numerous results are generated from the simulation which considers technical and economical variability. It is out of the scope of this paper to present all results in details. Here we present the most important results for conclusion, and further work directions. Other results are just presented for the illustration purposes.

Significant difference in the normalized power curve is visible both at the continuous power change, and total electrical energy production.

Figure 5, and 6 are illustrating power variation for one month for the WT 1, and WT 2 for the Case A. These are the two extremes, because WT 1 is the best, and WT 2 is the worst regarding total yearly electricity production. The difference is more than 200 %.

Table III presents the total results for all wind turbines related to the yearly generated electricity, a cost of energy (COE) based on the produced energy, cost of the system, and available price. It is assumed that feed-in tariff is in place with 100% power purchase by utility. Sellback rate is assumed based on the current rate in Croatia (0,135 US$/kWh[1]).

TABLE III
SIMULATIONS RESULTS – GENERATED ENERGY AND COE

WT#	Yearly generated energy (MWh)		Cost of energy (US$/kWh)	
	Simulation Case A	Simulation Case B	Simulation Case A	Simulation Case B
1	**7,22**	**5,46**	**0,158**	**0,234**
2	**3,07**	**2,23**	0,356	0,515
3	4,26	2,81	0,321	0,516
4	4,23	3,09	**0,370**	**0,526**
5	5,03	3,81	0,257	0,359
6	6,62	4,99	0,177	0,258
7	4,88	3,61	0,219	0,323

A. Cost of energy

Economical calculation is not showing positive results for any of the analysed WT. This clearly shows that better wind condition and more incentives are needed. Economical evaluation for this exercise was mainly focused to show relative difference for various small WT at the same location with the same wind speed conditions. Table III shows that difference in the cost of energy is more than twice between the best (0,158 US$/kWh for WT 1) and the worst (0,370 US$/kWh for WT 4) wind turbine. This is for the Case A simulation, and a similar ratio can be observed for the Case B simulation. Results for these two cases are showing that average wind speed has more important influence to the COE than system lifetime and tower height. This increase varies, depending on a wind turbine, between 40 and 60 %.

Certainly economical results could be obtained with more details and smaller uncertainty. However, difference between various small wind turbines seems very significant.

B. Total energy generation

Table III shows the difference between seven wind turbines for the amount of yearly produced electrical energy. This is at the same scale as for the COE. The worst turbine (WT 2) can produce 3,07 MWh, comparing to the best turbine (WT 1) which produces more than double - 7,22 MWh. Interestingly enough, the worst wind turbine for the COE is WT 2, while the worst turbine regarding the energy generation is WT 4.

This is for the Case A simulation, and a similar ratio is visible for the Case B simulation. Results for these two cases are showing that average wind speed has a very significant influence to the total yearly energy production. Difference of 25% higher wind speed, even with 40% lower tower (Case A - 5 m/s and 15 m; Case B - 4 m/s and 25 m) results in more than 30% energy production increase. This increase varies, depending on wind turbine, between 30 and 50 %. Importance of wind power curve is certainly emphasized with these significant differences.

Further investigation with tested power curves would be certainly very important.

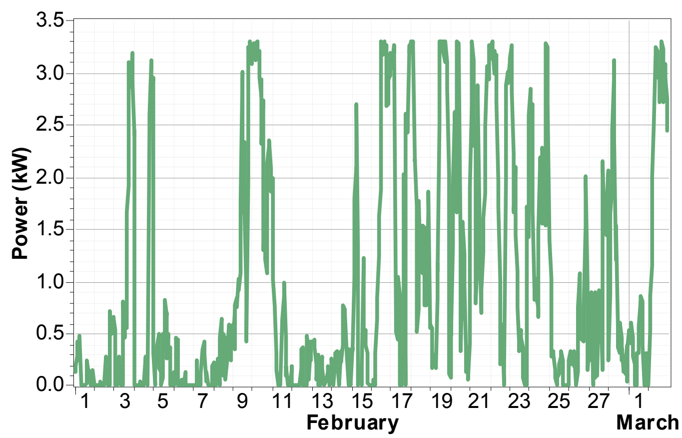

Fig. 5. Wind turbine power – one month for WT 1 Case A

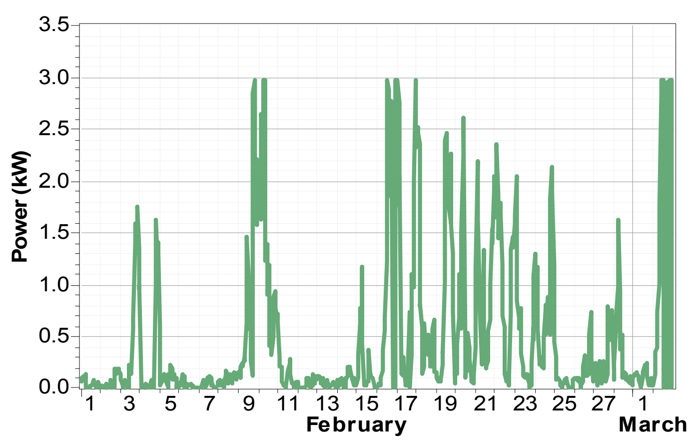

Fig. 6. Wind turbine power – one month for WT 2 Case A

C. Other results

A grid connected system of small rated power, as modeled

[1] This is in Croatian currency Kuna 0,64 kn/kWh, and it is based on the conversion rate between US$ and Croatian kn: 0,211 US$/kn.

here, can deliver all power to the grid. In case of limitations in the grid and a higher power of intermittent energy source, variations are very important. This is especially the case with off-grid system.

To illustrate some results which are reflecting this power generation variations, two additional results are briefly presented.

Figure 7 illustrates power duration curve. This illustrates for how many hours, during the year one can expect certain power production.

Figure 8 illustrates ranges of power production uncertainty at the monthly and daily level. Variations are significant, both between months and during the days.

This only illustrates numerically well known fact that wind power is a significantly intermittent energy source.

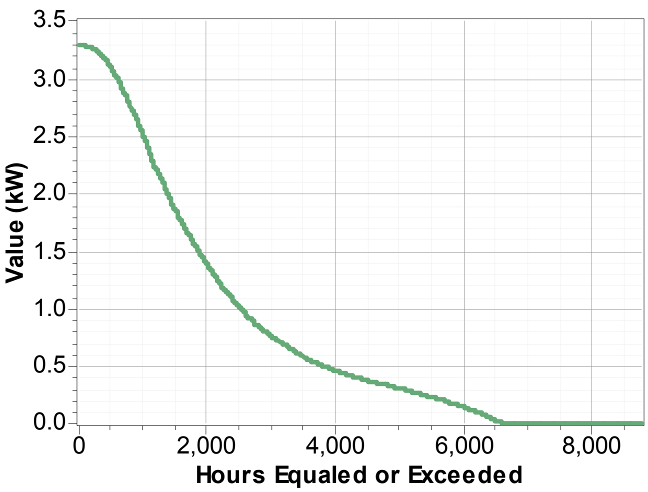

Fig. 7. Wind turbine 1 power duration curve, Case A

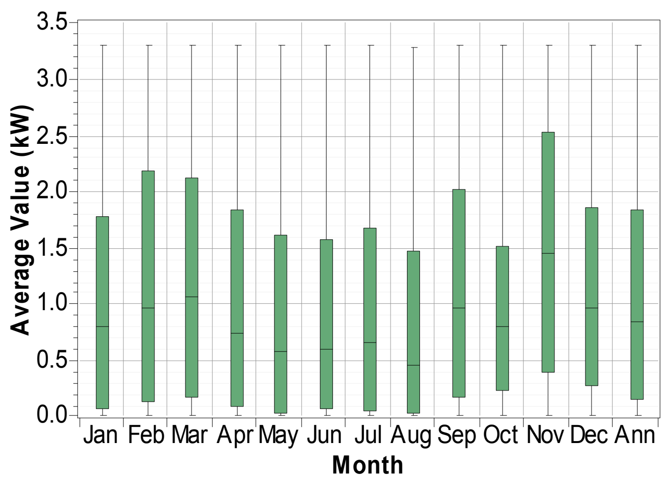

Fig. 8. Wind turbine 1 power mean, daily max, high, low, and min, Case A

V. CONCLUSION

Energy production was quantified for one year with hourly resolution because wind speed data used were hourly averages. Results from the analyzed wind turbines were compared, based on the power production and based on the economical parameters.. Comparisons of results from these seven models are showing the best selection of the small wind turbine for the particular wind location. A number of sensitivity analyses related to the scaled average wind speed and assumptions about project lifetime and replacement requirements are performed in order to investigate influence on the final conclusions.

Results are showing significant importance of the small wind turbine selection for the both total energy production and economical feasibility. Almost the same power rating with very different power curves is reflected in more than 100% difference between the worst and the best generator regarding both factors: power generation and cost of energy production.

However, it is important to keep in mind that these power curves are provided by respected manufacturers. A more detailed economic evaluation with independently tested power curves would be certainly interesting to test these differences.

VI. REFERENCES

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VII. Biographies

Zdenko Šimić holds PhD degree in EE from University of Zagreb, Faculty of Electrical Engineering and Computing, where he is an assistant professor. His work experience includes risk and reliability assessment for the nuclear and power systems applications, and renewable energy resource assessment. His research interests are on-line risk monitoring, optimization and multiple objective decisions related to the risk, reliability, operation and maintenance of complex technical systems, energy resources. He is the current president of the Croatian IEEE Power Engineering Society Chapter, and member of the IEEE Reliability Society and Croatian National Committee of CIGRE.

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Damir Šljivac holds PhD degree in EE from the Faculty of Electrical Engineering and Computing, University of Zagreb, Croatia. Currently he is an assistant professor at the Power System Department and vice-dean for education at Faculty of Electrical Engineering, J.J. Strosmayer University of Osijek, Croatia. He has participated in a number of expert studies and projects in the field of power system engineering. His research interests are in power system reliability, power system planning and electricity market. He is a member of IEEE Power Engineering Society, IEEE Reliability Society and Croatian National Committee of CIGRE.