Reliability Analysis of Wind Turbines Considering Constraints and Legislation

Nacef Tazi, Eric Châtelet, and Youcef Bouzidi

***Abstract*—Onshore wind turbine are subject to more and more regulations and constraints. To reach the optimal installed capacity with maximum reliability and profits, numbers of algorithms have been developed for wind farm power plants. However, according to literature, no exact methods have yet been tested on wind farms using real data and wind based conditions. In this article we develop the recent work that has been done until far on wind turbine power and reliability analysis, and apply an algorithm to find the best topology. The proposed resolution technique is based on finding the best topology of the system under the constraints of Performance (availability), Costs and the Global Warming Potential of the system. A case study is done using data and constraints similar to those collected from wind farm constructors, managers and maintainers. Multi-State Systems (MSS), Universal generating function (UGF), wind and Load charge functions are applied.**

***Index Terms*—Wind turbine, wind function, availability, MSS, UGF, power optimization, wind energy policy, optimization algorithm.**

I. Introduction

In the second semester of 2015, and for the first time in the history of renewable energy, southern countries have invested more in renewable energies than northern ones [1]. This increasing interest is directed more towards wind turbines than other renewable generators. Wind generators occupy a significant position not only because of unlimited wind source [2], but also for their lower costs and higher share of power production [3], [4]. However, the electricity produced from wind farms is variable and uncertain, it can in fact vary due to wind speed conditions or to unpredicted failures of wind turbine components. Accurate prediction of both these uncertainties helps decision makers in the management of the budget allocated for construction, operation and maintenance. Thus, it is necessary to assess these constraints for a wise investment [5], [6]. Consequently, the main question for investors is what is the capacity of future wind farms and how to reduce the risks of waste investments due to low availability or high costs in equipment not suitable for the wind farm location. This kind of problem is a topology optimization problem and was studied intensively this last decade by researches. In fact, many constraints should be assessed and reduced for a good investments; [7]-[9] are good research examples for wind farm layout / topology optimization under wake effects constraints. Others [10]-[12] proposed a topology optimization under energy cost constraint. Other studies used software such NEPLAN to assess the reliability/performance of wind farms under certain topologies [13]-[15], but only few research articles deal with wind farm topology optimization under both cost and performance constraints [16], [17]. What make more complicated to deal with these constraints is the multi-state system (MSS) that represent the wind farm. Even if the MSS reliability measures were intensively studied in [18]-[20], only few articles were found that deal with this reliability optimization including environment effects [21]. Thus, studying the topology optimization of wind farm under constraints of wind, performance and costs turn to be a good research gap. Nowadays, investors not only face these 3 constraints, but also regulation that impact wind farm investments. Although the costs of wind turbines stood still and shows a mean rate of 1 k€/kW, additional costs for the construction of the wind farms and their components, connection to the grid and dismantling costs make the decision makers look for efficient topology installation considering minimum costs and maximum benefits. We have also taken the time to look at French environmental regulation for wind farms, also called "ICPE, installations classées pour la protection de l'environnement", (facilities classified in view environmental protection). This classification, [22], of wind turbines concerns more the provision of financial guarantees in case of operator failure, cessation of operation, decommissioning or dismantling to completely restore the previous state of the site. This last regulation is more concerned with the investment costs of wind farms than the environmental aspect of this kind of installation.

To sum up, decision makers are faced with more and more constraints in order to manage the investment budgets of future wind farms. Further research is also conducted into operation and maintenance to develop the budget of this part of wind farm's life cycle efficiently, this part will not be treated in the present work. The aim of this work is to continue the work that have been done in this field to fill the research gap and using real wind, performance and costs data for best topology finding. This aim was proposed as a future works by researchers [16], [17].

In the last article [16], the main aim was to maximize multi-state system (MSS) reliability or minimize the investment cost of the system's topology. A UGF technique has been adapted to select and evaluate best configurations matching cost and performance level constraints. Our aim is to improve this methodology and the mathematical

Manuscript received October 4, 2016; revised February 24, 2017. This work is supported by the French Regional Council of Champagne Ardenne and the FEDER EU.

Nacef Tazi and Eric Châtelet are with the ICD-STMR, (UMR CNRS), University of Technology of Troyes, Troyes, France (e-mail: Nacef.tazi@utt.fr; naceftazi@gmail.com).

Youcef Bouzidi is with the ICD-CREIDD, (UMR CNRS), University of Technology of Troyes, Troyes, France.

doi: 10.18178/jocet.2017.5.6.420

formulation of the problem by adding new constraints that fit current wind farms. To meet that purpose, a wind speed model and power output model have been developed and transformed into a UGF model. The UGF reliability model of wind turbines has also been improved and coupled with a UGF wind model. Load model for wind energy demand has been presented and transformed. Thus, a better formulation of reliability has been developed, in this field we tried to fit the mathematical and probabilistic formulations with the industrial definitions [23]. We have also fitted the costs model with those last definitions [24]. GWP constraints are also added. Finally, an algorithm has been developed and an illustrative example is given.

This paper is organized as follows. In the next sections, we develop all the UGF models for our multi-state system, we also present the environmental and cost model for our system. A review of the French wind farm policymaking processes is proposed. Then, in Section III, we present the optimization technique used for best topology finding for future wind farms. An illustrative example is also given, and compared with last studies. Finally, we present our conclusions and directions for future research in Section IV.

II. Data & Methods

A. Universal Generating Function (UGF)

The UGF technique is widely used for the performance and reliability evaluation of a MSS [25], [26]. Different UGFs have been presented in this paper for wind speed & power output, availability of MSS components and load. An MSS UGF model is then combined in series or in parallel depending on the system, to generate the MSS final UGF model.

B. Wind Energy

Wind speed has great uncertainty due to the random nature of the weather. The power output of wind turbines is not only determined by the mechanical reliability and state of components, but is also subject to wind speed states. Different wind speed models have been found in the literature [27]-[29]. We also had the opportunity to discuss these models with wind turbine constructors and wind farm managers [23]. As a result, the wind speed output can be defined as (see Fig. 1):

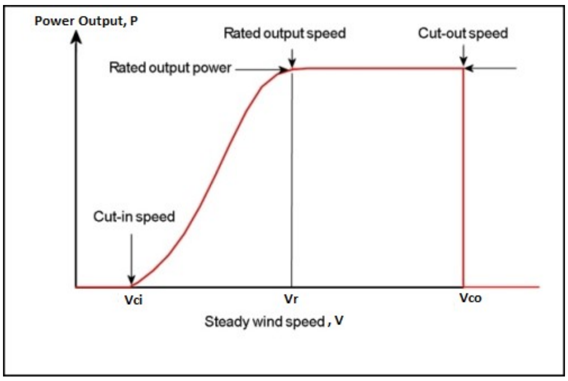

Fig. 1. Typical output of a WT.

The UGF model from wind turbine power output is defined as (1):

$$U_{il}^{w}(z) = \sum_{J_{iw}=1}^{Kiw} p_{j_{iw}}^{w} . z^{wp_{l,ji_w}} \tag{1}$$

where $p_{j_{iw}}^{w}$ and wp_{l,ji_w} are respectively the probability and power output of a single wind turbine '*l*' for wind speed state j_{iw} at bus '*i*', K_{iw} is the number of wind speed states at bus '*i*'.

C. UGF Model for Wind Turbine Mechanical States

Only two states were considered for wind turbine mechanical reliability. If we consider that the power output of a wind turbine in a failure state is "0" and $wp_{l_{jiw}}$ when it is in an operating state, then the UGF model for a wind turbine "*l*" at a defined bus "*i*" is (2):

$$U_{il}^{r}(z) = A_{il}^{r} . z^{wp_{l,jiw}} + (1 - A_{il}^{r}) . z^{0} \tag{2}$$

where A_{il}^{r} is the availability of wind turbine "*l*" at a defined bus "i".

D. UGF Model for MSS Models of a Wind Farm

Considering a UGF reliability models for wind turbine and wind speed states, one can obtain the sum of the power output of each wind turbine at different states. The UGF model is used for series - parallel systems to determine the final UGF model of all the wind turbines in the farm. For instance, by combining different wind turbines in a same bus with different wind speed states, we can obtain (3):

$$U_{i}^{w'}(z) = \sum_{J_{ig}=1}^{Kig} p_{j_{ig}}^{g} . z^{wp_{jig}} \tag{3}$$

where $p_{j_{ig}}^{g}$ and wp_{jig} are the probability and the power output of the wind farm for the state j_{ig} . The wind farm has K_{ig} states, which are $K_{ig} = K_{iw} \times K_{ir}$.

E. UGF for Load Model

Different load models have been found in literature, load or demand in a wind farm system also changes with time and is then uncertain [30], [31]. The UGF of multi-state load model at bus 'i' can be written (4):

$$U_{i}^{L}(z) = \sum_{i=0}^{M} p_{i}^{W_T} . z^{W_{T_i}} \tag{4}$$

where $p_{i}^{W_T}$ and $z^{W_{Ti}}$ are respectively the probability and load level at bus 'i'. The demand is divided into 'M' load levels or kinds of state during time.

In this section we have also tried to understand how the wind farm communicates with the grid and the buyer for the load demand and the power injected into the grid. In France, we found that 'RTE' (the French electricity grid company) sends daily wind speed information to wind farm managers, who calculate the rated power output that they can inject into the grid and send back the supposed satisfied demand related to the wind speed model and grid availability [32]. One can also note that an electricity provision contract is signed between the wind farm and RTE to buy all the electricity generated by the wind turbines.

F. Availability / Performance Model

So that our model reflects the reality on the ground, we approached many wind turbine manufacturers and managers, in order to assess the contractual availability and plausible penalties that could be generated by non-production [32]. The availability can be time-based availability (traditional one) or Energy-based availability. The first one is easy and simple to calculate and only depends on time. The second, depending on Predictable and production energy is new and not easy to calculate. In France, the availability definition varies from one wind energy actor to another. The manufacturer, for instance, guarantees a certain availability in function of efficiency or energy production. This availability can be calculated in relation to the produced energy or the number of functional hours. In general a graph for rated output power related to different wind speed states is given for every wind turbine technology. The availability is defined as reaching the power output for a wind speed state under load states constraints:

The UGF of the wind farm is then (5):

$$U(z) = \sum_{j_i=1}^{M} \sum_{j_{ig}=1}^{K_{ig}} p_{j_{ig}}^{g_{WP}} . p_{j_i}^{W_T} . z^{(WPj_{ig} - W_{Ti})} \tag{5}$$

This will be the basis for our final objective function of the developed algorithm, i.e. performance of a fixed topology under wind, reliability and load state is calculated using equation (5).

G. Penalties Due to Unsupplied Demand

The French wind farm owner signs a contract with both the buyer (EDF) and the constructor in order to maintain a contractual level of reliability and availability of wind turbines. Guarantees are applied on both sides (manager/constructor & manager/electricity buyer) [32].

- Manager / constructor penalties:

There is an availability target warranty that the constructor should furnish (in case of warranty contract) to enable the manager to supply the demand. We had the opportunity to discuss this kind of warranty with different wind farm managers and wind turbine constructors. In general, a bonus/malus system is set up: Penalties will be expected if the availability of the wind farm is x% less than the targeted availability. The constructor and the manager agree together on the x% rate between the targeted and the real availability.

- Manager / electricity buyer guarantees:

RTE & EDF are considered as the unique buyer of wind farm electricity in France. They generally agree on different contract clauses with the manager which also include the obligation to not supply electricity during grid maintenance downtime.

This section can be resumed in Fig. 2.

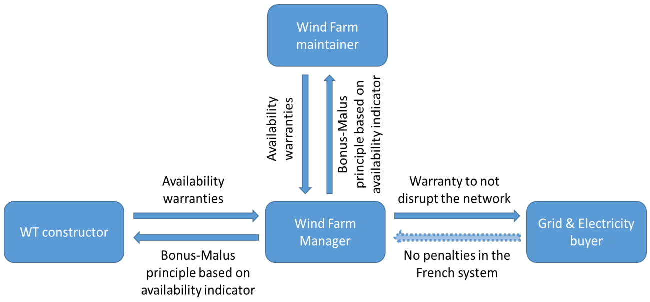

Fig. 2. Relationship between different actors in the wind industry.

The next table (see Table I) shows a European comparison, where long-term benefit contracts (FIT) and penalties for unbalancing the grid are applied:

TABLE I: WIND ENERGY FIT AND PENALTIES EXISTENCE FOR SOME EUROPEAN COUNTRIES [24]

Country	FIT	Penalties for imbalances
Austria	Yes	No
Belgium	No	Yes
Denmark	Yes	Yes
Finland	Yes	No
France	Yes	No
Germany	Yes	No
Greece	Yes	No
Ireland	Yes	No
Italy	Yes	No
Portugal	Yes	Yes
Spain	Yes	Yes
Sweden	No	Yes
Nederland	Yes	Yes
UK	No	Yes

One can note here that the countries which do not provide FIT for wind energy provide a quota system based on a certificate trading system instead [33].

H. Modeling the Cost of MSS

For our problem formulation, we will consider the total cost of each system topology, defined by the vectors of component's versions of wind farm.

Suppose that there are different types (versions) of wind turbines in the market $\{a_1,\ldots,a_{nw}\}$. To choose a specific type $a \in \{a_1,\ldots,a_{nw}\}$ of wind turbine, we use the operator δ_{il}^a described below: If the wind turbine '*l*' of the bus '*i*' is chosen $(a = a_{il})$, then $\delta_{il}^a = 1$, and $\delta_{il}^a = 0$ if not.

We have then (6):

$$\delta_{il}^a = \begin{cases} 1; if\ a = a_{il} \\ 0; if\ a \neq a_{il} \end{cases} \tag{6}$$

The cost of 'n' wind turbines in a wind farm is calculated as (7):

$$C_n = \sum_{i=1}^{n_i} \sum_{l=1}^{n_l} \delta_{il}^a C_{il} \tag{7}$$

For example, see Table II for these costs in France (2013):

TABLE II: AVERAGE COSTS FOR A WIND FARM PROJECT IN FRANCE [34]

Cost	k€/MW
C layout	147
C grid	75
C development	71

One can note that the dismantling costs are not included in this last array, the dismantling costs are subjects to "ICPE regulations" [35]. These regulations come into play in the dismantling and site restoration phase: dismantling the wind generators; excavation of the foundations; backfilling with similar earth, as well as the removal of areas affected by the crane work and access roads. Note also that the waste resulting from the demolition and dismantling must be recycled or disposed of by an approved establishment [35]. To sum up, the lands used in wind farms must be returned to their original state, before the erection of wind turbines. The costs of dismantling can be up to 50.000 €/MW [23], [35]. This last reform also obliges the wind farm managers to block this amount from the beginning of operations. Finally, after discussing this section with our industrial partners [23], we arrived at a figure of 1,343 M€/MW for an onshore wind farm (foundations, transport, wind turbine cost & set up, development and grid). This model cost will be used instead in the section III of this paper.

I. Modeling the Environmental Impacts of the System

One of the main indicators / indexes to assess the environmental impacts of wind farms is the Global warming potential index (GWP index). In order to simplify the algorithm inputs, only the GWP impacts of each wind turbine's farm version will be used, since the major environmental impacts of the wind farm are generated by the wind turbines [36]. According to literature, this indicator has a variation interval from 7 to 123 g.CO_2/kWh, this large variation was explained in previous references by [37]-[39]:

- Bigger turbine's power curve that reduce the GWP index;
- Weather conditions (average wind speed and frequency distribution);
- LCA assumptions, such as system boundaries, referring environmental database and expected lifetime also influence the results.

A recent study [40] represented this variation in Fig. 3, where we can see the GWP index of 2 to 3 MW turbines does not exceed 11 g.CO_2/kWh.

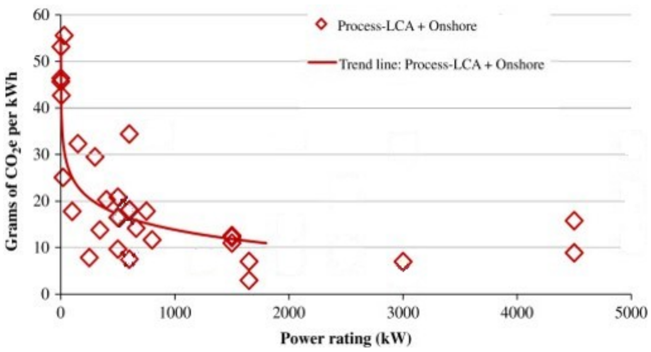

Fig. 3. Total GWP as a function of wind turbine power capacity.

From the other hand, the major installed wind turbine sizes in France and in the Champagne-Ardenne region particularly vary from 2 to 3 MW. Thus, we choose this size interval for our study to reflect the field data and we can see Table III for GWP values corresponding to major wind turbines available in the region. These values are data constructor values or data literature values if industrial data was not available.

We would like to point out that our main objective is to add the environmental impacts as a wind farm investment constraint. As this way, the decider can not only rely on economic and performance constraints, but also take account of the environment changes. Thus, more research should be made to take into account the uncertainties of this impact.

III. OPTIMIZATION TECHNIQUE

The problem formulated in this paper is a complicated combinatorial optimization problem. The constraints of the system are subject to uncertainty. The UGF model of the system should take into account not only the components' states, but also the wind and the load states. From all the optimization algorithms and according to the available data in the wind industry, we developed a simple algorithm to calculate the UGF of final availability of MSS matched with wind information. We then completed it with minimal topology generation to reach targeted performance under constraints of costs, and calculating the GWP emissions of results.

The proposed model is based on an enumerative algorithm. This will also be an opportunity for us to compare exact founded solutions with those proposed using metaheuristics [16], [17]. The proposed algorithm will inverse the process given in equation (5) that calculate the performance of a wind farm and gives the final objective function that is the best topology that allow us to have the best result from (5) under the constraints of wind and reliability (3), load (4) and costs (7). The optimization problem can be defined as (8):

$$\begin{cases} \arg\min\limits_{a_{il}} \; C_n(a_{il}) \\ A(a_{il}) \geq A_0 \end{cases} \tag{8}$$

where (a_{il}) are the component versions of a sub-system, with 'i' is the bus number and 'l' the turbine number.

$C_n(a_{il})$ is the objective function and the reliability constraint is characterized by a minimum value A_0. At this stage, minimal capacity of wind farm is not a constraint to respect in investment. Actually, minimal performance of the wind farm is defined by other criteria such as layout data (location, wind average, wake effect,…), technological data (performance of wind turbines) and local policies (availability contracts, production policy,…), reader can refer to sections (E.), (F.) and (G.) for more information about wind farm constraints and legislation.

A. Problem Representation

This study focuses on the application of an algorithm to find the best topology under certain constraints. To reflect the real wind farm configuration, one identical version is picked for the best topology. In fact, constructors and French wind farm managers are more and more concerned with optimizing the costs in case of new investments or repowering. The MSS will be combined with the wind states, and then again with load/charge states.

The enumerative algorithm is constructed as below:

1- Insert / add 1 MSS pack ;
2- MSS UGF reliability calculation under wind load;
3- Check if the reliability "R" is higher than the R_{obj}. If not, return to step 1;
4- MSS cost & GWP calculation;
5- Calculate cost "C" and compare it to "C_{min}" saved in best topologies. If cost is higher, return to step 1;
6- Save system configuration;
7- Check if the termination criterion was reached. If not, return to step1;

B. Illustrative Example

A wind farm system suppling energy is designed with five basic subsystems: wind turbines (sub 1), transformers (sub 2), electrical components (sub3) and other wind farm components such as wind farm lines and bus transformers (sub 4&5). Each sub-system of the MSS has different versions available on the market. Each version is characterized by a Capacity of production, Availability, Cost and GWP. The next figure (figure 4) shows a possible configuration of a wind turbine, see Table III and see Table IV resume the different characteristics of each sub-system's version, it must be noted here that the data proposed in the tables depends on the site, especially for wind turbines. Versions used in our illustrative example are listed below (alphabetic order):

ACCIONA, ENERCON, GAMESA, GE ENERGY, NORDEX, SIEMENS, SUZION & VESTAS.

Different levels of wind speed are modeled partially in Table V. The power system topology should be designed from available components and be able to meet the demand requirements under wind speed constraints at all load levels.

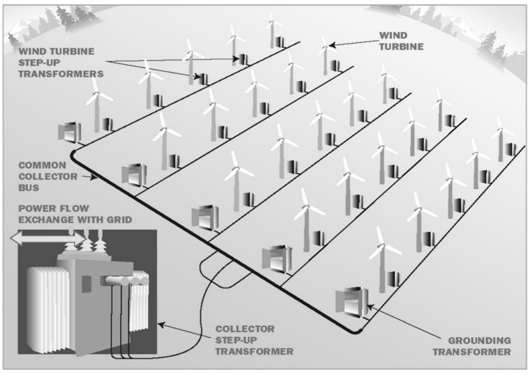

Fig. 4. Illustrative example.

For our illustrative example we chose a threshold reliability/performance for the MSS (I: 0.9300; II: 0.9985), and determined the minimal topology of the system.

Results (See Table VI) are shown for a single fixed reliability threshold. It shows the minimal topology under constraints. Each topology is defined by its component's versions, topology cost and GWP emissions. These results were found after introducing all data in the algorithm. For instance, in first results showed, a topology of 2 wind turbine of the 1st version can reach the reliability target of 0.93. Other results that fill this constraint are saved in the algorithm, but this topology cost is the lowest. The GWP emissions can also be a constraint in the decision process if wind farm regulations changes. It's the same for the last results, where the best topology under chosen constraints picks 3 wind turbines of the 6th version.

C. Comparative Study

We would like to point out that we tried to improve the proposed algorithm and reflect the reality by proposing our developed algorithm to different industrial partners. It can be seen that our method is more efficient and closer to reality than previous ones [16], [17]. Firstly, because the UGF models are more developed and a wind model is also introduced. Secondly, we tried to reflect the reality by interviewing several constructors, wind farm managers and maintainers and discussing our model with them. Finally, our algorithms tested all the possible combinations in order to determine the best topology for our system. Metaheuristics that are used in both the articles compared may find an approximation of the local or global minimum topology, but rarely the exact solution. For information, our UGF model has been tested and compared with ones already conducted [41].

IV. Conclusion

The best topology of a wind farm is directly influenced by internal and external constraints. The objective of this paper was to propose a first step investigation for decision makers making topology investments under wind, cost and performance constraints and considering GWP emissions. The main contribution and conclusion of the present study are summarized as follows:

- This study formulated an availability of a MSS based on internal and external constraints. Wind speed states have thus been applied to determine the availability / performance of the wind farm. Best topology is extracted from this last function;
- UGF models have been applied for the MSS;
- A review of the French wind energy policymaking was resumed.
- An enumerative algorithm was used to find the best topology of the MSS;
- A numerical case study was conducted for the best topology of future wind farms considering wind speed, availability, costs and GWP constraints;
- A comparative study addressed the advantages of the proposed algorithm compared to referred approaches. Another comparison has been made to assess the UGF model.

Our problem did not consider maintenance strategy nor turbine placement (considering wake effects), which require further research. Besides, our next step will be the extension of this model considering dependence between MSS components. More research should also be made in this topic taking into account the uncertainties of the constraints.

APPENDIX

TABLE III: GWP OF DIFFERENT VERSIONS OF WTS

WT used in wind farm	GWP (g CO2)
1	9.7
2	10.9
3	8.3
4	8.9
5	9.7
6	5
7	4
8	4.5
9	9.5

TABLE IV: CHARACTERISTICS OF THE SYSTEM ELEMENTS AVAILABLE IN THE MARKET

Sub no.	Dev no.	R	Per Ξ (MW)
1. Wind turbine	1	0.97	2
	2	0.98	2.5
	3	0.96	2
	4	0.971	2
	5	0.95	2.1
	6	0.975	2.3
	7	0.978	3.6
	8	0.98	3
	9	0.98	2.5
2. Transformers	1	0.86	2.5
	2	0.85	2.5
	3	0.84	2.5
	4	0.8	2.5
	5	0.75	2.5
3. Electrical components	1	0.739	2.5
	2	0.712	2.5
	3	0.685	2.5
	4	0.658	2.5
4. HV/MV transformers	1	0.977	2
	2	0.978	2.5
	3	0.978	2.1
	4	0.983	2
	5	0.981	2.1
	6	0.971	2
	7	0.983	2.5
	8	0.982	2.1
	9	0.977	2
5. MT lines	1	0.984	2
	2	0.983	2
	3	0.987	2
	4	0.981	2

TABLE V: PARAMETERS OF THE WIND SPEED & POWER OUTPUTS (SAMPLE OVERVIEW)

Time (hour)	U80 (m/s)	Load (MW)
00:00	4.25636	0.10
00:10	4,54607	0,10
00:20	4,48597	0,10
03:00	4,41144	0,10
03:10	5,36459	0,20
03:20	5,63669	0,20
03:30	5,46161	0,20
03:40	5,59143	0,20
05:50	9,50009	1,82
06:00	9,75567	1,91
06:10	9,91782	1,97
06:40	9,48084	1,81
09:30	9,64531	1,87
09:40	9,87848	1,96
09:50	10,1965	2,07
10:00	10,1176	2,04
10:10	9,81591	1,93
10:20	9,96362	1,99
10:30	10,1522	2,05
10:40	10,1713	2,06
10:50	9,69998	1,89
11:00	9,40981	1,79
11:10	9,37379	1,77
11:20	9,42546	1,79
11:30	9,81398	1,93
11:40	9,64822	1,87
11:50	9,65158	1,87
12:00	9,78561	1,92

TABLE VI: BEST TOPOLOGIES FOR CHOSEN CONSTRAINTS

Sub-system	N° component	Final 'A'	Final Cost (M€)	Final GWP (g CO2)
1	2*1			
2	2*2			
3	2*4	0.9314	5.3720	19.4
4	2*2			
5	2*3			
Sub-system	N° component	Final 'A'	Final Cost (M€)	Final GWP (g CO2)
1	3*6			
2	3*1			
3	3*2	0.9985	9.2667	15
4	3*2			
5	3*3			

ACKNOWLEDGMENT

We would like to thank in this section all the industrial partners [23] who have taken the time to review and discuss all the elements with us to improve our article and match it to their needs. We are also grateful to the anonymous referees for their helpful comments.

REFERENCES

[1] IRENA. IRENA. [Online]. Available: www.irena.org.
[2] L. Freris and D. Infield, *Les Energies Renouvelables Pour La Production D'electricite*, Paris: Dunod, 2009.
[3] E. Ashry, "Renewables 2010 global status report," GTZ REN21, Paris, 2010.
[4] D. McGinn, "Renewables 2013 global status report—Renewable energy policy network for the 21th century," REN 21, Paris, 2013.
[5] P. Tavner, "Reliability analysis for wind turbine," *Wind Energy*, pp. 1-18, 2006.

[6] H. Liu, "Four wind speed multi-step forecasting models using extreme learning machines and signal decomposing algorithms," *Energy Conversion & Management*, vol. 100, pp. 16-22, 2015.

[7] P. Hou, W. Hu, M. Soltani, and Z. Chen, "A novel energy yields calculation method for irregular wind farm layout," in *Proc. Industrial Electronics Society, IECON 2015 - 41st Annual Conference of the IEEE*, Yokohama, 2015.

[8] K. Kulkarni and P. Mittal, "A fast and effective algorithm to optimize the total number and placement of wind turbines," in *Proc. Global Humanitarian Technology Conference - South Asia Satellite (GHTC-SAS), 2014 IEEE*, Trivandrum, 2014.

[9] Deprada *et al*., "Power generation efficiency analysis of offshore wind farms connected to a SLPC (single large power converter) operated with variable frequencies considering wake effects," *Energy*, vol. 37, no. 11, pp. 455-468, 2012.

[10] H. Huang and C. Yun, "Distributed genetic algorithm for optimization," in *Proc. ISAP - Intelligent System Applications to Power Systems*, Niigata, 2007.

[11] G. Marmidis, S. Lazarou, and E. Pyrgioti, "Optimal placement of wind turbines in a wind park using Monte Carlo simulation," *Renewable Energy,* vol. 33, no. 17, pp. 1455-1460, 2008.

[12] R. Rahmani, A. Khairuddin, S. Cherati, and H. Pesaran, "A novel method for optimal placing wind turbines in a wind farm using Particle Swarm Optimization (PSO)," in *Proceeding IPEC*, Singapore, 2010.

[13] T. Winter, "Reliability and economic analysis of offshore wind power systems—A comparison of internal grid topologies," Chalmers University of Technology, Gothenburg, Sweden, 2011.

[14] S. Nikolovski, D. Lopic, K. Rekete, and G. Slipac, "The influence of wind park krš-pađene on reliability indices of 110 kV transmission network," in *Proc. Energy Market (EEM), 2011 8th International Conference on the European*, Zareb, 2011.

[15] M. Fleckenstein and G. Balzer, "Impact on reliability of electrical power supply by feeding of offshore wind parks," in *Proc. 7th International Conference on Electrical and Control Technologies, ECT 2012*, Lithuania, 2012.

[16] R. Meziane, "Reliability optimization using ant colony algorithm under performance and const constraints," *Electric Power Systems Research*, vol. 76, 2005.

[17] Meziane, Châtelet, Bouzidi, Boufala, Hamzi, and Amara, "Wind farm reliability optimization using harmony search under performance and budget constraints," in *Proc. Renewable and Sustainable Energy Conference (IRSEC), 2014 International*, Ouarzazate, 2014.

[18] G. Levitin and A. Lisnianski, "A new approach to solving problems of multi-state system reliability optimization," *Quality and Reliability Engineering International*, vol. 17, no. 12, pp. 93-104, 2001.

[19] T. Aven, "On performance measures for multi-state monotone systems," *Reliability Engineering and System Safety*, vol. 41, pp. 259-266, 1993.

[20] R. Brunelle and K. Kapur, "Review and classification of reliability measures for multi-state and continuum models," *IEEE Transactions*, vol. 31, pp. 1171-1180, 1999.

[21] W. Peng, G. Lalit, D. Yi, P. Loh, and M. Andrew, "Reliability-based long term hydro/thermal reserve allocation of power systems with high wind power penetration," in *Proc. Power & Energy Society General Meeting, 2009. PES '09, IEEE*, Calgary, 2009.

[22] F. E. Ministry, Décrêts, arrêtés, circulaires. [Online]. Available: http://www.installationsclassees.developpement-durable.gouv.fr/IMG/pdf/arrete_declaration.pdf

[23] B. N. Q. S. FEE, *Interviews with Different Actors in Wind Industry, Troyes-Reims-Paris,* Interview, 2016.

[24] R. E. S. (SER), "Etat des coûts de production de l'éolien terrestre en France," SER, Paris, 2014.

[25] Levitin, *Universal Generating Function and Its Application*, Springer, 2005.

[26] L. Linnianski, "Melt state system reliability assessment, optimization, application," *World Scientific*, 2003.

[27] Aigner, "Modeling wind power production based on numerical prediction models and wind speed measurements," in *Proc. 17th Power Systems Computation Conference*, 2011.

[28] A. Billinton, "Time-series models for reliability evaluation of power systems including wind energy," *Micro Electron Reliab*, pp. 1253-1261, 1996.

[29] J. Wen, "A review on reliability assessment for wind power," *Renewable and Sustainable Energy Reviews*, pp. 2485-2494, 2009.

[30] J Cochran. National Renewable Energy Laboratory, "Flexibility in 21th century power systems," NREL, 2014.

[31] B. M. Hodge, "Examining the variability of wind power output in the regulation time frame," National Renewable Energy Laboratory, 2012.

[32] RTE. [Online]. Available: http://www.RTE.fr.

[33] RES-Legal. (2016). Legal sources on renewable energy. [Online]. Available: http://www.res-legal.eu/

[34] SER. (2013). [Online]. Available: www.ser.fr

[35] V. Fröding, "THE ICPE reform in France, classification of wind turbines as environmentally hazardous facilities," *DEWI Magazine*, 2012.

[36] A. Anders, "Assessing the life cycle environmental impacts of wind power: A review of present knowledge and research needs," 2012.

[37] A. Fulvio, "Energy performances and life cycle assessment of an Italian wind farm," *Renewable & Sustainable Energy Reviews*, 2008.

[38] M. Lenzen and J. Munksgaard, "Energy and CO2 life-cycle analyses of wind turbines_review and applications," *Renewable Energy*, vol. 26, pp. 339-362, 2002.

[39] H. L. Raadal, "Life cycle greenhouse gas (GHG) emissions from the generation of wind and hydro power," *Renewable and Sustainable Energy Reviews*, vol. 15, pp. 3417-3422, 2011.

[40] A. Arvesen, "Assessing the life cycle environmental impacts of wind power: A review of present knowledge and research needs," *Renewable and Sustainable Energy Reviews*, vol. 16, pp. 5994-6006, 2012.

[41] G. Levitin, "A new approach to solving problems of multi-state system, reliability optimization," CS.JYU, pp. 14-18, 2004.

Nacef Tazi is a mechanical engineer, specialized in Quality, Maintenance and Industrial safety from "Ecole Nationale Supérieure d'Elerctricité et de Mécanique". He also holds a MS degree in Civil and Mechanical engineering from the Blaise-Pascal University and the French Institute for Advanced Mechanics. After a professional experience in heavy and environmental industry, he joins the University of Technology of Troyes as a PhD Student to work on the assessment of the availability and environmental impact of wind farms. The region of Troyes is the first region in France with largest wind farms capacity and wind-powered electricity generation.

Eric Châtelet is Professor at the University of Technology of Troyes (UTT, France) since 1999. He was Director of studies at UTT (2001-2004) and Director of academic programs (2005-2006). He was co-manager (2006-2007) of the national program of the National Agency of the Research in Global Security.

He was vice-director (2009-2013) of the Charles Delaunay Institute (ICD) and he is the head of the "Sciences and Technologies for Risk Management" team from 2010. His research is focused on stochastic modelling and optimization for maintenance and reliability, the performance analysis (risk) of complex systems and security / vulnerability analysis.

Youcef Bouzidi is an assistant professor at the University of Technology of Troyes (UTT) in the department of physics, mechanics and nanotechnology, a member of the CREIDD research centre on environmental studies & sustainability, member of international society of industrial ecology, SETAC, member of the French society of thermic and many scientific committees of international conferences. His main fields of research works are structured around circular economy, environmental assessment, eco-design, energy recovery, management and valorization of wastes, optimization and modelling.