

## TECHNICAL PERFORMANCE ENHANCEMENT OF DISTRIBUTION SYSTEMS VIA OPTIMAL DG DEPLOYMENT

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### ABSTRACT

*This paper presents a new strategy to improve the economic, technical and environmental aspects of distribution systems (DSs). This strategy depends on using both different types of the distributed generation (DG) units and capacitor banks together to accomplish the best level of improvement with reasonable cost. The problem is formulated through a multi-objective function, where the DG dynamic output and load variations are considered. Different constraints are considered including the number of units, the total DGs capacity, the total capacity of capacitor banks, voltage limits at all buses, and operating hours of diesel units. The genetic algorithm (GA) optimization technique is used for identifying the optimal allocation of units. The proposed framework is evaluated using IEEE 33-bus typical system. The results indicate better performance of the system with the use of the combination of DG types and capacitor banks.*

### INTRODUCTION

The DS is the last part of the electric network that is responsible for feeding the loads by electric energy within appropriate voltage limits. The physical nature of the connected loads may cause some technical issues related to active and reactive power losses in addition to the voltage drop that affects the reliability of the DS. The technical performance of the DS is considered the main core of feeding pure power to loads within the DS [1]. Moreover, the voltage stability index (VSI) is an indication of the voltage level to guarantee the voltage stability under different disturbances [2].

The rapid developments in DS motivate operators and researchers to invent different techniques to improve its performance. One of these techniques is using capacitor banks to reduce the power losses, improve the voltage profile and enhance VSI [3]. The second technique is to use DG units which are preferred since they provide both active and reactive power to meet the increasing power demand in DS [4]. On the other hand, the intermittent characteristics of DG units, such as wind turbine (WT) [5] and photovoltaic (PV) [6], encourage the use of hybrid units or a combination of DG types to achieve better performance. Inserting DGs in the DS leads to enhancing the technical aspects; nevertheless, leads to increasing the total cost. The increase of total cost is attributed to the high capital cost of DG units.

This paper presents a new framework to determine the optimal allocation of a combination of DG types versus using capacitor banks for improving all technical and economic aspects. The PV and wind turbine are considered as main units, while the diesel is used in the

standby mode at intervals that have low output power from other units to compensate the shortage of power. Also, the impact of using capacitor banks only on enhancing the technical aspects will be discussed. Moreover, the combination of DG types and capacitor banks will be studied to show how the technical aspects are improved versus using each technology separately. The dynamic output and the emission effect of DG types are taken into account in the optimization process.

### PROBLEM STATEMENT

The use of DG units in DS has numerous effects on improving all technical benefits especially the overall VSI (OVSI). However, they have a negative impact on the economic considerations due to increasing the total cost. On the other hand, the use of capacitor banks in the DS delivers reactive power that has a positive effect on enhancing the voltage profile and reducing the total losses. In addition, the use of capacitor banks has a positive effect on reducing the total cost due to its low capital cost. The new strategy of this paper is introduced to investigate the combination of both DG units and capacitor banks together to get better results for the economic and technical aspects as well.

### MATHEMATICAL DESCRIPTION AND SOLUTION

The main objectives and the constraints of the problem formulation will be described as follows:

#### Objective function

There are four main parts included in the multi-objective function added together to minimize the OVSI ( $f_{ovsi}$ ), total losses ( $f_{losses}$ ), voltage regulation ( $f_{VR}$ ) and total cost ( $f_{cost}$ ).

$$F = f_{ovsi} + f_{losses} + f_{VR} + f_{cost} \quad (1)$$

The first term included in the multi-objective function is the OVSI [2] that is defined as follows:

$$vsi_i = |V(s)|^4 - 4.0(P(m)r(m) + Q(m)x(m))|V(s)|^2 - 4.0(P(m)x(m) - Q(m)r(m))^2 \quad (2)$$

$$f_{ovsi} = ovsi = \frac{\sum_{i=2}^{NB} vsi_i}{NB-1} \quad (3)$$

where:  $P(m)$  is the active power delivered at node  $m$ ,  $Q(m)$  is the reactive power through node  $m$ ,  $x(m)$  and  $r(m)$  are the reactance and resistance of branch  $m$ ,  $V(s)$  is the voltage at node  $s$ . The first branch node is “ $s$ ” and the second branch node is “ $m$ ”.

The second term that is included in the multi-objective function is the energy losses ( $f_{losses}$ ) [7].

$$f_{\text{losses}} = \sum_{t=1}^T \left( \sum_{i=1}^{NB} \sum_{j=2}^{NB} (P_{\text{losses}_{i-j}} + (Q_{\text{losses}_{i-j}})) \right) \quad (4)$$

with:

$$(P_{\text{losses}_i} = P_{\text{gti}} - P_{\text{dti}}) \quad (5)$$

$$(Q_{\text{losses}_i} = Q_{\text{gti}} - Q_{\text{dti}}) \quad (6)$$

where:  $P_{\text{losses}_{i-j}}$  and  $Q_{\text{losses}_{i-j}}$  represent the active and reactive energy losses, respectively, of feeder  $i-j$  per hour,  $P_{\text{gti}}$  and  $P_{\text{dti}}$  are active power generated and load demand active power at bus  $i$ ,  $Q_{\text{gti}}$  and  $Q_{\text{dti}}$  are reactive generated and demand power at bus  $i$ , respectively.

The voltage regulation ( $f_{\text{VR}}$ ) is the third term included in the multi-objective function that is defined as follows:

$$f_{\text{VR}} = \sum_{j=1}^N (|V_{\text{nom}}| - |V_j|) / |V_{\text{nom}}| \quad (7)$$

where:  $V_{\text{nom}}$  is the reference voltage and  $V_j$  is the voltage at bus  $j^{\text{th}}$ .

The last term of the objective function is the total cost which belongs to the cost of the power generated by the grid, power delivered by DG units, the reactive power of the capacitor banks and the emission effect for each part, and it is defined as follows:

$$f_{\text{Cost}} = f_{\text{Pgrid\_cost}} + f_{\text{PDG\_cost}} + f_{\text{C\_cost}} \quad (8)$$

The cost function of the grid power is represented as follows:

$$f_{\text{Pgrid\_cost}} = \text{cost}_{\text{P}_{\text{grid\_gen}}} + \text{cost}_{\text{grid\_emiss}} \quad (9)$$

where:  $\text{cost}_{\text{P}_{\text{grid\_gen}}}$  and  $\text{cost}_{\text{grid\_emiss}}$  are the total grid power cost and the total emission effect cost related to the grid power.

$$\text{cost}_{\text{P}_{\text{grid\_gen}}} = C_{\text{grid}} * P_{\text{grid\_gen}} \quad (10)$$

$$\text{cost}_{\text{grid\_emiss}} = K_{\text{grid\_emiss}} * P_{\text{grid\_gen}} * C_{\text{Co2}} * T \quad (11)$$

where:  $C_{\text{grid}}$  represents the cost factor of the grid power (\$/MW). Also,  $P_{\text{grid\_gen}}$  belongs to the grid power (MW),  $C_{\text{Co2}}$  represents the cost factor of CO<sub>2</sub> emission (\$/ton) and  $K_{\text{grid\_emiss}}$  is the emission factor of the grid (kg/MWh).

The cost function related to DG units is represented as follows:

$$f_{\text{DG\_cost}} = \text{cost}_{\text{PDG}} + \text{cost}_{\text{DG\_emiss}} \quad (12)$$

where:  $\text{cost}_{\text{PDG}}$  represents the total cost related to power delivered by DG units and  $\text{cost}_{\text{DG\_emiss}}$  is the total emission effect cost related to DG units, where:

$$\text{cost}_{\text{PDG}} = C_{\text{DG\_Cap}} + C_{\text{DG\_O\&M}} \quad (13)$$

where:  $C_{\text{DG\_Cap}}$  is the total capital cost of DG units and  $C_{\text{DG\_O\&M}}$  is the DG total running cost, hence:

$$C_{\text{DG\_Cap}} = \sum_{\text{day}} 1000 * \frac{(C_{\text{Cap(DG)/365}} * P_{\text{DG\_Cap}})}{(1+d)^{yT}} \quad (14)$$

$$C_{\text{DG\_O\&M}} = \sum_{\text{day}} 1000 * \frac{C_{\text{O\&M(DG)} * P_{\text{DG\_gen}}}}{(1+d)^{yT}} \quad (15)$$

where:  $C_{\text{Cap(DG)}}$  represents the capital cost of each DG unit (\$/kW),  $P_{\text{DG\_Cap}}$  is the DG installation capacity,  $d$  belongs to the discount rate,  $C_{\text{O\&M(DG)}}$  is the DG running

cost (\$/kW), and  $P_{\text{DG\_gen}}$  is the generation power from DG unit.

where:

$$\text{cost}_{\text{DG\_emiss}} = K_{\text{DG\_emiss}} * P_{\text{DG\_gen}} * C_{\text{Co2}} * T \quad (16)$$

where:  $K_{\text{DG\_emiss}}$  is the emission factor of DG unit (kg/MWh).

The cost function of the capacitor banks is represented as follows:

$$f_{\text{C\_cost}} = C_{\text{C\_Cap}} + C_{\text{C\_O\&M}} \quad (17)$$

where:  $C_{\text{C\_Cap}}$  is the capacitor total capital cost and  $C_{\text{C\_O\&M}}$  is the capacitor total running cost.

$$C_{\text{C\_Cap}} = \sum_{\text{day}} 1000 * \frac{(C_{\text{Cap(C)/365}} * Q_{\text{C}})}{(1+d)^{yT}} \quad (18)$$

where:  $C_{\text{Cap(C)}}$  is the capacitor unit capital cost factor (\$/kvar) and  $Q_{\text{C}}$  is the total capacitor installation capacity.

$$C_{\text{C\_O\&M}} = \sum_{\text{day}} 1000 * \frac{C_{\text{O\&M(C)} * Q_{\text{C}}}}{(1+d)^{yT}} \quad (19)$$

where:  $C_{\text{O\&M(C)}}$  is the running cost factor of capacitor unit (\$/kvar). The parameters of the cost and the emission effect are presented in the Appendix 1 [8].

### System constraints

The constraints of the system and DG units are presented as follows:

i) The total DG capacity constraint limits the DG capacity lower than 40% of the load demand [4]:

$$\sum_{N=1}^{N_{\text{DG}}} P_{\text{DG}} \leq 0.4 \sum_{N=1}^{N_{\text{B}}} P_{\text{load}} \quad (20)$$

ii) The constraint of the voltage level [9]:

$$V_{\text{min}} \leq V_{\text{bus}} \leq V_{\text{max}} \quad (21)$$

iii) The constraint of total number of DG units [10]:

$$N_{\text{DG}} \leq N_{\text{DG\_max}} \quad (22)$$

iv) The constraint of voltage stability index (VSI) [2]:

$$\text{VSI}(i) > 0, i = 1, \dots, N_{\text{Br}} \quad (23)$$

v) The constraint of operating hours for the diesel type:

$$N_{\text{operation\_hours}} = n \text{ hours} \quad (24)$$

vi) The total capacity limit of capacitor banks ( $Q_{\text{C}}$ ):

$$\sum_{N=1}^{N_{\text{Cap}}} Q_{\text{C}} \leq 0.5 \sum_{N=1}^{N_{\text{B}}} Q_{\text{load}} \quad (25)$$

where:  $P_{\text{DG}}$  is the DG active power capacity and  $P_{\text{load}}$  is the load demand active power.  $V_{\text{bus}}$  is the bus voltage,  $V_{\text{min}}$ ,  $V_{\text{max}}$  are the minimum and maximum bus voltages, respectively,  $N_{\text{DG}}$  is the DG units' total number,  $N_{\text{DG\_max}}$  is the max units number,  $N_{\text{Br}}$  is the system total number of lines.  $N_{\text{Cap}}$  is the total number of capacitor banks,  $Q_{\text{C}}$  is the capacitor reactive power capacity,  $Q_{\text{load}}$  is the load reactive power and  $n$  is the rated operation hours of the standby diesel, where it is considered three hours per day in this study. The diesel will run at time intervals when the wind and PV units have low output power.

The multi-objective function is formulated as:

$$\text{min}(F) = \min\{W_1 f_{\text{VR}} + W_2 f_{\text{OVSI}} + W_3 f_{\text{losses}} + W_4 f_{\text{cost}}\} \quad (26)$$

where:  $W_1$  to  $W_4$  are weight factors of each objective with positive values. When a certain term is not required in the objective function, its weight factor is assigned to

be zero.

The equation of wind turbine (WT) is defined as follows [11] [12]:

$$P_{W_{Gen}} = -0.0183 * v_w^5 + 0.5106 * v_w^4 + 5.13 * v_w^3 + 29.9 * v_w^2 + 80.75 * v_w + 76.5 \quad (27)$$

where:  $v_w$  is the wind speed (m/s) that depends on the region under study and hence, the average wind speed over one day is selected as shown in Appendix 2 according to Hurgada city in Egypt. The WT specifications are presented as follows: The Cut-in wind speed ( $v_{ci}$ ) = 2.5 m/s, the cut-out wind speed ( $v_{co}$ ) = 28 m/s and the rated wind speed ( $v_{rated}$ ) = 12.5 m/s [11].

The GA technique is used to obtain optimal solutions for the optimization problems [13]. Fig. 1 summarizes the main steps for the proposed framework. Initial population is formed by inserting different DG types and capacitor banks at random buses. Then, the different technical and economic values are calculated through the power flow calculations. Then, the fitness function is evaluated by equation (26), and then the parents are selected from the population. Then, the offspring chromosomes are created by recombination processes. The previous steps are repeated based on improving all technical and economic values until reaching the termination criteria. Then, the results are displayed.

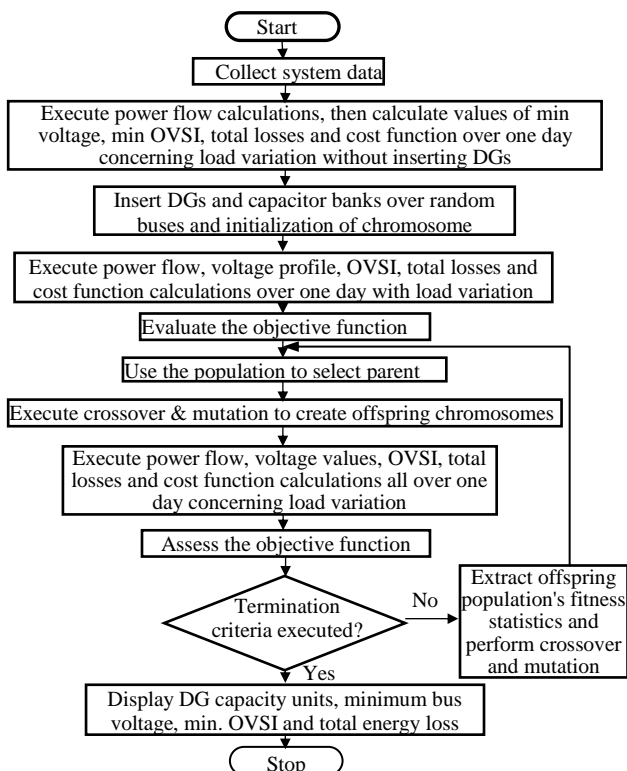


Fig. 1: Flowchart of the proposed framework using GA calculation

## CASE STUDY

The IEEE 33-bus typical system [14] has been used to

examine the framework. Fig. 2 shows the system that has a total load of 3.715 MW and 2.3 Mvar. The total system power losses per day are about 4.622 MWh and 3.083 Mvarh without inserting DGs during the day. Also, the OVSI is 0.7167 and the minimum bus voltage is 0.8938 pu at 120% of the base load. The DS is simulated using MATLAB® code.

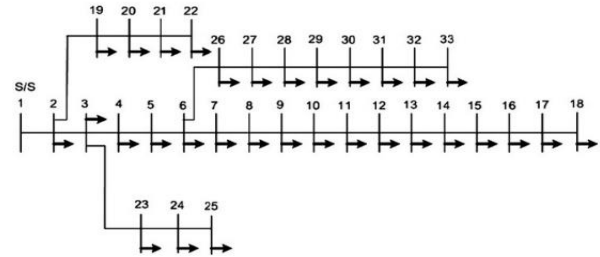


Fig. 2: The IEEE 33-bus typical system

## RESULTS AND DISCUSSION

Three cases are introduced to discuss the different percentage improvement for all technical and economic aspects. The first case includes the use of three DG types to enhance the OVSI, improve the minimum voltage, reduce the energy losses, and minimize the total cost. The second case is the use of capacitor banks. The third case is the use of both DG units and the capacitor banks. The three cases are identified regarding load variations over a day. Due to the different characteristic of DG types along the day, the total DG units' capacity is limited to be less than 40% of the total base load, but the total produced energy from DG units at daily hours does not exceed 30% of the base load. In addition, the constraint of the capacitor banks' total capacity is not to exceed 50% of the total reactive base load. The reason of this assumption is that the three DG types deliver the rest of reactive power. Moreover, the diesel operating hours to provide prime power are considered. It is used as a standby unit at times where the difference among the load and the power delivered from the PV and wind turbine exceeds the maximum values.

Table 1 shows the optimal allocations for the three cases considering the load variation over one day. For each case, each DG type is selected at the appropriate locations and sizes to perform the optimization process. Even if the technical aspects are improved regarding certain capacities and locations of DG units for the first case (DG units only), it is not necessary that the other cases have the same capacity. Table 2 shows that the OVSI has better values when using DG units only compared to other cases. In contrast, the use of capacitors only has the lowest values for OVSI. Nevertheless, the use of DG units with capacitor banks provides the best values for minimum bus voltages regarding the daily load variations. The use of three DG types resulted in appropriate improvement of all technical aspects but increases the total cost.

Table 1: Optimal location, capacity and type of units regarding different cases

DG bus no.	DG only		Cap. only (kvar)	DG with Cap.	
	Capacity (kW)	Type		Capacity (kW or kvar)	Type
4	---	---	---	249.6	PV
12	---	---	240	---	---
14	---	---	133.1	---	---
15	225.9	PV	---	134.1	Wind
16	250.2	Wind	---	---	---
17	---	---	---	245.5	Cap
18	201.9	Wind	---	211.4	Diesel
24	---	---	---	260.4	PV
27	---	---	---	95.4	Wind
28	---	---	168.9	---	---
29	---	---	---	146.3	PV
30	380.6	Diesel	224.3	285.8	Cap
31	101.4	PV	---	199.3	PV
32	---	---	201	---	---
33	318.7	PV	194.4	161.2	PV

Table 2: Percentage improvement for the technical values regarding different cases

Case	DG only	Cap only	DG with Cap	
	$W_{1,2,3,4}=-.25$	$W_{1,2,3,4}=-.25$	$W_{1,2,3,4}=-.25$	
Tech. values	Min. V (pu)	0.91	0.9156	0.916
	OVSI	0.7645	0.6155	0.7422
	Active energy losses (Mw)	3.2504	3.1818	2.8211
	Reactive energy losses (Mw)	2.1461	2.116	1.8922
	Total Cost (\$)	10327.52	8638.84	10185.93
% Improve ment	Min. V	1.81	2.43	2.48
	OVSI	6.67	-14.12	3.56
	P_losses	29.68	31.16	38.97
	Q_losses	30.39	31.37	38.63
	Cost	-17.9	1.38	-16.28

It is noted that the first case with DGs only causes the best percentage improvement for OVSI, i.e. 6.67%. Furthermore, the case of using capacitor banks only has a negative effect on OVSI values. Nevertheless, this case has the best percentage reduction value for the total cost with a positive value of 1.38% due to the low capital cost of capacitor banks. The case of using DG units with capacitor banks has the best percentage improvement for both the minimum voltage and total active and reactive energy losses with values equal to 2.48%, 38.97% and 38.63, respectively.

Figs. 3 and 4 show the provided power from the three DG types for the cases of using a combination of all DG types without and with capacitor banks, respectively. In the two cases, the standby diesel operates at periods of 17, 18 and 20 hours to compensate the provided power from wind and PV types at these intervals with the same total capacity limits.

The voltage profile for different cases at two-time intervals is shown in Figs. 5 and 6. From these figures, it is noted that the case of using DG with capacitors has the best voltage profile. This improvement is due to complementary action of the capacitor banks that compensate the reactive power taken from DG units to enhance the voltage profile with lower cost. On the other

hand, the DG units improve the OVSI, compensating the bad effect of capacitor banks on this index.

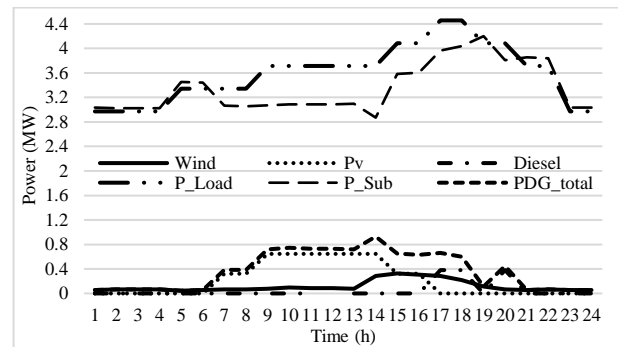


Fig. 3: Total load and output power per daily hours for the case of using DGs only

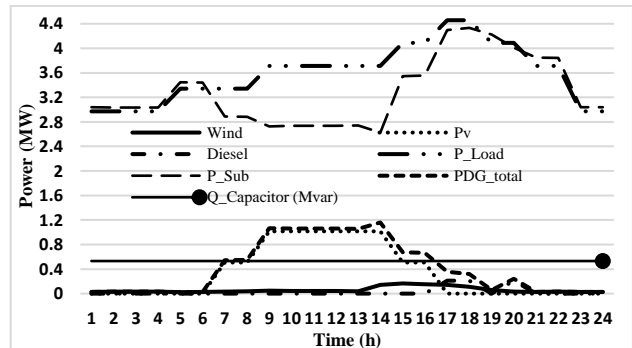


Fig. 4: Total load and Output power and per daily hours for the case of using a combination of DGs with capacitor banks

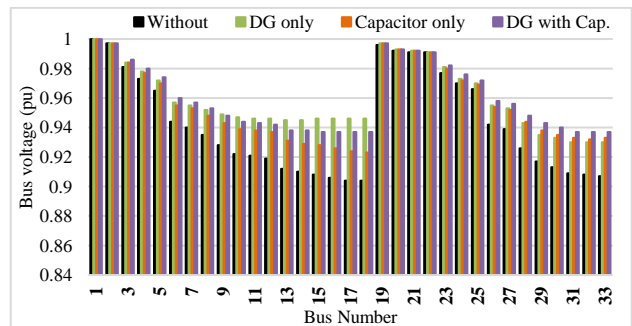


Fig. 5: Voltage profile for different cases at 16 h considering technical and economic aspects

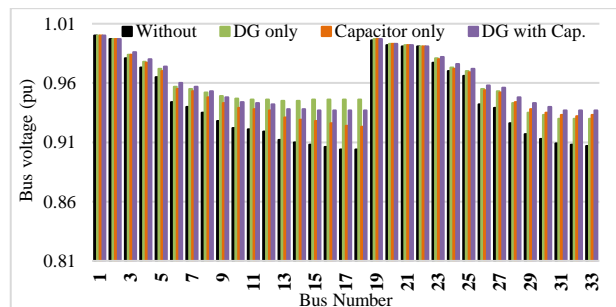


Fig. 6: Voltage profile for different cases at 17 h considering technical and economic aspects

## CONCLUSIONS

This paper introduced a comparison between three cases to improve both technical and economic aspects in distribution systems. The three cases include the use of DG units and capacitor banks separately. Moreover, a combination of DG and capacitor banks is investigated to optimize their operation. It is noted that the case of using DG units only improves the OVSI with better rates than other cases. However, it has a bad impact on the total energy cost. On the other hand, the case of using the capacitor banks reduces the total cost, enhances the status of minimum bus voltage and reduces the energy losses but it has a bad effect on the OVSI. Finally, the case of using DG units together with capacitor banks is advantageous compared to the two other cases since it improves the status of minimum bus voltage and reduces the energy losses compared to the two other cases. Furthermore, the percentage improvement of the OVSI is lower than the case of DG units only and better than the case of capacitor banks only. In addition, the percentage improvement of the total cost is lower than the case of the capacitor bank and better than the case of DGs only. So, the use of DGs with capacitor banks is preferred to obtain better results for improving all technical and economic aspects of the DS. Hence, the framework in this paper can be used by the operator to form the final decision for selecting any of the three cases according to the desired improvement for the different technical and economic aspects.

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## APPENDICES

**Appendix1:** The parameter of the cost of DGs under study

Source	Cost equation parameters			Emission(CO <sub>2</sub> ) kg/Mwh
Diesel	$C_{cap}=750$ \$/kW	$C_{O\&M}=0.04$ \$/ kW	$\alpha(\%) = \infty$	$K_{Diese\_emiss}=307$
Wind turbine	$C_{cap}=1477$ \$/kW	$C_{O\&M}=0.01$ \$/ kW		$K_{Wind\_emiss}=0$
PV	$C_{cap}=1388$ \$/kW	$C_{O\&M}=0.01$ \$/ kW		$K_{Pv\_emiss}=0$
Capacitor	$C_{cap(C)}=10$ \$/kvar	$C_{O\&M(C)}=0.01$ \$/ kvar		
Grid	$C_{sub}=65$ \$/MW			$K_{sub\_emiss}=143$
Emission	$C_{CO2}=220$ \$/ton			

**Appendix2:** ([www.weather.com](http://www.weather.com))

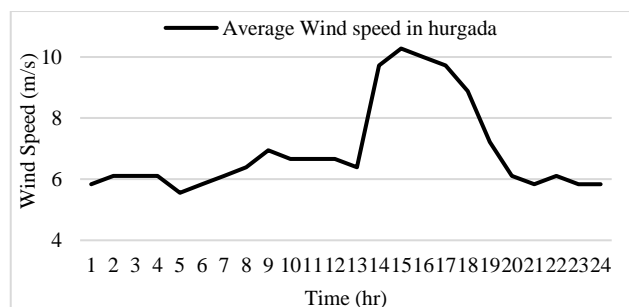


Fig. 9: Average wind speed curve versus daily hours