Decision Support Model for Optimal Design of Wind Technologies Based Techno–Economic Approach

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ABSTRACT This paper aims to propose a practical decision support model for the optimal design of future wind turbines based on available wind potential on the site of interest. A developed decision support model based a comprehensive wind turbine modeling and a constrained techno-economic optimization framework is presented. Optimization was subject to the Net Present Value (*NPV*) maximization of the net incomes from wind energy generation, under the constraints on wind turbine nominal power restriction and the maximum ratio permitted between the rotor diameter and tower hub height. Optimizations of rotor diameter and tower height sizing have direct impacts on energy and cost production, those parameters have been considered as the design variables. The optimal design selection considers: the nominal power, rotor diameter, and tower hub height, which led to the maximum *NPV* in a specific site. Furthermore, an analysis of the Levelized Cost of Energy production (*LCOE*) has been performed. The developed decision support model has been tested and applied to a case study to validate its application and performance. The developed model was verified and significant results were achieved using three different wind sites: Dakhla, Casablanca, and Tanger. Results showed that the optimal design of the wind turbine technologies is given by the limit conditions cited, conducting to the maximum *NPV* with low *LCOE* and more exploitation of available wind potential in Dakhla and Tanger; however Casablanca was found as no profitable site for wind projects presenting negative *NPV*.

NOMENCLATURE

$f(v)$:	Weibull probability density function
v:	Wind speed
C:	Weibull Scale parameter (m/s)
k:	Weibull Shape parameter
I:	Wind speeds class
P_i:	Wind Power (W)
$E_{c,i}$:	Wind kinetic energy (Joule)
$\dot{m}$:	Air mass flow (kg/s)
P:	Air density (kg/m3)
A:	Rotor swept surface (m^2)
v_i:	Wind speed of the ith class (m/s)

$P_{r,i}$:	Rotor power (W)
r:	Rotor index
$C_{p,r,i}$:	Rotor power coefficient
D:	Rotor diameter (m)
H:	Tower hub height (m)
$C_{p,r,max}$:	Rotor maximum power coefficient
v_{op}:	Optimal wind speed (m/s)
v_n:	Wind Turbine nominal wind speed (m/s)
u:	Wind speed operating range
N_b:	Number of blades
λ_{max}:	Maximum speed rate
ω:	Rotor angular rotational speed
c_d:	Drag coefficient
c_l:	Lift coefficient

AEP_t:	Annual Energy Production (Wh/year)
$C_{p,i}$:	Wind Turbine total efficiency
f_i^h:	Discretized Weibull function
$\mu_{gear,i}$:	Gearbox efficiency
$\mu_{gen,i}$:	Generator efficiency
ψ_{gear}:	Gearbox efficiency factor
P_n:	Wind Turbine Nominal power
P_{op}:	Optimal power
ψ_{gen}:	Generator efficiency factor
$P_{n,gen}$:	Generator nominal power
F_s:	Gearbox factor of service
$P_{gear,i}$:	Gearbox generated power
$AEP_{R,t}$:	Real Energy Produced in year t (kWh)
Φ:	Wind Turbine losses and failures
$LCOE$:	Levelized Cost of Energy ($/kWh)
I_t:	Investment made in year t ($)
$C_{OM,t}$:	Operation and Maintenance costs in year t ($)
PTC_t:	Production tax credit ($)
D_t:	Annual depreciation expense ($)
T_t:	Tax levy ($)
s:	Wind Turbine lifetime
m:	Discount rate
C_T:	Transportation cost
C_{TF}:	Transportation Cost Factor
C_{AI}:	Assembly and Installation cost
C_{EI}:	Electrical Interface cost
C_{EIF}:	Electrical Interface Cost Factor
C_{EP}:	Engineering and Permits cost
C_{EPF}:	Engineering and Permits cost Factor
C_{RCW}:	Roads and Civil Work cost
C_{RCWF}:	Roads and Civil Work Cost Factor
C_F:	Foundation cost
C_{WT}:	Wind Turbine cost
NPV:	Net Present Value
$C_{Sal,t}^{Incomes}$:	Incomes from electrical energy sales
$C_{Inc,t}^{Incomes}$:	Incomes from incentives for green energy production
$C_{Incomes,t}$:	Total yearly Incomes of the generated electricity
C_{Sal}:	Purchase tariff of electricity
C_{Inc}:	Sales due to incentives for green energy production
MV:	Moyne Voltage kWh price
η, ξ:	Dimensionless factors
N:	Rotor rotational speed
$WTDO$:	Wind Turbines Design Optimization
$WFLO$:	Wind Farm Layout Optimization
WF:	Wind Farm
WT:	Wind Turbine
COE:	Cost of Energy
NT_t:	Net Tax

I. INTRODUCTION

An important part of the kinetic energy contained in the wind is still unused by the Wind Turbines (WTs) implemented because of their wicked planning in addition to their economic challenges. Where, the necessity of a support for an optimal planning of future wind production chains and optimization of their technical and economic system for making strength decisions encouraging the investments in the wind energy field and enhancing its efficiency. This work is dealing with these issues through an efficient design and optimization procedure of WT technical parameters including: rotor diameter (D), the hub height of tower (H), and the nominal power (P_n) for a specific site. The Net Present Value (NPV) of the net incomes obtained from wind energy generation, is cited as the objective function of the optimization to be maximized under constraints. This may be performed using the annual wind distribution available in a selected site.

The decision support systems optimizing the Wind Farm (WF) design are more and more needed to facilitate and strength the exploitation of wind sources. In the context of WF design two subjects are of interest: the WTs Design Optimization (WTDO) and Wind Farm Layout Optimization (WFLO) [1]. The WFLO is aimed at the overall optimization of WTs in the whole WF, via optimizing the layout of WTs, while the WTDO is the single WT optimization, by optimal designing the turbine parameters [2].

In the literature many authors studied the impact of WFLO and WTDO simultaneously, [3] provided a framework for WFLO and optimized D and H of the WT to accelerate the design, analysis and optimization of WF using real WF terrain and conditions. The framework contained a set of analytical wake models and wake superposition schemes that take into account the partial influence of one turbine on another, resulting in increased Annual Energy Production (AEP_t), reduced cost and land usage. Wind wake effect was also one of the criteria adopted to choose the best alternative for a hybrid operation of WFs [60]. Authors in [4] developed a new optimization model capable of dealing with a wide range of issues pertaining the wind-powered hydrogen supply system from the WT size and height to the WF layout selection, in addition to the strategic onshore or offshore allocation of WFs in order to minimize the total daily cost of this system. In [5] authors have optimized WFs by coupling complete turbine design and layout optimization as well as including two different turbine designs in a fixed 1-to-1 ratio in a single WF. H, D, P_n, tower diameter, tower shell thickness, and implicit blade chord-and-twist distributions were cited as turbine design variables. Results proved that coupled turbine design and layout optimization were superior to sequentially optimizing turbine design, then turbine layout and the application of two different turbine designs in the same WF reduce the Cost of Energy (COE). These studies did not evaluate the revenues of a project with such optimized design and its feasibility that attracts the investors.

However, other authors have been interested either in WFLO only or just WTDO. At WFLO level, Abdulrahman and Wood [6] optimized the layout of WFs for onshore and offshore conditions including different commercial turbines using a Matlab genetic algorithm, where three objective

functions were performed: the output power, the capacity factor, and the cost per output power. They announced that the optimization of the maximum capacity factor acts as a mid-point between the two design extremes of maximizing power and minimizing the cost of energy. Another optimization way was carried out by Wang *et al.* [7] using the novel optimized WF control strategy and multiple WT *H* selections for a real WFLO. Smaller *COE* production and larger WF efficiency were achieved and different *H* applications demonstrated a good flexibility of WT implementation than constant *H* turbines. An optimization study of a realistic offshore WF design layout was performed by Charhouni *et al.* [8] to design WF area that maximizes the extraction of wind power with low cost. By two steps: (1) optimal design as a function of WTs placement was determined using genetic algorithm with continuous layout representation, then (2) impact of four selected commercial WTs on WF objectives was analyzed. They found that designing WF with big WTs gives the best design layout with a selection based on *D* and the number of WTs. For, Antonini *et al.* [9] the WFLOs in both flat and complex terrains were presented using a gradient-based algorithm and an adjoint method for the gradient calculations. This enabled the use of computational fluid dynamics models to accurately simulate wake effects and terrain-induced flow characteristics. Significant improvements in AEP_t were realized by optimal siting turbines over complex terrains exploiting both turbine and terrain induced flow features. These studies had also the objective of maximizing the efficiency of WFs with low cost evaluating sometimes the commercial WTs effect in objectives achievement, but there wasn't any improvement in the design of these existing technologies according to wind potential on the site of installation.

On the other hand, many studies were focused just on WTDO either optimization of blade, tower, *D*, P_n or a combination of those parameters:

- Optimization of WT blade and tower at the same time was much carried out. Ashuri *et al.* [1] presented the first design optimization effort that simultaneously designed a WT blade and tower subject to constraints on fatigue, stresses, deflections and frequencies with the Levelized Cost of Energy (*LCOE*) as the objective function to be minimized. The integrated methodology showed a 2.3 % decrease in the *LCOE* for a representative Dutch site. Zhu *et al.* [10] showed an efficient method for multi-objective optimization design of WTs at the system level through a coupled blade-tower model. The non-dominated sorting genetic algorithm was used to achieve the best tradeoff solutions between the following objectives: maximizing the AEP_t and minimizing the WT mass. Satisfactory results that can both increase the AEP_t and decrease the mass were obtained. Also, Yang *et al.* [11] presented a method to optimize WT at low wind speed areas and found a tradeoff between the blade length and *H* that minimize the *COE*. They resulted in a more efficient *H* enhancement effect than

D for the low wind speed turbine to minimize the *COE*. These studies had in general a low *COE* as an objective function of the optimization.

- Other Researchers were focused only on WT blade design optimization, Balijepalli *et al.* [12] performed a design optimization study of small scale WT blades for a Solar Updraft Tower and their aerodynamic parameters performance increasing the maximum power output extraction from wind. Sessarego *et al.* [13] Applied neural networks for the design optimization of a curved WT blade using an aero-elastic simulator with synthetic inflow turbulence, which contributed to 1 % more power production on average with a slight increase of mean thrust on the rotor of 0.02 % compared to the straight one. For, Tahani *et al.* [14] to capture the maximum amount of available power, an optimization of the geometry of a WT blade design and influence investigation of geometrical parameters including chord and twist distributions and also airfoils on the performance of the turbine in 1 % and 8 % turbulence intensities was presented. Cognet *et al.* [15] Interested in material optimization of WTs for the flexible blades to maximize the overall turbine efficiency, for any required geometry of classical horizontal axis turbines; resulted in 5 % and 20 % lighter than the current rigid blades. Researches cited above aimed to just maximize the efficiency of WT and no economic assessment was done.

- Song *et al.* [2] and Mellal and Pecht [16] proposed an optimal and a multi-objective design optimization of WTs respectively considering the altitude. The objectives of those designs were: the energy cost minimization by considering the rotor radius and *H* in both cases plus maximization of the P_n for Mellal and Pecht. However, P_n was cited as a design variable for Song *et al.* That later observed that optimal *COE* and the optimized rotor radius increased with the increase of altitude, while Mellal and Pecht observed that the *COE* increased and the P_n decreased when the altitude increased. So both studies worked in the same objective and high altitude site as interest.

- According to Wass [17] Future large scale WTs will have aspect ratios closer to 0.5 nearing 200 m in diameter. This prediction was a result of an optimization study for an optimum *H* to *D* ratio, using an Excel based optimization program of a simulated turbine. The main optimization method used was the *COE* minimization and found the highest load factor to predict the height and diameter that had the cheapest initial capital cost and the highest AEP_t. This study improved the design of a simulated turbine with *D*, *H* and localization variation, reducing its *COE*. In this paper a more powerful, economical evaluation is carried out.

Considering the above mentioned studies, it can be concluded that the main objective in WF optimizations was the wind energy efficiency enhancement with low *COE* production. In this work, we focused only on WTDO.

On one side, *COE* was the most economical indicator used in the WTDOs evaluation. In general, there are several economical parameters used in the evaluation of the profitability of an investment or project and construction feasibility of WF like [2]: *COE* [11], *NPV* [18], the Internal Rate of Return [19], the Payback Period [20], and the Present Value of Cost [21]. Probably the most popular and most sophisticated economic valuation technique is the *NPV* approach, It consists in discounting all future cash flows in and out resulting from the innovation project with a given discount rate [22]. Ouammi *et al.* [23] carried out a decision framework to optimally plan WFs with technology selection among the commercialized ones in the distribution network, where the *NPV* of the WF investment over a given planning horizon for various bus locations was maximized. In the goal to guide the agent's decision-making in the electricity sector, Aquila *et al.* [24] proposed an optimization methodology that defines the optimal combination of WFLO and WT equipment type deployed, in order to maximize the overall welfare of the electricity sector, where the objective functions were: the energy density and the *NPV* using power levels and selling price of the energy parameters. Also, in the same context of site selection and the optimal technology to be installed, Ouammi *et al.* [25] proposed an Environmental Decision Support System for the sustainable design of WFs. Where the design of the wind turbine technology had been optimally specified according to a set of existing technologies, the *NPV* was also considered as an objective function to be maximized under the following constraints: number of WTs in the sites, minimum energy demand, and regulation to be satisfied through wind resource in a specific location. In this paper, the objective of the design provided is to maximize the wind turbine net revenues where, the NPV was the suitable economic indicator for this study.

On the other side, in the same context of WTDO, many optimizations have resulted in WT blade structures that lead to extract the maximum wind available. In general, the optimal design of the WT was based mostly on a selection among commercialized technologies that were tested and had presented maximum NPV or minimum LCOE. There wasn't any suggestion of the adequate technology function the wind profile of the site studied. That's makes the objective of this research. So, based on the wind potential of the site selected and other input parameters needed in simulation cited in the design variables in section II, our study provide a decision support model that gives the suitable design parameters (D, H and Power) for the wind turbine that is not yet available in the market presenting maximum NPV of wind system revenues. An evaluation of the *LCOE* in parallel with the optimization was carried out. For that, an improvement of the optimization module in [25] was realized. That makes the originality of our study and constitutes the subject of this paper performed through the following steps:

- Firstly, developing a decision support model starting from WT technology modeling to its optimum design. Optimization was subject to the *NPV* of wind energy net

incomes maximization under scale constraints mainly *D* and *H*, whose have a powerful influence and contribution on techno-economic optimization of WTs. This model was ready to be transformed and ran through any kind of existing algorithms.
- Secondly, the techno-economic optimization problem had been resolved having as objective, finding the best compromise between WT variables, including *D*, *H* and *P_n*, which showed the best value for the *NPV*. In addition to an analysis of the *LCOE* of the optimized technology.

Finally, the developed decision support framework model was validated using a case study with determined wind characteristics on a selected site. This model impacts all the authorities interested in the wind energy sector, including: Researchers, engineers, and industries working on the development of WT technologies. On the other hand, it supports investors and decision makers to avoid oversizing issues and coming to the suitable design for their sites of implementation. A discussion of the results obtained was then shown.

II. PROBLEM MODELING

In this section, the developed decision support model for optimal WT technology design determination in the studied site is presented in detail.

In this paper, the WT is assumed to contain three main elements: the rotor, the gearbox, and the generator. The proposed model does not consider characteristics of the plant such as the possibility to react better to fluctuations of the wind due to the system inertia, the availability of strategies to start and to stop according to the wind pattern. The computation of the rotor power coefficient by aerodynamic methods needs a lot of data, involving the geometry of the blade. In this paper an analytical relation has been used that was fitted to experimental data.

The wind density is assumed to change only with the hub height. The Weibull parameters depend on the wind characteristics of the specific location. These parameters are used to define the new Weibull parameters at the hub height. The ratio coefficients of drag and lift is assumed to be constant equals to 120.

A. WIND TURBINE PRODUCTTION MODEL

1) WEIBULL DISTRIBUTION

The wind speed distribution is a very important parameter to evaluate the output of a WT. Numerous studies for different locations of the world have shown that the Weibull two-parameter distribution gives favorable fits to the wind speed distributions [26]. This distribution is characterized by a probability density function called Weibull probability density which represents the probability of observation of a wind speed *v* in (m/s), defined by [23]:

$$f(v) = (\frac{k}{C})(\frac{v}{C})^{k-1} exp(-(\frac{v}{C})^k) \qquad (1)$$

With: *C* (m/s) and *k* are the Weibull scale and shape parameters successively.

Several methods were used for the determination of Weibull probability density function parameters; the selected method was the Standard Deviation Method that showed a good fit of the observed data in Dakhla site presented in Fig. 1, presenting minimum error of 0.011 and 1 for root means square error and determination coefficient respectively. The same method was also demonstrated as the best method in Tanger and Dakhla sites from [26].
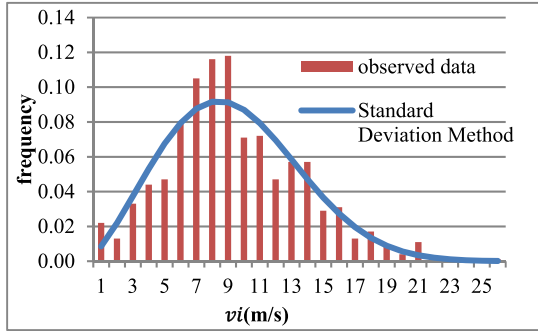

FIGURE 1. Weibull distribution for Dakhla site measured at 10m of height.

2) WIND POWER

Wind power (P_i) is the derivative of wind kinetic energy ($E_{c,i}$) and it's a theoretical power that cannot be fully recovered by the WT.

$$P_i = \frac{dE_{c,i}}{dt} = \frac{1}{2}\dot{m}v_i^2 \tag{2}$$
$$\dot{m} = \rho A v_i \tag{3}$$

where i is the class index of wind speeds, v_i is the wind speed of the ith class, $\dot{m}$ is the mass flow of air (kg/s), ρ (kg/m3) is the air density and (A) is the surface swept by the rotor.

$$P_i = \frac{1}{2}\rho A v_i^3 \tag{4}$$

3) ROTOR POWER

Rotor power ($P_{r,i}$) is the wind power P_i transformed into mechanical energy by the rotor of WT technology is given by [23]:

$$P_{r,i} = P_i * C_{p,r,i} \tag{5}$$

$C_{p,r,i}$ Is the rotor power coefficient and r refers to WT rotor.

$$P_{r,i} = \frac{1}{2}\rho C_{p,r,i}A v_i^3 \tag{6}$$
$$A = \frac{\pi D^2}{4} \tag{7}$$
$$C_{p,r,i} = C_{p,r,max} \exp\left[-\frac{(lnv_i - lnv_{op})^2}{2(lnu)^2}\right] \tag{8}$$
$$v_{op} = \frac{v_n}{exp\left[3(lnu)^2\right]} \tag{9}$$

where D is the rotor diameter (m), $C_{p,r,max}$ is the rotor maximum power coefficient, v_{op} the optimal wind speed, u

is the parameter of operating range of the wind speed and v_n is the nominal wind speed of wind technology.

The Betz law determines that a WT will never be able to convert more than 59.3 % [27]of the kinetic energy contained in the wind into mechanical energy. The maximum rotor power coefficient is expressed by the following equation:

$$C_{p,r,max} = 0.593$$
$$\times \left[\frac{\lambda_{max}(N_b)^{0.67}}{1.48 + ((N_b)^{0.67} - 0.04)\lambda_{max} + 0.0025(\lambda_{max})^2} - \frac{1.92(\lambda_{max})^2 N_b}{1 + 2\lambda_{max}N_b}\cdot\frac{C_d}{C_l}\right] \tag{10}$$
$$\lambda_{max} = \frac{\omega D}{2v_{op}} \tag{11}$$

where N_b is the number of blades, λ_{max} maximum speed rate, ω is the rotor angular rotation speed, and c_d/c_l is the ratio between drag and lift coefficients.

4) ANNUAL ENERGY PRODUCTION

AEP_t is the Annual Energy Production of the WT technology in a selected site [23], [26]:

$$AEP_t = \frac{8760}{2}\rho A \sum_{i=1}^{I} v_i^3 f_i^h C_{p,i} \tag{12}$$

where $C_{p,i}$ is the total efficiency of a WT and f_i^h is the Weibull function discretized with height for the site selected.

$$C_{p,i} = C_{p,r,i} \mu_{gear,i} \mu_{gen,i} \tag{13}$$

where $\mu_{gear,i}$ and $\mu_{gen,i}$ are the gearbox and the generator efficiencies respectively of the WT.

$$\mu_{gear,i} = 1 - \left[(1 - \psi_{gear})\left(\frac{P_n}{4P_{r,i}} + \frac{3}{4}\right)\right] \tag{14}$$
$$\psi_{gear} = 0.89(P_n)^{0.012} \tag{15}$$
$$P_n = P_{op}.exp(4.5(lnu)^2) \tag{16}$$
$$P_{op} = \frac{1}{2}\rho C_{p,r,max}A(v_{op})^3 \tag{17}$$

where P_n is the WT nominal power, ψ_{gear} is the efficiency factor of the gearbox and P_{op} is the optimal power corresponding to $C_{p,r,max}$ for the optimal wind speed v_{op}.

$$\mu_{gen,i} = 1 - \left[(1 - \psi_{gen})\left(5(\frac{P_{gear,i}}{P_{n,gen}})^2 + 1\right)\left(\frac{P_{n,gen}}{6P_{gear,i}}\right)\right] \tag{18}$$
$$\psi_{gen} = 0.87(P_n)^{0.014} \tag{19}$$
$$P_{gear,i} = \mu_{gear,i}P_{r,i} \quad \forall i \tag{20}$$
$$P_{n,gen} = P_n\psi_{gen}\psi_{gear}F_s \tag{21}$$

where ψ_{gen} is the generator efficiency factor, $P_{n,gen}$ nominal power of the generator, $P_{gear,i}$ generated power by the gearbox and F_s is the factor of service named also working

coefficient of the gearbox for different WT regulations: stall-constant-speed (SCS); pitch-constant-speed (PCS) or pitch-variable-speed (PVS) [26].

$$F_s = \begin{cases} 1.75 \ if \ PCS \\ 1.25 \ if \ PVS \\ 2 \ if \ SCS \end{cases}$$

The Real electrical energy AEP_R produced discounting the losses occurred in the WT became:

$$AEP_{R,t} = \phi AEP_t \qquad (22)$$

ϕ Represents the losses and failures in the overall WT.

B. LEVELIZED COST OF ENERGY MODEL

The *LCOE* can be defined as the present value of the price of the produced electrical energy considering the economic life of the plant typically 20 years for wind generators and the costs incurred in: the construction, operation-maintenance, and the fuel costs. Fuel cost and royalties equal to zero for wind [28] After a deep study of *LCOE*, we resulted in the following equation [28], [29]:

$$LCOE = \frac{\sum_{t=0}^{s} \frac{(I_t + C_{OM,t} - PTC_t - D_t + T_t)}{(1+m)^t}}{\sum_{t=1}^{s} AEP_{R,t}} \qquad (23)$$

where I_t presents the investment made in year t ($), $C_{OM,t}$ is operation and maintenance costs in year t ($), PTC_t is the Production Tax Credit ($), D_t is the annual depreciation expense ($), T_t, is Tax levy ($), $AEP_{R,t}$ is the Real Electrical generation in year t (kWh), s is the WT lifetime and m is the Discount rate.

Wind energy production gradually decreases over its lifetime, perhaps due to falling availability, aerodynamic performance or conversion efficiency. WTs are found to lose 1.6 $\pm$0.2 % of their output per year, increasing the levelized cost of electricity by 9 % [30]. According to that and adapting the formula (23) to the economic procedure applied in the country of the evaluated site, the *PTC* was not available so *LCOE* equation becomes:

$$\rightarrow LCOE = \frac{\sum_{t=0}^{s} \frac{(I_t + C_{OM,t} - D_t + T_t)}{(1+m)^t}}{\sum_{t=1}^{s} AEP_{R,t}(1-0.016)} \qquad (24)$$

1) INVESTMENT MODEL

The investment cost model I_t adopted in our study was a modified model of the National Renewable Energy Laboratory study [31], where the WT cost model (C_{WT}) was a result of our performed study discussed and presented in the result section. I_t Includes the following costs:

$$I_t = C_T + C_{AI} + C_{EI} + C_{EP} + C_{RCW} + C_F + C_{WT} \qquad (25)$$

where C_T is the Transportation cost, C_{AI} is the Assembly and Installation cost, C_{EI} is the Electrical Interface cost, C_{EP} is the Engineering and Permits cost, C_{RCW} is the Roads and Civil Work cost and C_F is the Foundation cost.

$$C_T(\$) = P_n * C_{TF} \qquad (26)$$

$$C_{TF}(\$/kW) = 1.581E - 5 * (P_n)^2 - 0.0375 * P_n + 54.7 \qquad (27)$$

C_{TF} is Transportation Cost Factor

$$C_{AI}(\$) = 1.965 * (H * D)^{1.1736} \qquad (28)$$

$$C_{EI}(\$) = P_n * C_{EIF} \qquad (29)$$

$$C_{EIF}(\$/kW) = 3.49E - 6 * (P_n)^2 - 0.0221 * P_n + 109.7 \qquad (30)$$

C_{EIF} is the Electrical Interface Cost Factor

$$C_{EP}(\$) = P_n * C_{EPF} \qquad (31)$$

$$C_{EPF} = 9.94E - 4 * P_n + 20.31 \qquad (32)$$

C_{EPF} is the Engineering and Permits cost Factor

$$C_{RCW} = P_n * C_{RCWF} \qquad (33)$$

$$C_{RCWF} = 2.17E - 6 * (P_n)^2 - 0.0145 * P_n + 69.54 \qquad (34)$$

C_{RCWF} is the Roads and Civil Work Cost Factor

$$C_F = 303.24 * (H * A)^{0.4037} \qquad (35)$$

2) STRAIGHT LINE DEPRECIATION

Straight line depreciation is a method used to estimate the real value of the I_t at the end of WT lifetime [28]. In this study the real value was cited at zero in order to recover totally the I_t over the WT lifetime, this was the formula adopted:

$$D_t(\frac{\$}{year}) = \frac{I_t}{s} \qquad (36)$$

3) TAXES

Wind electricity sales revenues are associated necessarily with tax payment [28]. In this study, the tax System applied in the selected Country site is the Value Added Tax, It is applicable when a service is performed, goods are delivered or in case of imports. The applicable tax rate was cited at 14%, applies to electrical energy [32].

4) OPERATION AND MAINTENANCE COSTS

The Operation and Maintenance costs $C_{OM,t}$ are an important factor, which need automated fault detection systems in wind turbines [61]. In this paper, $C_{OM,t}$ present the variable costs made in year t; defined as a percentage of the Investment cost and the Incomes from $AEP_{R,t}$ sales [23]:

$$C_{OM,t} = \eta C_{Sal,t}^{Incomes} + \xi I_t \qquad (37)$$

5) INCOMES

The total yearly Incomes of the generated electricity are composed of two streams: Incomes from electrical energy sales $C_{Sal,t}^{Incomes}$ and Incomes from incentives for green energy production $C_{Inc,t}^{Incomes}$ [23].

$$C_{Incomes,t} = C_{Sal,t}^{Incomes} + C_{Inc,t}^{Incomes} \qquad (38)$$

$$C_{Sal,t}^{Incomes} = C_{Sal} AEP_{R,t} \qquad (39)$$

$$C_{Inc,t}^{Incomes} = C_{Inc}AEP_{R,t} \quad (40)$$

where C_{Sal} is the purchase tariff of electricity and C_{Inc} is Sales due to incentives for green energy production.

C. OPTIMIZATION PROBLEM

Optimization problems are important, particularly in engineering design and decision-making, they consist of determining the feasible solution that corresponds to the extreme value of the objective function [33]. In this paper, the optimization objective is to find the optimal technical characteristics including: D, H, and rated power of machinery; that defines the WT technology design according to wind potential of the selected site. Optimization in our case uses Weibull distribution of wind speeds updated with H. Optimization methods are based in general on three characteristics: design variables, constraints, and the objective function. These parameters are described in the following subsections.

1) DESIGN VARIABLES

Present the input parameters adjusted within lower and upper limits in order to achieve the optimum solution [6], [8]. In this study the selected design variables were: H and D, to observe their effect on *NPV* and *LCOE*. The developed optimization model needs other input parameters, like: the operating range of the wind speed *(u),* the nominal wind speed of wind technology (v_n), and rotor rotational speed (N). For that, an analysis of technical characteristics of 23 existing technologies in the market and most used is carried out [35]. Average adopted was 18.15 rpm for N and 13.2 m/s for v_n. However u was selected from [35].

2) CONSTRAINTS

Constraints are all the restrictions that the optimization should be subject to [6], [8]. Over the optimization of the WT design in this study, all the developed decision support model equations presented before were considered. Furthermore, two other constraints were defined [36]:

- One geometrical constraint, represented in the ground clearance between the blade tip and the ground, where a safety clearance of 15 m was cited by

$$\frac{D}{2} + 15 \leq H \quad (41)$$

- The second constraint was the restriction of maximum output power; view its direct impact on the rotor cost and its lifetime.

$$P_n \leq M \quad (42)$$

With M is the maximum power value allowed for the WT technology

- In addition, Lower and upper bound limits of design variables are also the simplest form of constraints [6]. From the analysis performed before mentioned in the design variables subsection of this

section [34], the most commonly installed power capacity used was in the range of 2 MW. For that, in the next calculations, the M power value and rotor diameter limits were cited to vary from 1 MW up to 2.5 MW and from 40 m to 130 m respectively.

$$1MW \leq M \leq 2.5MW \quad (43)$$
$$40m \leq D \leq 130m \quad (44)$$

3) OBJECTIVE FUNCTION

Is the optimized parameter either minimized or maximized [6]. As discussed before, the optimized function in this study is the *NPV* of all incomes from energy output maximization. *NPV* is a financial indicator used to assess the profitability of an investment; it represents the sum of cash flows. A developed equation from [23], [28] is expressed by equation (45).

$$NPV = -I_{t=0} + \sum_{t=1}^{s} \frac{C_{Incomes,t} - C_{OM,t} - NT_t}{(1+m)^t}) \quad (45)$$

$$NT_t = T_t - D_t \quad (46)$$

With NT_t, were the Net Taxes.

III. RESULTS AND DISCUSSION

In this section, the results obtained are presented and analyzed. As discussed before, this paper aims to present a decision support model that is able to define the optimal design parameters of a WT subject to the available potential of each site. In order to verify its efficiency in finding the optimal design for a specific site selected, the developed model presented previously is tested and applied to a case study. Three Moroccan wind sites were selected for this study, with the average wind speed V and Weibull parameters measured at 10 m of height (form factor k and scale factor C [37], [26] presented in Table 4.

The variation of H impacts the wind speed; this change was computed by extrapolating the Weibull parameters at new heights using the known ones at the initial height (10m) presented in Table 4. A modified method of Justice and Mikhail [58], [59] was used.

The evaluation had considered for the Operation and Maintenance cost a $\eta = 1 \%$ and $\xi = 2 \%$, also the following economic parameters: C_{Sal}, the purchase tariff of electricity in Morocco was 0.094 \$/kWh [38], and C_{Inc}, Sales due to incentives for green energy production was 0.053 \$/kWh. C_{Inc} was estimated in accordance with the Law 13-09 on renewable energies, where the operator can sell the electricity produced to The National Electricity Office (NEO) for a right to use the transmission network set at 0.08 MAD/kWh and a sale price negotiated within the framework of a sales contract negotiated between the operator and NEO. The feed-in tariff is expected to be around 60 % of NEO 's Moyne Voltage (MV) electricity sales tariff [39]. For the peak hours MV = 1.4157 MAD = 0.088 \$/kWh [40]. With, Dirham-Dollard-Euro change in 17/07/2020 (1 \$ = 0.88 € = 9.58 MAD).

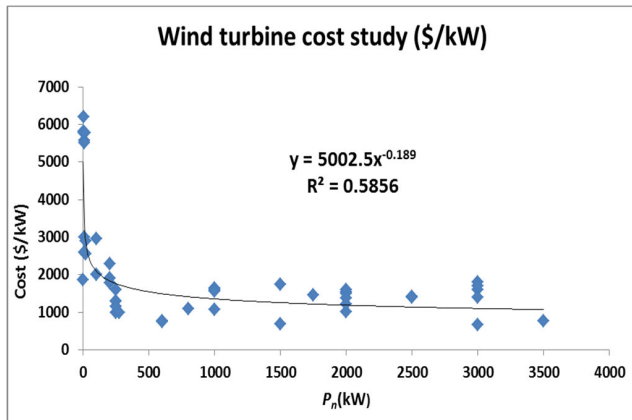**FIGURE 2.** Wind Turbine installation cost function nominal power.

FIGURE 3. Optimized wind turbine technology investment cost disk.

FIGURE 4. Investment model validation.

A. WIND TURBINE COST ASSESSMENT

Viewing that the cost of WT technology is the most expensive component in the investment; we decided to involve a bibliographic study of this cost variation according to available data in the literature and market. This study has assembled 48 wind turbines with different capacities from [28] and [31], [41]–[56], then we fitted a curve by power regression; Coming with a WT cost model that estimate the cost of WT technology for any rated power in ($/kW) with an accepted determination coefficient $R^2 = 0.59$. R^2 varies from 0 to 1 and more it's nearer to 1, more the observed results are described [57]. The model found is described in Fig. 2 and it demonstrates that more the WT technology is important, more its cost became shipper. Between 2 MW to 3.5 MW of WT power with nearly a step of 250 kW intervals, a few decrease is observed in the installed cost.

The model generated from this figure was adopted in this study as the WT cost (C_{WT}) estimation, needed for investment cost evaluation and for the developed decision support model verification in general. Using as an equation, the following formula:

$$C_{WT}(\$/kW) = 5002.5 * (P_n)^{-0.189} \qquad (47)$$

Through a numerical application of the investment cost model using an optimized WT technology by the present decision support model of 2 MW, this developed WT cost model was validated. Fig. 3 presents the results observed and it confirms that C_{WT} is the most important part in investment, with 82 % of share and 18 % for the rest costs.

B. DECISION SUPPORT MODEL VALIDATION

In this section, the performance of the decision support model developed before in the section 2 is verified in two steps:

- Firstly, the developed model, including *LCOE* and *NPV*, are based mainly on investment cost I_t and the real energy produced $AEP_{R,t}$. Wind energy generally has the same mathematical model. However, the I_t was defined differently in literature. That lead us to verify the performance of the adopted I_t model in this study and it
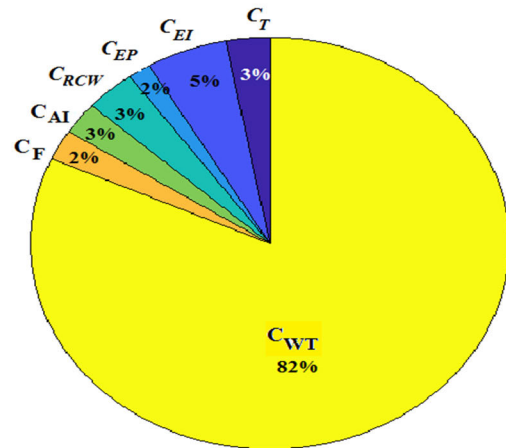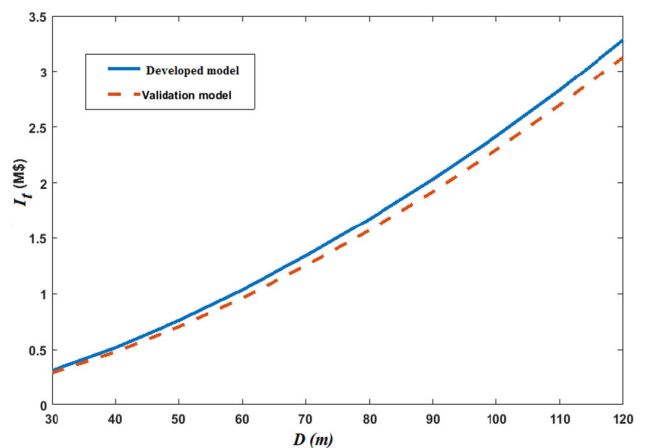
was validated with a previous existing model in the literature [23] at different rotor diameters. A compatibility was observed from the progressions of the I_t, *LCOE* and the *NPV* generated from both models presented in Fig. 4, 5 and 6. So, the developed decision support model works correctly.

- Secondly, the constrained optimization problem was resolved and validated through three widely used optimization algorithms in the WTDO: Genetic algorithm (GA), Fmincon, and the Particle Swarm Optimization algorithm (PSO). Nearly identical results were provided from all algorithms, as presented in Fig. 7. That shows that, the presented optimization problem could be resolved through any kind of algorithms used in WTDO.

C. INVESTMENT COST STUDY

Investment is the first cost determined before starting any project and it's one of the important decision making signs. In wind projects, it's affected by many elements like: WT cost, Transportation cost, and other costs as mentioned before in equation (25). This section will present evaluation results of this cost. The detailed investment model adopted in this
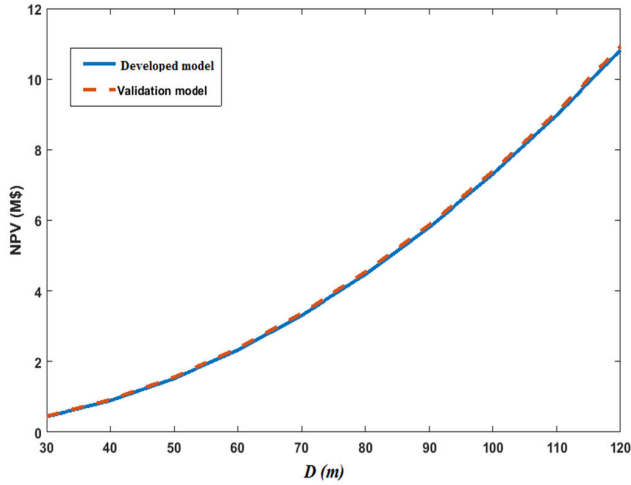
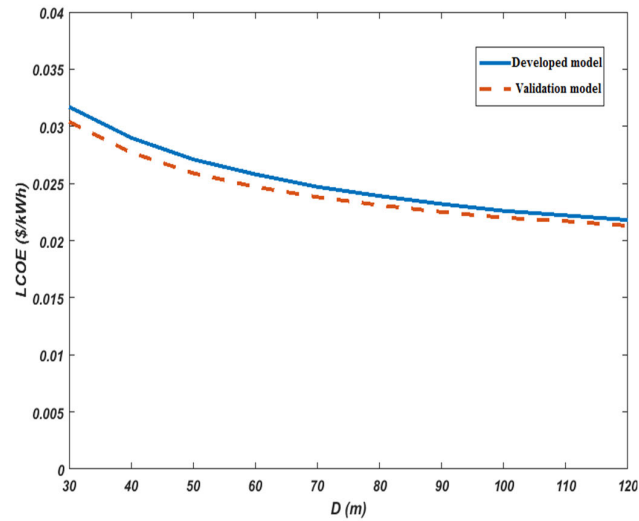**FIGURE 5.** NPV model validation.

FIGURE 7. Optimization problem validation.

FIGURE 6. LCOE model validation.

FIGURE 8. Assembly and Installation costs (CAI) and Foundations cost (CF) function rotor diameter variation.

study presented before by equations (26 up to 35) shows that, it is function initially of the main WT design parameters researched by this study: rotor diameter (D), Tower hub height (H), and WT nominal power (P_n). To examine how its cost acts to the variation of these parameters, we involve a study; whose results are presented in Fig. 8 and 9.

- Fig. 8 presents Assembly and Installation costs (C_{AI}) and Foundations cost (C_F) function rotor diameter variation. Linear and exponential trend lines were observed in the evolution of C_F and C_{AI} respectively; At 100 m of diameter, the C_{AI} cost exceeds the C_F cost, this can be explained by the fact that more the rotor diameter increase, more the blades length increase and more the gearbox and generator units needed are bigger. So, from 100 m of WT rotor diameter, to collect and install all these components is much more expensive than the cost of foundation construction.

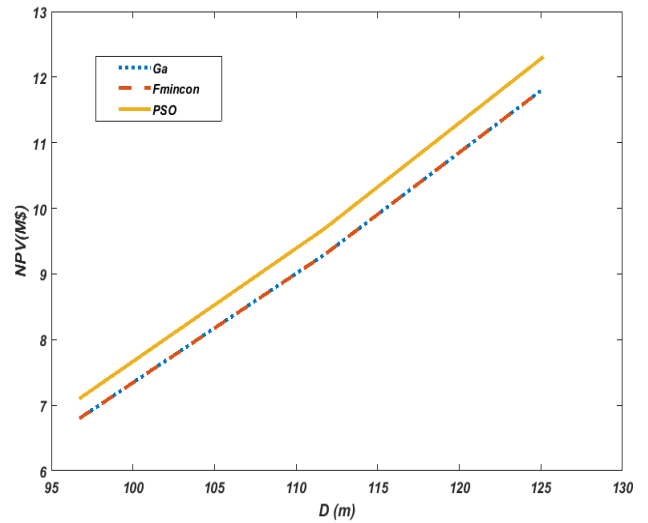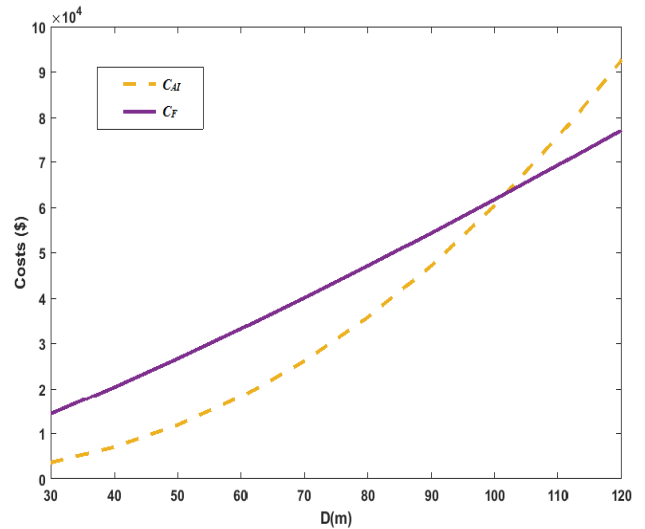- Fig. 9 shows the costs curve of: Roads and Civil Work (C_{RCW}), Transportation (C_T), Engineering, and

Permits (C_{EP}), and Electrical Interface (C_{EI}) function WT nominal power P_n variation. Terrain and roads preparation, getting the permission and certifications for installation in addition to the material needed for electrical energy connection like transformer and an important wiring conducted to expensive costs components (C_{EI} and C_{RCW}) per kW installed followed by C_T and C_{EP} costs. Since 2 MW power nearly of WT technology, C_T passes above C_{RCW} cost, which could be explained also as mentioned in the previous paragraph by the biggest material transported. More precisely due to the long blades transported in this power range of WT bringing on, high cost of transportation.

D. OPTIMAL DESIGN PARAMETERS RESULTS

In this phase, the results of the optimization problem of the decision support model developed are presented, defining the
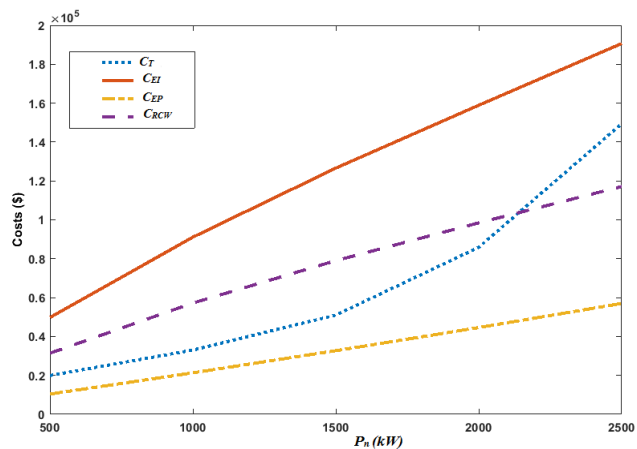
FIGURE 9. Roads and Civil Work costs (C_{RCW}), Transportation (C_T), Engineering and Permits (C_{EP}), and Electrical Interface (C_{EI}) curve function wind turbine nominal power variation.
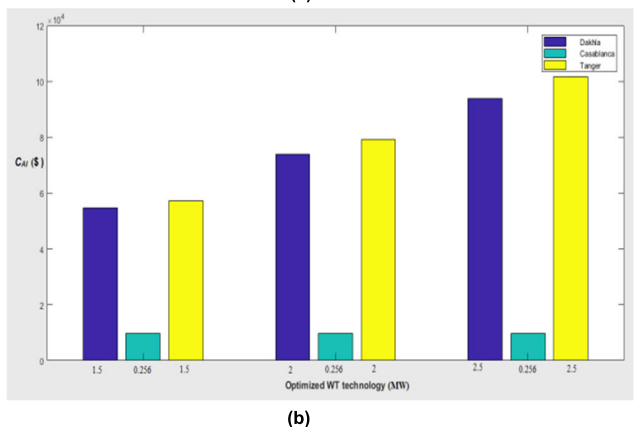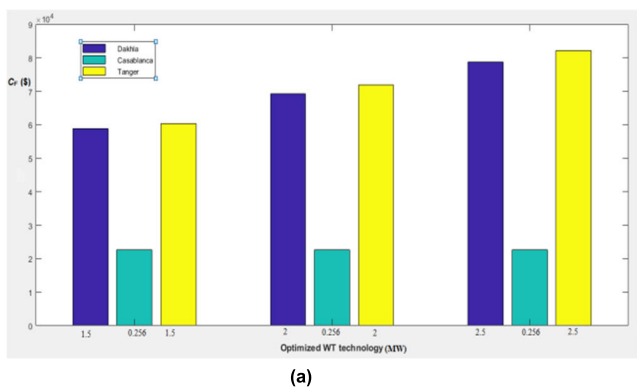

(a)

(b)

FIGURE 10. Fondation cost C_F and Assembly and Installation cost C_{AI} for the optimized WTs in Dakhla, Casablanca and Tanger.

TABLE 1. Optimized WT technologies design parameters for the selected sites.

Site	constraints	Optimized WT technical parameters			Coresponding NPV(M$)
		P_n (MW)	D (m)	H (m)	
Dakhla	$P_n \leq 1.5$ MW	1.5	97	63	6.80
	$P_n \leq 2MW$	2	112	71	9.30
	$P_n \leq 2.5$ MW	2.5	125	78	11.82
Tantan	$P_n \leq 1.5$ MW	0.256	40	35	-0.23
	$P_n \leq 2MW$	0.256	40	35	-0.23
	$P_n \leq 2.5$ MW	0.256	40	35	-0.23
Tanger	$P_n \leq 1.5$ MW	1.5	99	64	1.61
	$P_n \leq 2MW$	2	116	73	2.33
	$P_n \leq 2.5$ MW	2.5	130	80	3.04

TABLE 2. Optimized WTs economic indicators estimated for each site.

Site	P_n(MW)	I_t (M$)	$C_{OM,t}$ (M$/y)	$C_{Sal,t}^{Incomes}$ (M$/)	$C_{Inc,t}^{Incomes}$ (M$/)	$C_{Incomes,t}$ (M$/y)	T_t (M$/y)	D_t (M$/y)
Dakhla	1.5	2.287	0.053	0.711	0.399	1.110	0.148	0.114
	2	2.910	0.068	0.960	0.539	1.499	0.200	0.145
	2.5	3.537	0.083	1.211	0.680	1.892	0.253	0.177
Casablanca	0.256	0.542	0.011	0.012	0.006	0.018	0.001	0.027
Tanger	1.5	2.291	0.049	0.270	0.151	0.421	0.052	0.115
	2	2.918	0.062	0.367	0.206	0.574	0.072	0.146
	2.5	3.517	0.075	0.462	0.260	0.722	0.091	0.176

optimal design characteristics found for the WT technology in the studied sites presented before. According to the constraints on D, H and defined in section II and by restricting the upper limit of rated power permitted at 1.5, 2, and 2.5 MW, three different WT technologies have been found as optimal solutions in Dakhla and Tanger. A linear propagation between the nominal power P_n and the *NPV* was observed when the selected site has a medium and powerful wind profile, view that the optimal WT design was found at the limit

power constraints cited in Dakhla and Tanger as presented in Table 1. The optimized WT design results in those both locations were acceptable presenting good *NPV*. However, a single optimized WT design was provided in Casablanca despite the increase in the allowed power constraint; that

TABLE 3. Rotor maximun power coefficient, $C_{p,r,max}$, generated energy, $AEP_{R,t}$ and LCOE for the optimized technologies.

Site	P_n (MW)	k_2	C_2 (m/s)	$AEP_{R,t}$ (GWh/y)	$C_{p,r,max}$	LCOE ($/kWh)
Dakhla	1.5	2.534	11.832	7.564	0.512	0.023
	2	2.543	11.912	10.211	0.512	0.022
	2.5	2.552	11.978	12.887	0.510	0.022
Casablanca	0.256	1.481	4.276	0.123	0.511	0.185
Tanger	1.5	1.726	6.967	2.869	0.490	0.042
	2	1.733	7.034	3.909	0.479	0.040
	2.5	1.739	7.087	4.917	0.468	0.039

TABLE 4. Weibull parameters and average wind speed of the sites selected.

Site	k	C(m/s)	V(m/s)
Dakhla	2.38	10.58	9.38
Casablanca	1.42	3.8	3.45
Tanger	1.62	6.012	5.38

could be explained by the low wind potential available in that site. Where, the results showed a negative value for the NPV, which demonstrate that the profitability of a project in that site is not profitable. As the objective function was to maximize the *NPV* subject to constraints announced before, the *NPV* was found to be much affected by the enhancement of rotor diameter; which increase also the energy output ($AEP_{R,t}$) and investment cost (I_t). Table 2 shows that, the increase in the investment in the optimized technologies in Dakhla and Tanger does not affect much the *NPV* results in front of the important incomes ($C_{Incomes,t}$) estimated to be generated over the WT lifetime. That explains the results obtained. Tax payment (T_t) and depreciation amount (D_t) increase also with incomes and investment generated respectively. Table 2 demonstrates well, why the NPV calculated was negative in Casablanca site, related to the low incomes $C_{Incomes,t}$ registered. Also, a change in the investment I_t was observed by changing the location. As the power of the optimized WTs in Dakhla and Tanger was closed, the cost parameters depending on power were the same; leading to near I_t in those sites. Cost parameters of the I_t which varies with the diameter D mainly C_F and C_{AI} show more the effect of location in the I_t generated. Fig. 10 present the results obtained and we can observe that every location has its own C_F and C_{AI} costs.

Generated energy ($AEP_{R,t}$) and its cost (*LCOE*) of each optimized WT in different sites are presented in Table 3. k_2 and C_2 are the extrapolated Weibull parameters in accordance with Height (H) provided by the decision support model for the optimized WTs in each site. More the design of WT technology is big, more the *LCOE* produced decreases. In this study, rotor maximum power coefficient $C_{p,r,max}$ and the *LCOE* were found approximately constant because there is not widely difference between the power ranges provided for

these optimized WT technologies. That reinforces our study involved before, presented in the WT cost assessment section, when the cost of the kW installed was observed approximately constant in this power range. In the end, it seems that the third optimized WT design provided by the present decision support model is the most suitable for the studied sites, mainly Dakhla and Tanger providing the best trade-off between *NPV*, *LCOE* and the generated energy. AEP_t. While, Cacsablanca was classified as no profitable site for wind projects.

IV. CONCLUSION AND FUTURE WORKS
In this paper, a new decision support model based techno-economic optimization procedure for optimal WT design is developed and proposed. By selecting three different wind sites, the developed model is verified and significant results are achieved. This model gives the adequate WT design, function the available wind potential in the selected site. This developed model interacts well with the variation of location, it demonstrates that the investment I_t change and shows the profitability of a project with the optimized WT design of the studied sites. Casablanca was found as no profitable site for wind projects because of the low wind potential available which leads to negative *NPV*. However, the optimized WTs designs in Dakhla and Tanger have presented good *NPV* results. This model acts as an aid for strength decision making in the wind sector, where the most suitable WT design information is provided for the site of interest. In this research, optimization of: the layout of the optimized WT technologies in the WF, WT materials, and aerodynamic effects, were not included in the optimization design, which constitute a recommendation for future works.

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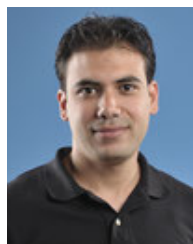
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