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Techno-Economic Comparison of Operational Aspects for Direct Drive and Gearbox-Driven Wind Turbines

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Abstract—The majority of wind turbines currently in operation have the conventional Danish concept design—that is, the three-bladed rotor of such turbines is indirectly coupled with an electrical generator via a gearbox. Recent technological developments have enabled direct drive wind turbines to become economically feasible. Potentially, direct drive wind turbines may enjoy higher levels of availability due to the removal of the gearbox from the design. However, this is only a theory: so far not substantiated by detailed analytic calculation. By providing such a calculation, this paper enables us to quantitatively evaluate technical and economic merits of direct drive and gearbox-driven wind turbines.

Index Terms—Markov chain, operational comparison, reliability, wind turbines.

I. INTRODUCTION

WORLDWIDE installed capacity of wind generation is growing significantly and is likely to continue to increase in the future. The twin policy objectives of energy security and climate change mitigation have resulted in economic incentives, which in turn, have driven investment in wind energy. Taking the U.K. as an example, Fig. 1 shows how the installed capacity has grown since 2005—by the end of 2008, the installed capacity broke through the 3 GW barrier [1]. This 3 GW capacity consists of 2276 individual wind turbines (WTs) [2], the vast majority of which are conventional Danish concept, gearbox-driven machines. However, recent technical strides have enabled direct drive machines to become economically feasible.

Since a gearbox is not included in the direct drive concept, it is clear that the reliability and availability of the WT will improve—if it can be assumed that all other factors remain unchanged. On the other hand, it has been reported in the paper that failure rates of electrical components and generators of direct drive wind turbines are significantly higher than those of gearbox-driven equivalents [3], [4]. The purpose of this paper is to establish if there is a technical and/or economic advantage in deploying direct drive wind turbines instead of gearbox-driven

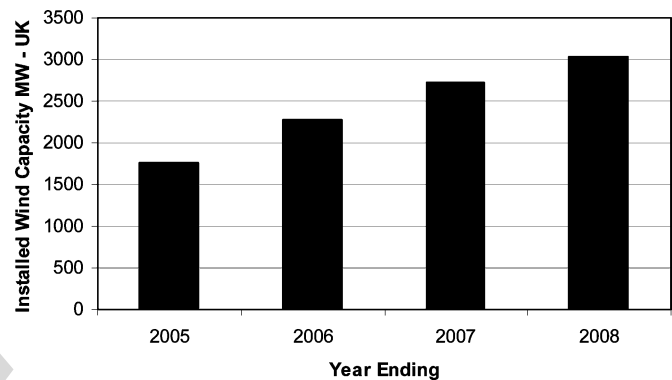


Fig. 1. Recent growth in U.K. wind generation capacity [2].

machines. This analysis is based on quantitative modeling of the operation, failure, and maintenance of wind turbine units as proposed in [5]. Such an operational comparison of different wind turbine concepts is not available in the existing literature.

II. COMPARISON OF CONCEPTS

A. Conventional Danish Concept—Gearbox Driven

The conventional Danish concept comprises a three-bladed upwind rotor, which revolves on the horizontal axis (sometimes called horizontal axis wind turbine, HAWT). The coupling between rotor and electrical generator is indirect and is achieved via a gearbox in order to increase the rotational speed to a level that can drive a relatively small-diameter, lightweight induction generator. A conceptual view of the energy conversion process for such a typical modern wind turbine is outlined in Fig. 2.

The whole wind turbine assembly rotates into the prevalent wind direction on its vertical axis by means of an electromechanical yaw system. Once facing into the wind, control of the mechanical input power is achieved either by aerodynamic design of the rotor (stall control) or by actively changing the angle of attack of the rotor blades to the wind (pitch control) via electrical motors or hydraulics.

The electrical configuration of Danish concept WTs is influenced by mechanical aspects, as one main objective of the WT mechanical design is to minimize the weight at the top of the tower, where the nacelle (containing the generator) is located in modern HAWTs. This means the generator has to be as light as possible and must have a relatively small physical footprint. For this reason, induction generators are employed: induction generators have the added advantage of being more robust than

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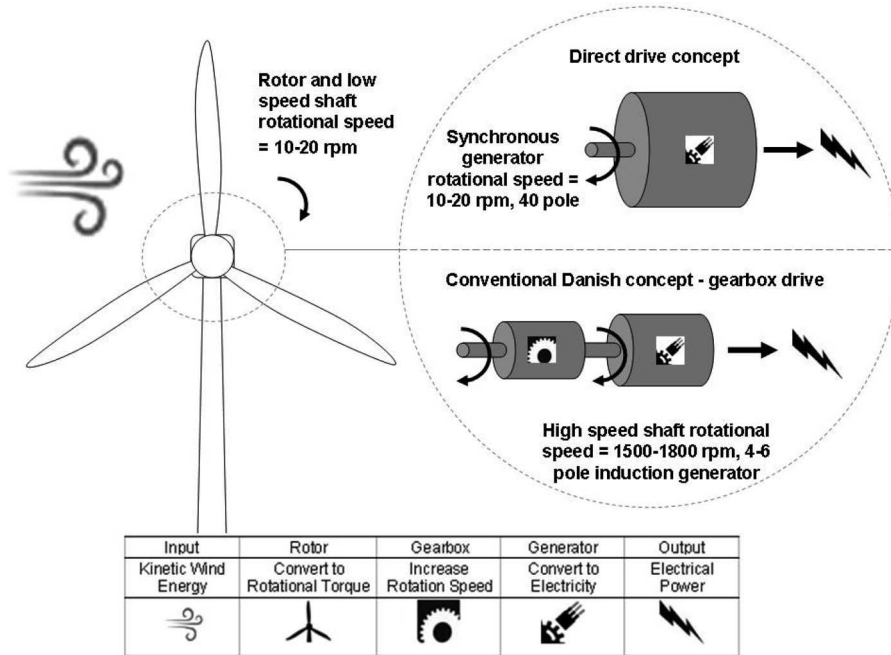


Fig. 2. Process diagram for gearbox-driven and direct drive wind turbines.

69 synchronous generators and tend to have fewer electrical faults.
 70 However, due to the low rotational speed of the wind turbine
 71 rotor, a gearbox has to be used to increase the rotation from tens
 72 of revolutions per minute at the gearbox input to thousands at
 73 the output. The primary reason for this is the low number of
 74 induction generator poles.

75 The older Danish concept WT's that operated at fixed speed
 76 employed squirrel cage induction generators; however, newer
 77 variable speed technology has resulted in a switch to doubly fed
 78 induction generators (DFIG), which are now the dominant wind
 79 turbine generator configuration. The reason for the dominance
 80 of this configuration is that it represents a good compromise
 81 between economy and performance. It is relatively economic
 82 because it has only a partial electronic converter rated at $\sim 30\%$
 83 of the generator output [6], not a full converter.

84 B. Direct Drive Concept

85 In a direct drive WT, the main rotor is coupled to the generator
 86 input shaft, eliminating the need for a gearbox in the design. In
 87 order to generate power at such a low rotation speed, the gener-
 88 ator has to have many pole pairs, and usually a synchronous
 89 generator is employed. This implies much greater dimensions
 90 and weight as compared with an induction generator. In addition,
 91 a fully rated electronic power converter is required, which
 92 increases the cost of the system.

93 C. Types of Comparison

94 There are several examples in the published literature where
 95 a comparison is made between the two concepts. For example,
 96 Tavner *et al.* [3] focused on how the configuration of the
 97 WT generator and converter in different design concepts af-
 98 fected overall WT reliability. The data utilized by the authors

had enough detail to enable a direct reliability comparison of
 three WT concepts: fixed speed with gearbox, variable speed
 with gearbox, and variable speed direct drive (no gearbox: syn-
 synchronous generator). The main conclusion was that direct drive
 systems are less reliable than models with a gearbox because
 the potential increase in reliability due to elimination of gear-
 box failures is cancelled out by increased generator, inverter,
 and electrical system failures.

Interestingly, the authors recognized that overall availability
 would also be affected by component repair times: In this sense
 direct drive systems may have an advantage, as mean time to
 repair (MTTR) for a gearbox is likely to be very much more
 than MTTR for an electronics subassembly. As yet, no other
 research has addressed this operational comparison of the two
 concepts.

Echavarria *et al.* [4] analyzed a similar dataset, which pro-
 vides some highly relevant information regarding the reliability
 of the two WT concepts. In particular, the data suggest that gener-
 ator failures in direct drive WT's are roughly two times the
 gearbox-driven equivalent (0.22 failures per annum compared
 with 0.12 suggested by Tavner *et al.* [7]). Similarly, power elec-
 tronics failures in direct drive synchronous machines are quan-
 tified as 1.03 failures per annum compared to 0.661 suggested
 in [7] for the induction machine equivalent.

Polinder *et al.* [6] examine direct drive and gearbox-driven
 WT concepts from the viewpoint of design and economic per-
 formance. The authors define a typical Danish concept WT with
 a three-stage gearbox (3GDFIG) and a direct drive machine cou-
 pled to a synchronous generator (DDSG). Three other concepts
 are also defined (DFIG with a single-stage gearbox, permanent
 magnet direct drive, and permanent magnet single-stage
 gearbox) but these are not considered in this paper due to the
 fact that they are not currently deployed in significant numbers.

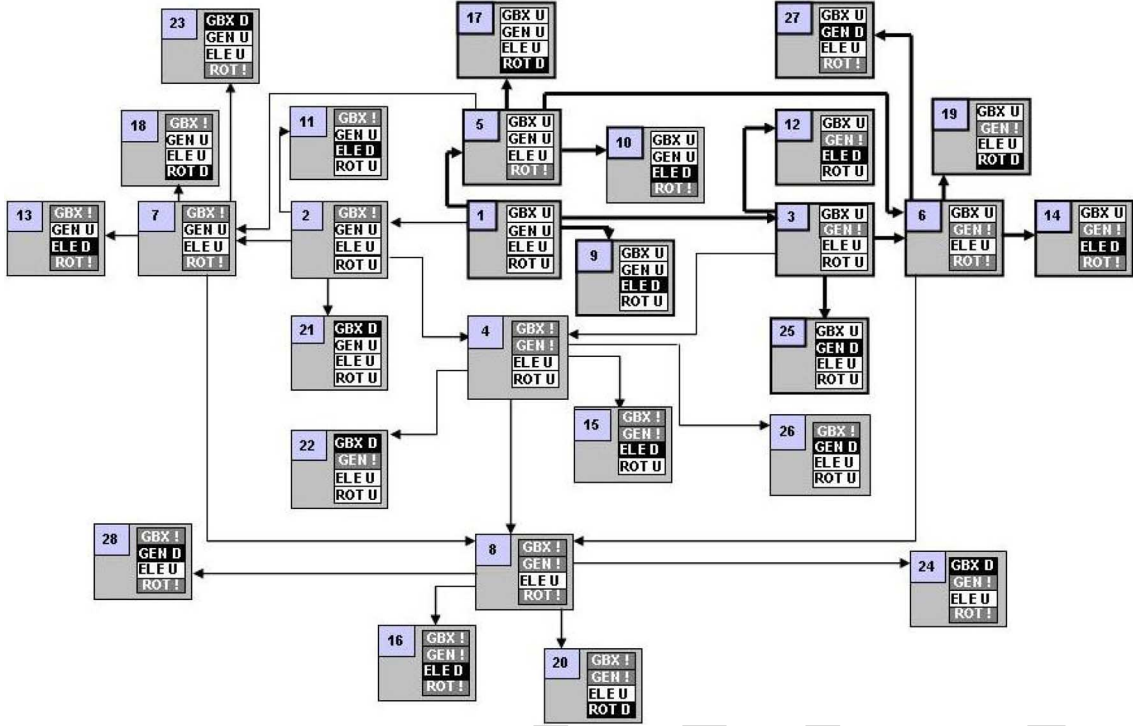


Fig. 3. Markov chain of key wind turbine components. Bold arrows and boxes indicate direct drive system.

132 The authors again highlight the need for further work to better
 133 understand the reliability and availability benefits of adopting
 134 different WT design concepts—a requirement which this paper
 135 aims to meet.

136 III. MODELING OF WIND TURBINE CONCEPTS

137 A. Physical Modeling of Wind Turbine Components

138 In order to build an accurate operational model, the key physical
 139 components of the WT must be identified and a suitable
 140 mathematical representation decided upon. It was reported in [5]
 141 that using a combination of failure rate data, downtime estimates,
 142 and expert opinion, the key components of a gearbox-driven WT
 143 could be identified as follows:

- 144 1) gearbox (GBX);
- 145 2) generator (GEN);
- 146 3) rotor blades (ROT); and
- 147 4) inverter, electronics, and control (ELE).

148 In terms of the mathematical representation, a Markov chain
 149 solved via Monte Carlo simulation (MCS) was identified in pre-
 150 vious studies as a suitable model framework [5]. The Markov
 151 chain representation has been very successfully applied to power
 152 systems infrastructure deterioration and failure modeling, in-
 153 cluding wind turbines [8], [9]. The main problem with these an-
 154 alytically solved models is that the introduction of constraints,
 155 such as weather-constrained maintenance, makes obtaining a so-
 156 lution rather difficult. Although not computationally efficient,
 157 MCS methods overcome this difficulty and have been applied
 158 to similar problems in the past [10], [11]. Since the problem
 159 considered is essentially a planning problem, the time required
 160 to get the solution is of little importance.

161 It has been assumed that three states are sufficient to capture
 162 the deterioration and failure processes of the GBX, GEN, and
 163 ROT. ELE failures are assumed to be instantaneous and, there-
 164 fore, require only binary representation. When all four compo-
 165 nents are modeled in a single Markov state-space, the total
 166 number of states is 54. This is cut down to 28 by assuming that
 167 degradation and failure events of different WT components can-
 168 not happen concurrently. Furthermore, for a GBX, GEN, or ROT
 169 failure to occur, the system must transit through the deteriorated
 170 (intermediate) state before outright failure.

171 The possible Markov states and transitions for the overall WT
 172 system are visualized in Fig. 3. The three possible deteriora-
 173 tion levels are indicated as fully up (U), deteriorated (!), and
 174 down (D).

175 All 28 states and transitions are possible for the case of
 176 gearbox-driven WTs. The obvious physical difference when
 177 modeling a direct drive WT is that there are no gearbox states.
 178 Thus, the bold arrows in Fig. 3 refer to the transitions and states
 179 that represent direct drive WTs, as a 12-state subset.

180 The arrows in Fig. 3 represent transition probabilities (e.g.,
 181 probability of transition from state a to state b is $p_{a,b}$), whose
 182 magnitude must be estimated. These probabilities depend only
 183 on the current state of the system (s) at current time t_k .
 184 Equation 1 expresses this “memory-less” property of a Markov
 185 chain

$$185 \quad p_{a,b} = p(s_b, t_{k+1} | s_a, t_k) \quad k = 1, 2, 3, \dots \quad (1)$$

186 Furthermore, the transition probabilities are constant in time:
 187 This is the “time-stationary” property. The magnitude of all
 188 transition probabilities from one state (a) to all others in the

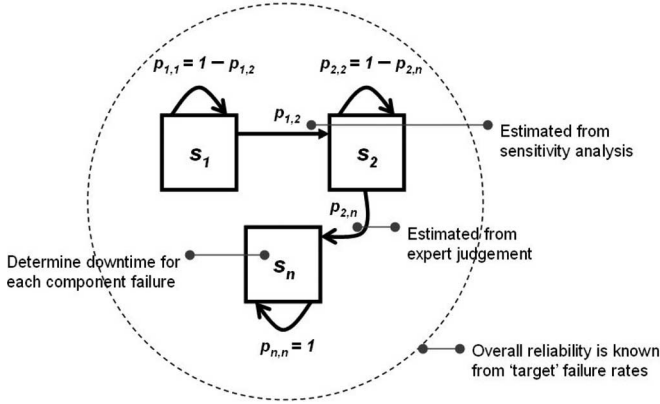


Fig. 4. Parameter estimation for Markov chain.

189 system must sum to unity. This is shown in (2)

$$\sum_b p_{a,b} = 1 \quad a = 1 \dots n \quad (2)$$

190 where n is the total number of system states. For convenience,
 191 the transition probabilities for the whole system are expressed
 192 in a transition probability matrix (TPM). For the case of the
 193 system in Fig. 3, the TPM is shown in (3). Note that only the
 194 possible transitions (indicated in Fig. 3. with arrows) need to be
 195 estimated—all other probabilities are equal to zero

$$\text{TPM} = \begin{bmatrix} p_{1,1} & p_{1,2} & \dots & p_{1,28} \\ p_{2,1} & p_{2,2} & \dots & \dots \\ \dots & \dots & \dots & \dots \\ p_{28,1} & \dots & \dots & p_{28,28} \end{bmatrix} \quad (3)$$

196 The TPM values are estimated based on the partial informa-
 197 tion available, as illustrated in Fig. 4. A good estimate of the
 198 overall reliability (“target” failure rate) is known from the work
 199 of Tavner *et al.* [7].

200 Similarly, downtime estimates can be made for the outage of
 201 the key components [5]. The probability of an outright failure
 202 in a deteriorated condition ($p_{2,n}$) can be estimated based on
 203 expert opinion of times to failure. The remaining parameters can
 204 then be estimated by conducting sensitivity analyses (previously
 205 reported in [5]).

206 B. Data for Physical Model

207 The study of Tavner *et al.* [7] provided estimates of compo-
 208 nent failure rates based on populations of Danish and German
 209 WTs. The German population was larger (over 4,000 machines)
 210 and the population consisted of more modern WTs. Therefore,
 211 the German figures are used to fit the gearbox-drive WT physical
 212 model.

213 On the other hand, Echavarria *et al.* [4] suggest modifications
 214 to the GEN and ELE failure rates for direct drive machines.
 215 Taking this into account, the target failure rates for both WT
 216 concepts can be visualized in Fig. 5.

217 Downtimes for the failure types are as follows: GBX—30
 218 days, GEN—21 days, ELE—1 day, and ROT—30 days. They
 219 are based on domain knowledge elicited in [5]. Using this

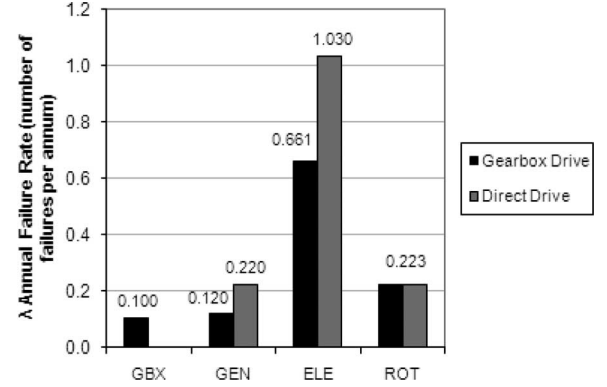


Fig. 5. Reliability for gearbox-driven and direct drive wind turbines.

information, the TPM parameters were estimated based on the
 iterative procedure devised in [5]. The procedure is based on
 sensitivity analysis estimation of the unknown parameter $p_{1,2}$
 (see Fig. 4).

The Markov chain has been defined for both gearbox-driven
 and direct drive concepts. In the following sections, other as-
 pects of operational modeling—which are common to both
 concepts—are discussed.

228 C. Energy Yield Modeling

229 There are two main components to the energy yield model.
 230 These are the wind speed model and the power curve model. The
 231 wind speed (WS) model previously used by the authors [5] was
 232 based on a single parameter autoregressive process, or AR(1).
 233 This is displayed in (4), where μ is the mean of a wind speed
 234 time series, ϕ is the autoregressive parameter and the process is
 235 driven by a Gaussian white noise function ε_t .

$$\text{WS}_t - \mu = \phi (\text{WS}_{t-1} - \mu) + \varepsilon_t \quad (4)$$

236 The dataset used to fit the model was sourced from a su-
 237 pervisory control and data acquisition (SCADA) system of a
 238 U.K. wind farm. Estimation of ϕ and ε_t was achieved by lin-
 239 ear least squares, while classification of the model was based
 240 on inspection of the autocorrelation and partial-autocorrelation
 241 functions.

242 The power curve model is based on a manufacturers’
 243 datasheet for a 2 MW WT [12], which is sampled and the theo-
 244 retical equation for the power (P) in the wind (5) is matched
 245 to the data samples by modeling the coefficient of performance
 246 C_p

$$P = \frac{1}{2} \rho \pi r^2 v^3 (\times C_p). \quad (5)$$

247 In (5), ρ is air density (kg/m^3), r is the rotor radius (m), and v
 248 is air velocity through the WT rotor (m/s). The re-created power
 249 curve is shown in Fig. 6 and has cut in, rated, and cut out wind
 250 speeds of 4, 14, and 25 m/s, respectively. It is assumed that both
 251 WT concepts adhere to the same power curve.

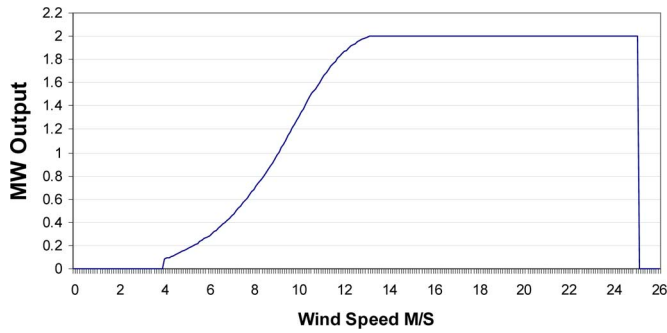


Fig. 6. Power curve for 2 MW wind turbine [12].

252 D. Maintenance Modeling

253 It is assumed that a six-monthly periodic maintenance plan
 254 is adopted for both WT concepts. The assumptions in the main-
 255 tenance model are that maintenance actions restore the WT to
 256 the fully up state (state 1 in Fig. 3) and that each maintenance
 257 visit involves a one-day outage. The model can easily accom-
 258 modate condition-based maintenance (CBM), but since mainte-
 259 nance paradigms are not the focus of this paper, this possibility
 260 is neglected.

261 If a component failure occurs, a maintenance team is dis-
 262 patched immediately. There is a probability that a component
 263 replacement is necessary (replacement factor $\beta = 0.6$) or that it
 264 can be repaired ($1 - \beta = 0.4$). This is based on an analysis by
 265 Ribrant and Bertling [13] who highlighted that around 60% of
 266 gearbox failures require a replacement rather than a repair ac-
 267 tion. Similar figures have not been published for the other WT
 268 components; therefore, due to the lack of data, they are assumed
 269 to have the same probabilities of repair and replacement as the
 270 gearbox.

271 If the component can be repaired, it is restored instanta-
 272 neously to a functional state. If a replacement is required, down-
 273 time lasts as follows: GBX—30 days, GEN—21 days, ELE—1
 274 day, and ROT—30 days. This is based on the experience of a
 275 wind farm operator. Furthermore, maintenance actions are con-
 276 strained by wind speed as in [5]. This means that nacelle-related
 277 replacements need wind speed conditions of less than 10 m/s,
 278 while rotor maintenance cannot be conducted in wind speeds
 279 over 7 m/s.

280 E. Costs and Revenue

281 It is of interest to compare the economic merits of the two WT
 282 configurations. Therefore, a cost model has been built which
 283 generates revenue from energy yield and incurs maintenance
 284 and replacement costs.

285 Polinder *et al.* provided costs for gearbox-driven and direct
 286 drive wind turbine components rated at 3 MW [6]. Figures can
 287 be derived for 2 MW machines of both types assuming that the
 288 cost varies linearly with the rating. These costs are provided in
 289 Table I. The rotor cost was not provided in [6] and so the value
 290 derived previously by the authors of this paper is adopted [5].
 291 In the case of a component replacement, the full cost in Table I

TABLE I
COMPONENT COSTS FOR WIND TURBINE CONCEPTS

Component	Gearbox driven	Direct drive
	Cost £	
GBX	121,733	N/A
GEN	177,066	313,740
ROT	210,000	210,000
ELE	22,133	66,400

is incurred. In the case of a repair, it is assumed that only 10%
 of this cost is incurred (repair cost factor $\alpha = 0.1$).

Besides the costs of the components themselves, the cost of
 labor and equipment hire has been included. Andrawus [14]
 showed that skilled labor for WT repairs costs around £50/h. It
 has been assumed that three crew working an 8 h shift consti-
 tute one maintenance action. Therefore, the cost of labor (C_{LAB})
 is £1200 per action. Similarly, hire rates for telescopic cranes
 (C_{EQ}) needed to perform nacelle component lifting operations
 have been quantified by industry sources [15] as £1500 per
 week. Lost revenue due to downtime is also taken into account
 (R_{LOST})—this is wind speed-dependent. These costs are com-
 bined with the component costs (see Table I) to calculate re-
 placement (6), repair, (7) and O&M cost (8)

$$C_{replace} = \beta\lambda (C_{CAP} + C_{LAB} + C_{EQ} + R_{LOST}) \quad (6)$$

$$C_{repair} = (1 - \beta)\lambda \times (\alpha C_{CAP} + C_{LAB} + C_{EQ} + R_{LOST}) \quad (7)$$

$$C_{O\&M} = C_{replace} + C_{repair} \quad (8)$$

The revenue model for the WT is based on the energy yield in
 each one-day simulation interval. Using equations (4) and (5),
 this energy yield Y can be calculated as the power (see Fig. 6)
 multiplied by a time interval Δt . The energy yielded in a year is
 then calculated by summing the output over all individual days
 in the year.

The revenue stream R can then be calculated by applying
 equation (9). MP represents the market price for electricity and
 renewable obligation certificates (ROCs). For this paper, MP_{elec}
 and MP_{ROC} are set to £36 and £40 per MWh, respectively.
 Although in reality, electricity and ROC prices fluctuate, the
 annual mean is adequately represented by the figures presented
 as

$$R = Y (MP_{elec} + MP_{ROC}) - C_{O\&M} \quad (9)$$

It is important to note that any differences in yield between the
 two WT concepts will be related to the reliability and downtime
 (see Fig. 5 and Section III-D) of the two WT concepts, rather
 than to the differences in the electrical design. This is because the
 same power curve (Fig. 6) has been used for both WT concepts.

Polinder *et al.* showed that the theoretical difference in yield
 between a 3 MW direct drive machine (DDSG) and a typical
 3 MW DFIG (DFIG3G) is +150 MWh [6], if the detail of the
 electrical machine design is taken into account. Assuming
 this difference scales linearly with WT rating, it means that for
 the 2 MW machines considered in this paper, the direct drive
 machine yields roughly 100 MWh more per annum than the

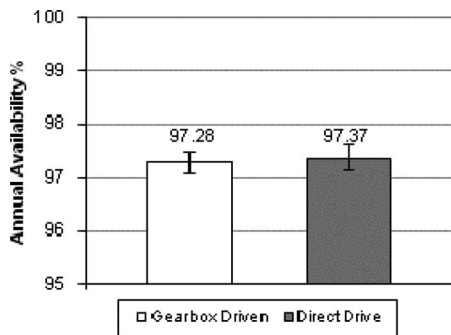


Fig. 7. Availability comparison of wind turbine concepts.

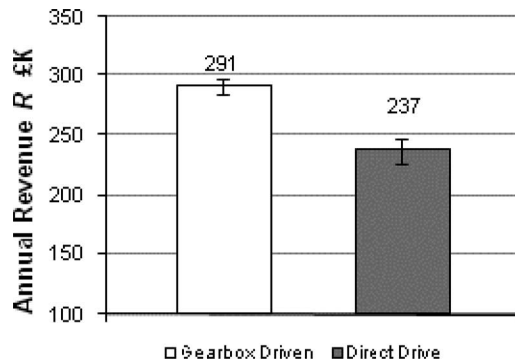


Fig. 8. Economic comparison of wind turbine concepts.

331 DFIG. Applying (9) and neglecting the O&M cost, this translates
 332 to £7600 more revenue per annum for the direct drive machine.
 333 Therefore, the annual revenue for the direct drive machine has
 334 been boosted by £7600 per annum in the studies that follow.

335 F. Program Operation

336 The models outlined in this section were coded in FORTRAN
 337 95, with the SCADA database interface for the wind speed
 338 model written using f90SQL [16]. The statistical programming
 339 language R was used to fit the wind speed model defined in (4).
 340 The resultant capacity factor of the wind turbine based on the
 341 simulated wind speed and power curve is just under 30%.

342 The confidence limit L of the simulation results can be measured
 343 by applying (10). Taking the Student- t distribution, and
 344 setting the level of confidence to 95%, it means that L can be
 345 specified, provided that the number of samples (N) and standard
 346 deviation (σ) of the quantity are known. L is shown in the results
 347 as confidence bands that specify the accuracy of the results

$$L = \pm \frac{2.045 \times \sigma}{\sqrt{N}}. \quad (10)$$

348 IV. RESULTS

349 A. Operational Comparison of Concepts

350 Two comparisons are made in order to benchmark the operational
 351 merits of the two WT concepts: a technical comparison
 352 and an economic comparison. The first result in Fig. 7 compares
 353 the overall availability of the two concepts.

354 It can be seen that despite removing the gearbox from the
 355 design, the direct drive concept has similar overall availability
 356 to the gearbox-driven machine. Although the availability is
 357 marginally better for the case of the direct drive machine, the
 358 confidence limits show that this technical benefit is uncertain.
 359 It should be noted that grid availability is not included in this
 360 paper.

361 The second result, displayed in Fig. 8, shows the revenue
 362 generated (9) for both concepts. This shows that the gearbox-
 363 driven design has a much larger economic benefit than the direct
 364 drive concept.

365 The contribution to the revenue of increased energy yield due
 366 to avoidance of downtime is negligible in the case of Fig. 8
 367 (direct drive machine avoids loss of ~ 6.35 MWh more energy

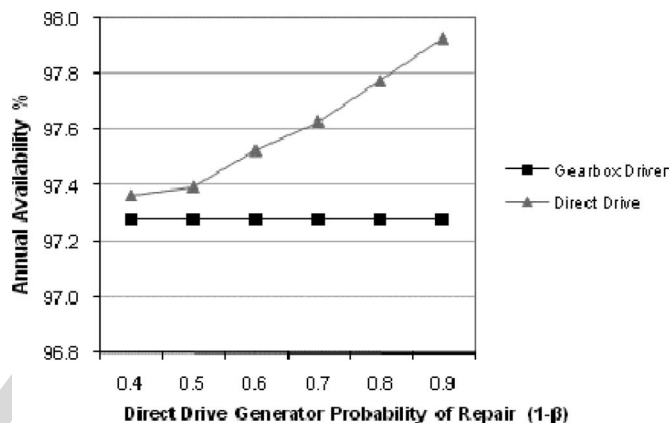


Fig. 9. Availability improvement of direct drive wind turbine as a function of generator reparability.

than gearbox-driven, economic benefit = £482 per annum).
 Therefore, the large disparity in revenue (\sim £44 000 per annum)
 must be due to incurred repair and replacement costs. The large
 increase in cost and failure rate for the generator in particular
 appears to economically handicap the direct drive concept.

374 B. Operational Impact of Generator Reparability

375 One possible explanation of the superior economic performance
 376 of the gearbox-drive concept is that a replacement factor
 377 (β) of 0.6 per failure (see Section III-D) may represent a pes-
 378 simistic view of the “reparability” of a WT synchronous gener-
 379 ator. Indeed, it has been reported elsewhere [3] that the increase
 380 in generator failure rate for the direct drive concept is related
 381 to electrical failures rather than mechanical failures. Electrical
 382 faults will be less likely to involve a complete component re-
 383 placement; therefore, the robustness of the conclusion drawn
 384 from Fig. 8 is tested by modeling different levels of reparability
 385 for the direct drive generator.

386 The replacement factor β was reduced from the base value of
 387 0.6–0.1, as shown in Fig. 9. This figure shows that the opera-
 388 tional availability of the direct drive concept WT can be signifi-
 389 cantly higher than the gearbox-driven WT, if a high proportion
 390 of synchronous generator failures are minor electrical failures
 391 rather than severe mechanical failures (e.g., bearing problems).

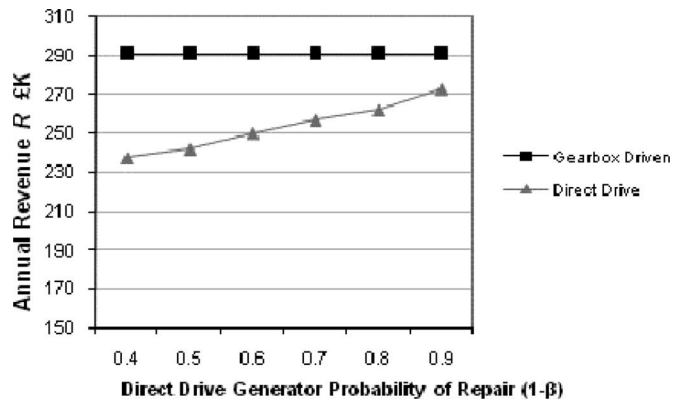


Fig. 10. Revenue increase of direct drive wind turbine as a function of generator reparability.

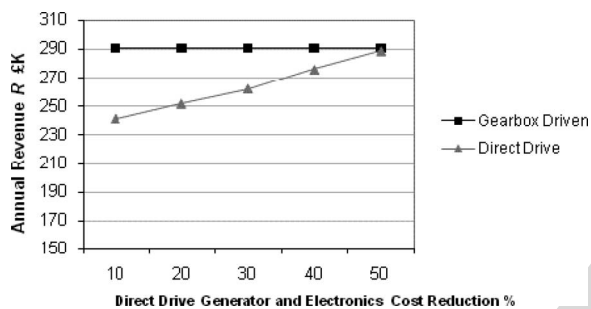


Fig. 11. Revenue increase of direct drive wind turbine as a function of component cost reduction.

392 The economic impact of this variation is illustrated in Fig. 10.
 393 This figure shows that even for an optimistic scenario, the annual
 394 revenue of the direct drive WT is still \sim £20 000 less than the
 395 equivalent gearbox-driven WT. This aspect of WT component
 396 reparability has not received much attention in the literature, but
 397 Fig. 10 in particular shows that it is a significant factor when
 398 conducting operational modeling of WT concepts. More studies
 399 of the type conducted by Ribrant and Bertling [13] will be
 400 needed in order to better understand the reparability of different
 401 WT components and their effect on operational metrics such as
 402 availability and revenue. Analysis of WT failures in the con-
 403 text of repairs and replacements along with their probabilities
 404 and costs are crucial for a deep understanding of wind farm
 405 operational issues.

406 C. Operational Impact of Component Cost Reduction

407 In the WT marketplace, there is currently one company that
 408 builds 2MW direct drive machines on an industrial scale [17];
 409 however, other large WT manufacturers have identified direct
 410 drive machines as an avenue for future production [18]. With
 411 more players in the market, it may be possible to significantly
 412 reduce the direct drive component cost through a refinement
 413 of mass production manufacturing processes. Therefore, it is
 414 of interest to review the effect on the economic case for direct
 415 drive machines if component costs are lowered. Such a review is
 416 provided in Fig. 11, where the GEN and ELE component costs
 417 are reduced in 10% steps to 50% of the original Table I values.

The final result shows that if substantial cost reductions in
 direct drive technology are achieved in the future, this measure
 may be enough to make the technology cost-competitive with
 DFIGs. However, very large cost reductions of 50%+ will be
 required. At current prices, the economic argument for a switch
 to direct drive technology, for the onshore conditions evaluated,
 appears to be weak.

V. CONCLUSION

An operational comparison of direct drive and gearbox-driven
 wind turbines has been presented in this paper. The results sug-
 gest that there may be a technical advantage in deploying direct
 drive machines over more established gearbox-driven designs
 (see Fig. 9). In all cases, the economic analysis shows that
 gearbox-driven machines are still preferable, unless manufactur-
 ing costs of direct drive technology can be significantly reduced
 (see Fig. 11).

There are some issues that need to be better understood in
 order to make more precise comparisons of these technologies.
 One is that the repair probability of the components needs to be
 investigated, in a manner similar to the one presented in [13]
 but for all WT components. The failure rate increase for a syn-
 chronous generator relative to an induction generator (reported
 in [3], [4]) will be made up mainly of electrical-related failures
 rather than mechanical failures. It would be interesting to see
 what proportion of direct drive WT generator failures are low
 downtime (e.g., 1–3 days) as opposed to a mechanical failure of
 a rotating component, which in some cases could take as long as
 60 days to replace [14]. Such an analysis would aid understand-
 ing of WT failure modes and make operational comparisons
 more accurate.

This study was carried out for fairly typical onshore condi-
 tions, but the conclusions may be linked to the site conditions.
 Direct drive machines are perceived by some manufacturers as
 primarily an offshore technology [18]. By modeling the offshore
 wind resource, logistics, increased downtimes, and offshore ac-
 cess constraints, it may be possible to determine if direct drive
 machines would become more economically attractive in off-
 shore conditions than the analysis presented in this paper shows.
 The conclusions of the results in this paper and any further anal-
 ysis as described will be of value to both manufacturers and
 operators of wind turbines.

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tion or International Conference on Electricity Distribution, and International 541
Energy Agency. 542
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Techno-Economic Comparison of Operational Aspects for Direct Drive and Gearbox-Driven Wind Turbines

David McMillan, *Member, IEEE*, and Graham W. Ault, *Member, IEEE*

Abstract—The majority of wind turbines currently in operation have the conventional Danish concept design—that is, the three-bladed rotor of such turbines is indirectly coupled with an electrical generator via a gearbox. Recent technological developments have enabled direct drive wind turbines to become economically feasible. Potentially, direct drive wind turbines may enjoy higher levels of availability due to the removal of the gearbox from the design. However, this is only a theory: so far not substantiated by detailed analytic calculation. By providing such a calculation, this paper enables us to quantitatively evaluate technical and economic merits of direct drive and gearbox-driven wind turbines.

Index Terms—Markov chain, operational comparison, reliability, wind turbines.

I. INTRODUCTION

WORLDWIDE installed capacity of wind generation is growing significantly and is likely to continue to increase in the future. The twin policy objectives of energy security and climate change mitigation have resulted in economic incentives, which in turn, have driven investment in wind energy. Taking the U.K. as an example, Fig. 1 shows how the installed capacity has grown since 2005—by the end of 2008, the installed capacity broke through the 3 GW barrier [1]. This 3 GW capacity consists of 2276 individual wind turbines (WTs) [2], the vast majority of which are conventional Danish concept, gearbox-driven machines. However, recent technical strides have enabled direct drive machines to become economically feasible.

Since a gearbox is not included in the direct drive concept, it is clear that the reliability and availability of the WT will improve—if it can be assumed that all other factors remain unchanged. On the other hand, it has been reported in the paper that failure rates of electrical components and generators of direct drive wind turbines are significantly higher than those of gearbox-driven equivalents [3], [4]. The purpose of this paper is to establish if there is a technical and/or economic advantage in deploying direct drive wind turbines instead of gearbox-driven

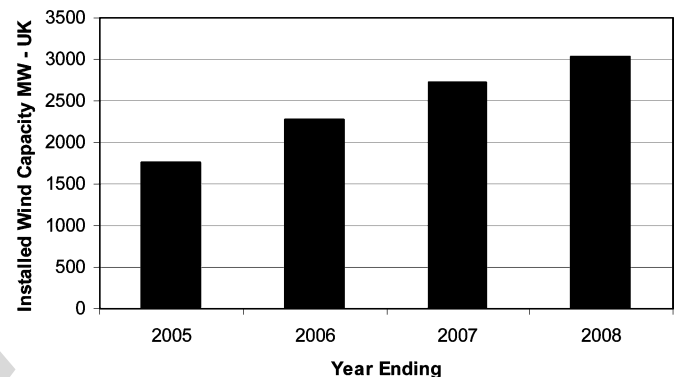


Fig. 1. Recent growth in U.K. wind generation capacity [2].

machines. This analysis is based on quantitative modeling of the operation, failure, and maintenance of wind turbine units as proposed in [5]. Such an operational comparison of different wind turbine concepts is not available in the existing literature.

II. COMPARISON OF CONCEPTS

A. Conventional Danish Concept—Gearbox Driven

The conventional Danish concept comprises a three-bladed upwind rotor, which revolves on the horizontal axis (sometimes called horizontal axis wind turbine, HAWT). The coupling between rotor and electrical generator is indirect and is achieved via a gearbox in order to increase the rotational speed to a level that can drive a relatively small-diameter, lightweight induction generator. A conceptual view of the energy conversion process for such a typical modern wind turbine is outlined in Fig. 2.

The whole wind turbine assembly rotates into the prevalent wind direction on its vertical axis by means of an electromechanical yaw system. Once facing into the wind, control of the mechanical input power is achieved either by aerodynamic design of the rotor (stall control) or by actively changing the angle of attack of the rotor blades to the wind (pitch control) via electrical motors or hydraulics.

The electrical configuration of Danish concept WTs is influenced by mechanical aspects, as one main objective of the WT mechanical design is to minimize the weight at the top of the tower, where the nacelle (containing the generator) is located in modern HAWTs. This means the generator has to be as light as possible and must have a relatively small physical footprint. For this reason, induction generators are employed: induction generators have the added advantage of being more robust than

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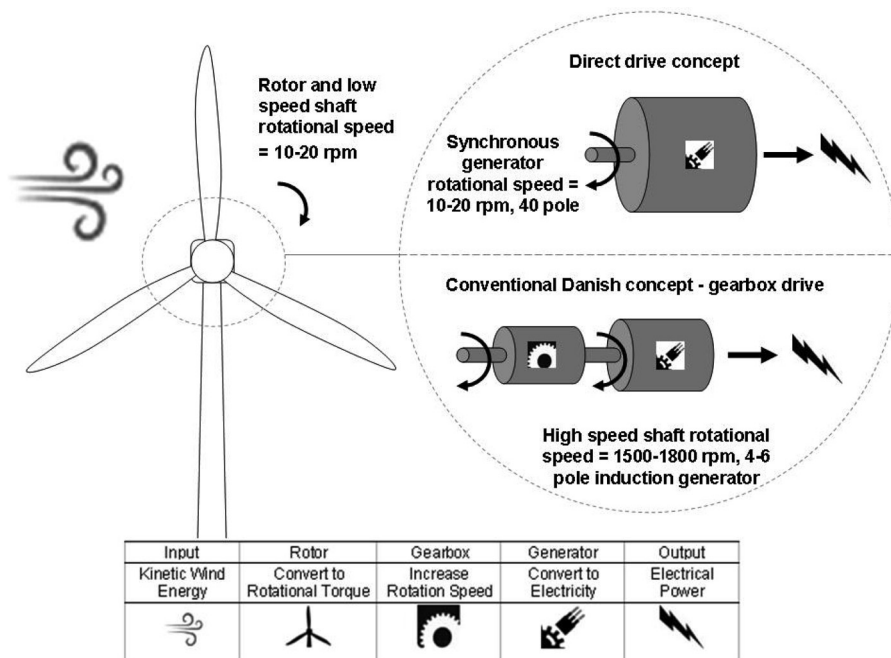


Fig. 2. Process diagram for gearbox-driven and direct drive wind turbines.

69 synchronous generators and tend to have fewer electrical faults.
 70 However, due to the low rotational speed of the wind turbine
 71 rotor, a gearbox has to be used to increase the rotation from tens
 72 of revolutions per minute at the gearbox input to thousands at
 73 the output. The primary reason for this is the low number of
 74 induction generator poles.

75 The older Danish concept WT's that operated at fixed speed
 76 employed squirrel cage induction generators; however, newer
 77 variable speed technology has resulted in a switch to doubly fed
 78 induction generators (DFIG), which are now the dominant wind
 79 turbine generator configuration. The reason for the dominance
 80 of this configuration is that it represents a good compromise
 81 between economy and performance. It is relatively economic
 82 because it has only a partial electronic converter rated at $\sim 30\%$
 83 of the generator output [6], not a full converter.

84 B. Direct Drive Concept

85 In a direct drive WT, the main rotor is coupled to the generator
 86 input shaft, eliminating the need for a gearbox in the design. In
 87 order to generate power at such a low rotation speed, the gener-
 88 ator has to have many pole pairs, and usually a synchronous
 89 generator is employed. This implies much greater dimensions
 90 and weight as compared with an induction generator. In addition,
 91 a fully rated electronic power converter is required, which
 92 increases the cost of the system.

93 C. Types of Comparison

94 There are several examples in the published literature where
 95 a comparison is made between the two concepts. For example,
 96 Tavner *et al.* [3] focused on how the configuration of the
 97 WT generator and converter in different design concepts af-
 98 fected overall WT reliability. The data utilized by the authors

had enough detail to enable a direct reliability comparison of
 three WT concepts: fixed speed with gearbox, variable speed
 with gearbox, and variable speed direct drive (no gearbox: syn-
 synchronous generator). The main conclusion was that direct drive
 systems are less reliable than models with a gearbox because
 the potential increase in reliability due to elimination of gear-
 box failures is cancelled out by increased generator, inverter,
 and electrical system failures.

Interestingly, the authors recognized that overall availability
 would also be affected by component repair times: In this sense
 direct drive systems may have an advantage, as mean time to
 repair (MTTR) for a gearbox is likely to be very much more
 than MTTR for an electronics subassembly. As yet, no other
 research has addressed this operational comparison of the two
 concepts.

Echavarria *et al.* [4] analyzed a similar dataset, which pro-
 vides some highly relevant information regarding the reliability
 of the two WT concepts. In particular, the data suggest that gener-
 ator failures in direct drive WT's are roughly two times the
 gearbox-driven equivalent (0.22 failures per annum compared
 with 0.12 suggested by Tavner *et al.* [7]). Similarly, power elec-
 tronics failures in direct drive synchronous machines are quan-
 tified as 1.03 failures per annum compared to 0.661 suggested
 in [7] for the induction machine equivalent.

Polinder *et al.* [6] examine direct drive and gearbox-driven
 WT concepts from the viewpoint of design and economic per-
 formance. The authors define a typical Danish concept WT with
 a three-stage gearbox (3GDFIG) and a direct drive machine cou-
 pled to a synchronous generator (DDSG). Three other concepts
 are also defined (DFIG with a single-stage gearbox, permanent
 magnet direct drive, and permanent magnet single-stage
 gearbox) but these are not considered in this paper due to the
 fact that they are not currently deployed in significant numbers.

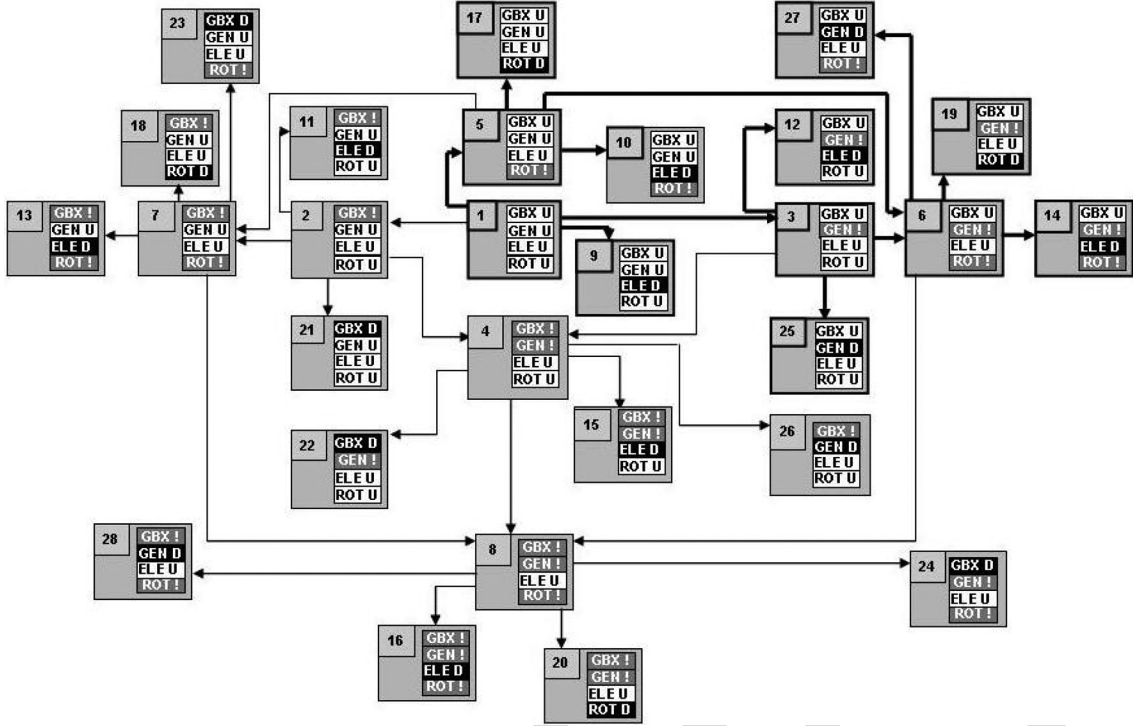


Fig. 3. Markov chain of key wind turbine components. Bold arrows and boxes indicate direct drive system.

132 The authors again highlight the need for further work to better
 133 understand the reliability and availability benefits of adopting
 134 different WT design concepts—a requirement which this paper
 135 aims to meet.

136 III. MODELING OF WIND TURBINE CONCEPTS

137 A. Physical Modeling of Wind Turbine Components

138 In order to build an accurate operational model, the key physical
 139 components of the WT must be identified and a suitable
 140 mathematical representation decided upon. It was reported in [5]
 141 that using a combination of failure rate data, downtime esti-
 142 mates, and expert opinion, the key components of a gearbox-
 143 driven WT could be identified as follows:

- 144 1) gearbox (GBX);
- 145 2) generator (GEN);
- 146 3) rotor blades (ROT); and
- 147 4) inverter, electronics, and control (ELE).

148 In terms of the mathematical representation, a Markov chain
 149 solved via Monte Carlo simulation (MCS) was identified in pre-
 150 vious studies as a suitable model framework [5]. The Markov
 151 chain representation has been very successfully applied to power
 152 systems infrastructure deterioration and failure modeling, in-
 153 cluding wind turbines [8], [9]. The main problem with these an-
 154 alytically solved models is that the introduction of constraints,
 155 such as weather-constrained maintenance, makes obtaining a so-
 156 lution rather difficult. Although not computationally efficient,
 157 MCS methods overcome this difficulty and have been applied
 158 to similar problems in the past [10], [11]. Since the problem
 159 considered is essentially a planning problem, the time required
 160 to get the solution is of little importance.

161 It has been assumed that three states are sufficient to capture
 162 the deterioration and failure processes of the GBX, GEN, and
 163 ROT. ELE failures are assumed to be instantaneous and, there-
 164 fore, require only binary representation. When all four compo-
 165 nents are modeled in a single Markov state-space, the total
 166 number of states is 54. This is cut down to 28 by assuming that
 167 degradation and failure events of different WT components can-
 168 not happen concurrently. Furthermore, for a GBX, GEN, or ROT
 169 failure to occur, the system must transit through the deteriorated
 170 (intermediate) state before outright failure.

171 The possible Markov states and transitions for the overall WT
 172 system are visualized in Fig. 3. The three possible deteriora-
 173 tion levels are indicated as fully up (U), deteriorated (!), and
 174 down (D).

175 All 28 states and transitions are possible for the case of
 176 gearbox-driven WTs. The obvious physical difference when
 177 modeling a direct drive WT is that there are no gearbox states.
 178 Thus, the bold arrows in Fig. 3 refer to the transitions and states
 179 that represent direct drive WTs, as a 12-state subset.

180 The arrows in Fig. 3 represent transition probabilities (e.g.,
 181 probability of transition from state a to state b is $p_{a,b}$), whose
 182 magnitude must be estimated. These probabilities depend only
 183 on the current state of the system (s) at current time t_k .
 184 Equation 1 expresses this “memory-less” property of a Markov
 185 chain

$$186 p_{a,b} = p(s_b, t_{k+1} | s_a, t_k) \quad k = 1, 2, 3, \dots \quad (1)$$

187 Furthermore, the transition probabilities are constant in time:
 188 This is the “time-stationary” property. The magnitude of all
 189 transition probabilities from one state (a) to all others in the

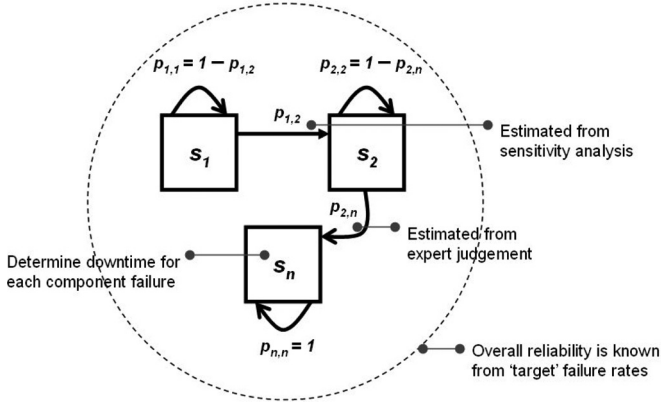


Fig. 4. Parameter estimation for Markov chain.

189 system must sum to unity. This is shown in (2)

$$\sum_b p_{a,b} = 1 \quad a = 1 \dots n \quad (2)$$

190 where n is the total number of system states. For convenience,
 191 the transition probabilities for the whole system are expressed
 192 in a transition probability matrix (TPM). For the case of the
 193 system in Fig. 3, the TPM is shown in (3). Note that only the
 194 possible transitions (indicated in Fig. 3. with arrows) need to be
 195 estimated—all other probabilities are equal to zero

$$\text{TPM} = \begin{bmatrix} p_{1,1} & p_{1,2} & \dots & p_{1,28} \\ p_{2,1} & p_{2,2} & \dots & \dots \\ \dots & \dots & \dots & \dots \\ p_{28,1} & \dots & \dots & p_{28,28} \end{bmatrix} \quad (3)$$

196 The TPM values are estimated based on the partial information
 197 available, as illustrated in Fig. 4. A good estimate of the
 198 overall reliability (“target” failure rate) is known from the work
 199 of Tavner *et al.* [7].

200 Similarly, downtime estimates can be made for the outage of
 201 the key components [5]. The probability of an outright failure
 202 in a deteriorated condition ($p_{2,n}$) can be estimated based on
 203 expert opinion of times to failure. The remaining parameters can
 204 then be estimated by conducting sensitivity analyses (previously
 205 reported in [5]).

206 B. Data for Physical Model

207 The study of Tavner *et al.* [7] provided estimates of compo-
 208 nent failure rates based on populations of Danish and German
 209 WTs. The German population was larger (over 4,000 machines)
 210 and the population consisted of more modern WTs. Therefore,
 211 the German figures are used to fit the gearbox-drive WT physical
 212 model.

213 On the other hand, Echavarria *et al.* [4] suggest modifications
 214 to the GEN and ELE failure rates for direct drive machines.
 215 Taking this into account, the target failure rates for both WT
 216 concepts can be visualized in Fig. 5.

217 Downtimes for the failure types are as follows: GBX—30
 218 days, GEN—21 days, ELE—1 day, and ROT—30 days. They
 219 are based on domain knowledge elicited in [5]. Using this

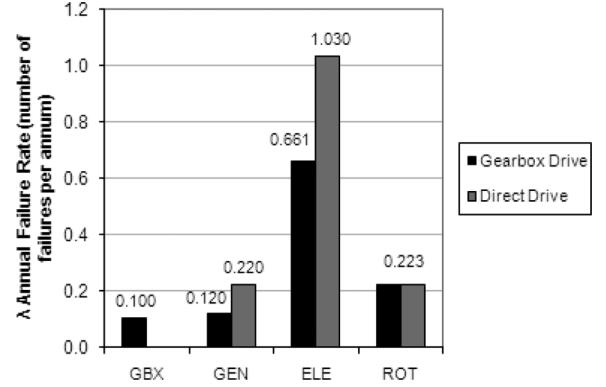


Fig. 5. Reliability for gearbox-driven and direct drive wind turbines.

information, the TPM parameters were estimated based on the
 220 iterative procedure devised in [5]. The procedure is based on
 221 sensitivity analysis estimation of the unknown parameter $p_{1,2}$
 222 (see Fig. 4).
 223

The Markov chain has been defined for both gearbox-driven
 224 and direct drive concepts. In the following sections, other aspects
 225 of operational modeling—which are common to both
 226 concepts—are discussed.
 227

228 C. Energy Yield Modeling

229 There are two main components to the energy yield model.
 230 These are the wind speed model and the power curve model. The
 231 wind speed (WS) model previously used by the authors [5] was
 232 based on a single parameter autoregressive process, or AR(1).
 233 This is displayed in (4), where μ is the mean of a wind speed
 234 time series, ϕ is the autoregressive parameter and the process is
 235 driven by a Gaussian white noise function ε_t .

$$\text{WS}_t - \mu = \phi (\text{WS}_{t-1} - \mu) + \varepsilon_t \quad (4)$$

236 The dataset used to fit the model was sourced from a super-
 237 visory control and data acquisition (SCADA) system of a
 238 U.K. wind farm. Estimation of ϕ and ε_t was achieved by linear
 239 least squares, while classification of the model was based
 240 on inspection of the autocorrelation and partial-autocorrelation
 241 functions.

242 The power curve model is based on a manufacturers’
 243 datasheet for a 2 MW WT [12], which is sampled and the theo-
 244 retical equation for the power (P) in the wind (5) is matched
 245 to the data samples by modeling the coefficient of performance
 246 C_p

$$P = \frac{1}{2} \rho \pi r^2 v^3 (\times C_p) \quad (5)$$

247 In (5), ρ is air density (kg/m^3), r is the rotor radius (m), and v
 248 is air velocity through the WT rotor (m/s). The re-created power
 249 curve is shown in Fig. 6 and has cut in, rated, and cut out wind
 250 speeds of 4, 14, and 25 m/s, respectively. It is assumed that both
 251 WT concepts adhere to the same power curve.

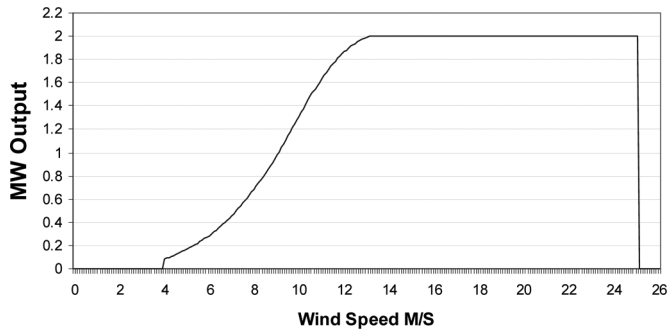


Fig. 6. Power curve for 2 MW wind turbine [12].

252 D. Maintenance Modeling

253 It is assumed that a six-monthly periodic maintenance plan
 254 is adopted for both WT concepts. The assumptions in the main-
 255 tenance model are that maintenance actions restore the WT to
 256 the fully up state (state 1 in Fig. 3) and that each maintenance
 257 visit involves a one-day outage. The model can easily accom-
 258 modate condition-based maintenance (CBM), but since mainte-
 259 nance paradigms are not the focus of this paper, this possibility
 260 is neglected.

261 If a component failure occurs, a maintenance team is dis-
 262 patched immediately. There is a probability that a component
 263 replacement is necessary (replacement factor $\beta = 0.6$) or that it
 264 can be repaired ($1 - \beta = 0.4$). This is based on an analysis by
 265 Ribrant and Bertling [13] who highlighted that around 60% of
 266 gearbox failures require a replacement rather than a repair ac-
 267 tion. Similar figures have not been published for the other WT
 268 components; therefore, due to the lack of data, they are assumed
 269 to have the same probabilities of repair and replacement as the
 270 gearbox.

271 If the component can be repaired, it is restored instanta-
 272 neously to a functional state. If a replacement is required, down-
 273 time lasts as follows: GBX—30 days, GEN—21 days, ELE—1
 274 day, and ROT—30 days. This is based on the experience of a
 275 wind farm operator. Furthermore, maintenance actions are con-
 276 strained by wind speed as in [5]. This means that nacelle-related
 277 replacements need wind speed conditions of less than 10 m/s,
 278 while rotor maintenance cannot be conducted in wind speeds
 279 over 7 m/s.

280 E. Costs and Revenue

281 It is of interest to compare the economic merits of the two WT
 282 configurations. Therefore, a cost model has been built which
 283 generates revenue from energy yield and incurs maintenance
 284 and replacement costs.

285 Polinder *et al.* provided costs for gearbox-driven and direct
 286 drive wind turbine components rated at 3 MW [6]. Figures can
 287 be derived for 2 MW machines of both types assuming that the
 288 cost varies linearly with the rating. These costs are provided in
 289 Table I. The rotor cost was not provided in [6] and so the value
 290 derived previously by the authors of this paper is adopted [5].
 291 In the case of a component replacement, the full cost in Table I

TABLE I
 COMPONENT COSTS FOR WIND TURBINE CONCEPTS

Component	Gearbox driven Cost £	Direct drive Cost £
GBX	121,733	N/A
GEN	177,066	313,740
ROT	210,000	210,000
ELE	22,133	66,400

is incurred. In the case of a repair, it is assumed that only 10%
 of this cost is incurred (repair cost factor $\alpha = 0.1$).

Besides the costs of the components themselves, the cost of
 labor and equipment hire has been included. Andrawus [14]
 showed that skilled labor for WT repairs costs around £50/h. It
 has been assumed that three crew working an 8 h shift consti-
 tute one maintenance action. Therefore, the cost of labor (C_{LAB})
 is £1200 per action. Similarly, hire rates for telescopic cranes
 (C_{EQ}) needed to perform nacelle component lifting operations
 have been quantified by industry sources [15] as £1500 per
 week. Lost revenue due to downtime is also taken into account
 (R_{LOST})—this is wind speed-dependent. These costs are com-
 bined with the component costs (see Table I) to calculate re-
 placement (6), repair, (7) and O&M cost (8)

$$C_{replace} = \beta\lambda (C_{CAP} + C_{LAB} + C_{EQ} + R_{LOST}) \quad (6)$$

$$C_{repair} = (1 - \beta)\lambda \times (\alpha C_{CAP} + C_{LAB} + C_{EQ} + R_{LOST}) \quad (7)$$

$$C_{O\&M} = C_{replace} + C_{repair} \quad (8)$$

The revenue model for the WT is based on the energy yield in
 each one-day simulation interval. Using equations (4) and (5),
 this energy yield Y can be calculated as the power (see Fig. 6)
 multiplied by a time interval Δt . The energy yielded in a year is
 then calculated by summing the output over all individual days
 in the year.

The revenue stream R can then be calculated by applying
 equation (9). MP represents the market price for electricity and
 renewable obligation certificates (ROCs). For this paper, MP_{elec}
 and MP_{ROC} are set to £36 and £40 per MWh, respectively.
 Although in reality, electricity and ROC prices fluctuate, the
 annual mean is adequately represented by the figures presented
 as

$$R = Y (MP_{elec} + MP_{ROC}) - C_{O\&M} \quad (9)$$

It is important to note that any differences in yield between the
 two WT concepts will be related to the reliability and downtime
 (see Fig. 5 and Section III-D) of the two WT concepts, rather
 than to the differences in the electrical design. This is because the
 same power curve (Fig. 6) has been used for both WT concepts.

Polinder *et al.* showed that the theoretical difference in yield
 between a 3 MW direct drive machine (DDSG) and a typical
 3 MW DFIG (DFIG3G) is +150 MWh [6], if the detail of the
 electrical machine design is taken into account. Assuming
 this difference scales linearly with WT rating, it means that for
 the 2 MW machines considered in this paper, the direct drive
 machine yields roughly 100 MWh more per annum than the

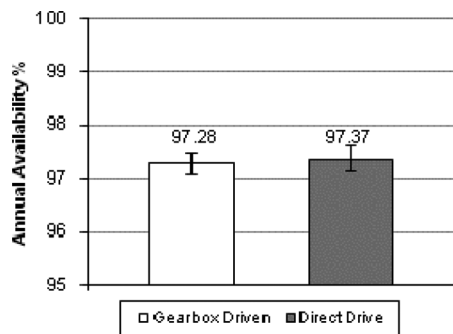


Fig. 7. Availability comparison of wind turbine concepts.

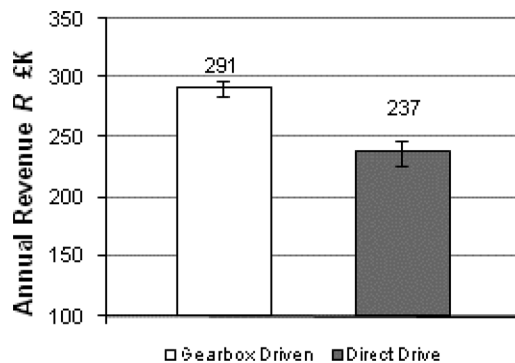


Fig. 8. Economic comparison of wind turbine concepts.

331 DFIG. Applying (9) and neglecting the O&M cost, this translates
 332 to £7600 more revenue per annum for the direct drive machine.
 333 Therefore, the annual revenue for the direct drive machine has
 334 been boosted by £7600 per annum in the studies that follow.

335 F. Program Operation

336 The models outlined in this section were coded in FORTRAN
 337 95, with the SCADA database interface for the wind speed
 338 model written using f90SQL [16]. The statistical programming
 339 language R was used to fit the wind speed model defined in (4).
 340 The resultant capacity factor of the wind turbine based on the
 341 simulated wind speed and power curve is just under 30%.

342 The confidence limit L of the simulation results can be measured
 343 by applying (10). Taking the Student- t distribution, and
 344 setting the level of confidence to 95%, it means that L can be
 345 specified, provided that the number of samples (N) and standard
 346 deviation (σ) of the quantity are known. L is shown in the results
 347 as confidence bands that specify the accuracy of the results

$$L = \pm \frac{2.045 \times \sigma}{\sqrt{N}}. \quad (10)$$

348 IV. RESULTS

349 A. Operational Comparison of Concepts

350 Two comparisons are made in order to benchmark the operational
 351 merits of the two WT concepts: a technical comparison
 352 and an economic comparison. The first result in Fig. 7 compares
 353 the overall availability of the two concepts.

354 It can be seen that despite removing the gearbox from the
 355 design, the direct drive concept has similar overall availability
 356 to the gearbox-driven machine. Although the availability is
 357 marginally better for the case of the direct drive machine, the
 358 confidence limits show that this technical benefit is uncertain.
 359 It should be noted that grid availability is not included in this
 360 paper.

361 The second result, displayed in Fig. 8, shows the revenue
 362 generated (9) for both concepts. This shows that the gearbox-
 363 driven design has a much larger economic benefit than the direct
 364 drive concept.

365 The contribution to the revenue of increased energy yield due
 366 to avoidance of downtime is negligible in the case of Fig. 8
 367 (direct drive machine avoids loss of ~ 6.35 MWh more energy

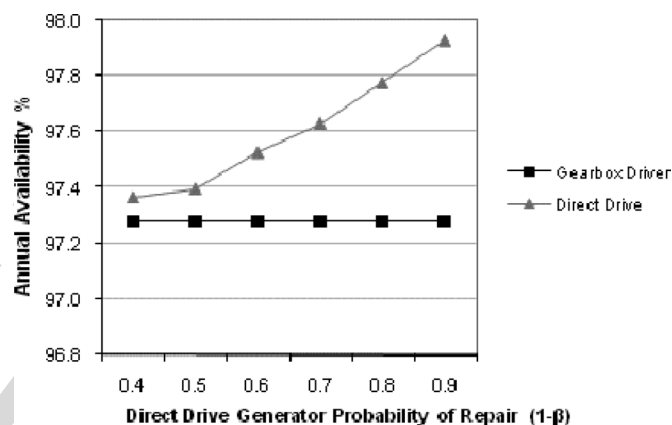


Fig. 9. Availability improvement of direct drive wind turbine as a function of generator reparability.

than gearbox-driven, economic benefit = £482 per annum).
 Therefore, the large disparity in revenue (\sim £44 000 per annum)
 must be due to incurred repair and replacement costs. The large
 increase in cost and failure rate for the generator in particular
 appears to economically handicap the direct drive concept.

374 B. Operational Impact of Generator Reparability

375 One possible explanation of the superior economic performance
 376 of the gearbox-drive concept is that a replacement factor
 377 (β) of 0.6 per failure (see Section III-D) may represent a pes-
 378 simistic view of the “reparability” of a WT synchronous gener-
 379 ator. Indeed, it has been reported elsewhere [3] that the increase
 380 in generator failure rate for the direct drive concept is related
 381 to electrical failures rather than mechanical failures. Electrical
 382 faults will be less likely to involve a complete component re-
 383 placement; therefore, the robustness of the conclusion drawn
 384 from Fig. 8 is tested by modeling different levels of reparability
 385 for the direct drive generator.

386 The replacement factor β was reduced from the base value of
 387 0.6–0.1, as shown in Fig. 9. This figure shows that the opera-
 388 tional availability of the direct drive concept WT can be signifi-
 389 cantly higher than the gearbox-driven WT, if a high proportion
 390 of synchronous generator failures are minor electrical failures
 391 rather than severe mechanical failures (e.g., bearing problems).

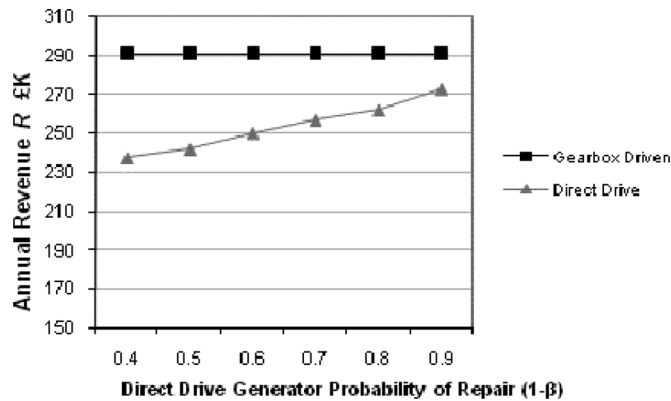


Fig. 10. Revenue increase of direct drive wind turbine as a function of generator reparability.

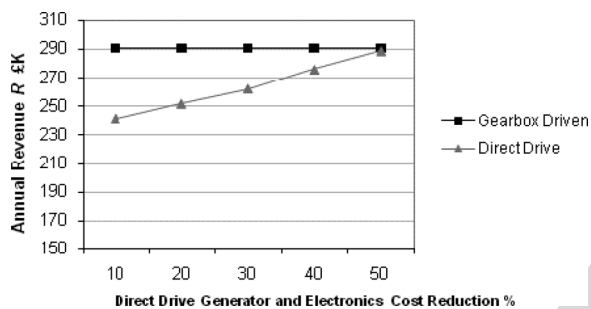


Fig. 11. Revenue increase of direct drive wind turbine as a function of component cost reduction.

392 The economic impact of this variation is illustrated in Fig. 10.
 393 This figure shows that even for an optimistic scenario, the annual
 394 revenue of the direct drive WT is still \sim £20 000 less than the
 395 equivalent gearbox-driven WT. This aspect of WT component
 396 reparability has not received much attention in the literature, but
 397 Fig. 10 in particular shows that it is a significant factor when
 398 conducting operational modeling of WT concepts. More studies
 399 of the type conducted by Ribrant and Bertling [13] will be
 400 needed in order to better understand the reparability of different
 401 WT components and their effect on operational metrics such as
 402 availability and revenue. Analysis of WT failures in the con-
 403 text of repairs and replacements along with their probabilities
 404 and costs are crucial for a deep understanding of wind farm
 405 operational issues.

406 C. Operational Impact of Component Cost Reduction

407 In the WT marketplace, there is currently one company that
 408 builds 2MW direct drive machines on an industrial scale [17];
 409 however, other large WT manufacturers have identified direct
 410 drive machines as an avenue for future production [18]. With
 411 more players in the market, it may be possible to significantly
 412 reduce the direct drive component cost through a refinement
 413 of mass production manufacturing processes. Therefore, it is
 414 of interest to review the effect on the economic case for direct
 415 drive machines if component costs are lowered. Such a review is
 416 provided in Fig. 11, where the GEN and ELE component costs
 417 are reduced in 10% steps to 50% of the original Table I values.

The final result shows that if substantial cost reductions in
 direct drive technology are achieved in the future, this measure
 may be enough to make the technology cost-competitive with
 DFIGs. However, very large cost reductions of 50%+ will be
 required. At current prices, the economic argument for a switch
 to direct drive technology, for the onshore conditions evaluated,
 appears to be weak.

425 V. CONCLUSION

An operational comparison of direct drive and gearbox-driven
 wind turbines has been presented in this paper. The results sug-
 gest that there may be a technical advantage in deploying direct
 drive machines over more established gearbox-driven designs
 (see Fig. 9). In all cases, the economic analysis shows that
 gearbox-driven machines are still preferable, unless manufactur-
 ing costs of direct drive technology can be significantly reduced
 (see Fig. 11).

There are some issues that need to be better understood in
 order to make more precise comparisons of these technologies.
 One is that the repair probability of the components needs to be
 investigated, in a manner similar to the one presented in [13]
 but for all WT components. The failure rate increase for a syn-
 chronous generator relative to an induction generator (reported
 in [3], [4]) will be made up mainly of electrical-related failures
 rather than mechanical failures. It would be interesting to see
 what proportion of direct drive WT generator failures are low
 downtime (e.g., 1–3 days) as opposed to a mechanical failure of
 a rotating component, which in some cases could take as long as
 60 days to replace [14]. Such an analysis would aid understand-
 ing of WT failure modes and make operational comparisons
 more accurate.

This study was carried out for fairly typical onshore condi-
 tions, but the conclusions may be linked to the site conditions.
 Direct drive machines are perceived by some manufacturers as
 primarily an offshore technology [18]. By modeling the offshore
 wind resource, logistics, increased downtimes, and offshore ac-
 cess constraints, it may be possible to determine if direct drive
 machines would become more economically attractive in off-
 shore conditions than the analysis presented in this paper shows.
 The conclusions of the results in this paper and any further anal-
 ysis as described will be of value to both manufacturers and
 operators of wind turbines.

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Energy Agency. 542
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- Q1: Author: Please check the edit changes in this sentence for correctness.
- Q2: Author: Please check the edit changes in this sentence for correctness.
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