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INFLUENCE OF MULTIPLE DEGRADING COMPONENTS ON GAS TURBINE FUEL CELL HYBRID SYSTEM LIFETIME

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ABSTRACT

Energy system reliability and operational cost depend highly on the performance degradation experienced by system components. In complex systems, degradation of each single component affects matching and interactions of different system parts. Gas turbine fuel cell hybrid systems combine two different technologies to produce power with an extremely high conversion efficiency. Severe performance decay over time currently limits high temperature fuel cells lifetime; although at a different rate, gas turbine engines also experience gradual deterioration phenomena such as erosion, corrosion, and creep. This work aims at evaluating, for the first time, the complex performance interaction between degrading components in a hybrid system. The effect of deterioration in gas turbine pressure ratio and efficiency on fuel cell performance was analyzed, and at the same time, the impact of the degrading fuel cell thermal output on turbine blade aging was modeled to estimate a remaining useful lifetime.

INTRODUCTION

Small-scale technologies are nowadays playing an increasingly important role in power systems to accommodate a growing penetration of non-dispatchable renewable energy sources (NDRES). Micro gas turbine and internal combustion engine based systems are acquiring the role of grid supporters in this new energy mix. Micro gas turbines are playing a main role in the distributed generation applications, because of their flexibility that allows to operate in partnership with renewable sources in an extremely volatile energy market. Flexibility is mandatory for peaking unit, while high efficiency, even in off-design condition, is the key point to reduce carbon emissions for generators designed to run continuously [1].

The combination of a micro gas turbine (mGT) and a solid oxide fuel cell (SOFC) in a hybrid system has been considered for decades as a promising technology for low-emissions power generation [2-4]. The efficiency of a hybrid system can be generally above 50% even for 100 kW size and up to 60% for 1 MW size, making it suitable for distributed generation applications [4, 5]. Similar efficiency level can be reached by combined cycles; however, plant sizes in the range 400 - 1000 MW are not suitable for distributed generation, so paying transformation losses in the efficiency chain. Although many theoretical studies showed the environmental and economic benefits of SOFC-GT hybrid systems, the main obstacles to commercialization are considered the fuel cell high cost and limited lifetime [6].

As stated before, not just design efficiency but also its variations with load (off-design performance) and over time (degradation) are crucial from an environmental and economic point of view. Hybrid systems gather the advantages of two very different systems on the efficiency side, with an excellent off-design characteristic, but have to deal with mutual interaction of degradation mechanisms. In this scenario, it is becoming even more necessary to guarantee system availability and reliability, and to reduce lifecycle costs, which depend highly on components degradation over time. Predicting elements and components life (or time between overhauls, TBO) is a fundamental step to estimate the possible economic return.

Mechanisms limiting SOFC operating life have been widely investigated [7, 8]. In previous work by the Authors, the effect of fuel cell degradation over time on the hybrid system performance and economic return was analyzed [9, 10]. In those studies, the fuel cell was considered the only component experiencing performance deterioration, while gas turbine degradation was neglected. With this assumption, it was suggested that, in contrast with most of the performance analyses in the literature, the power share between SOFC and mGT should be about 50:50 to maximize the economic return.

As all the engines, gas turbines experience wear and tear over time. Typical degradation phenomena include compressor fouling, blade erosion, hot corrosion, and creep, among others. An extensive review of gas turbine degradation was provided by Kurz [11]. Existing studies generally focus on large machines, while performance deterioration in micro gas turbines is rarely discussed, without analyzing the economic impact [12, 13]. Nevertheless, micro gas turbine degradation can be reasonably considered to occur following the same mechanisms as in large turbomachinery. In particular, micro gas turbine blades are normally uncooled, limiting the turbine inlet temperature (TIT) to 950°C for nickel alloys blades, e.g. IN738 [14, 15]. For this reason, temperature-induced aging phenomena of the blades (e.g. creep) can be a major issue. Different models, ranging from finite elements to probabilistic and real-time approximate models, have been proposed to estimate blades remaining lifetime [16-19]. The effect of turbine load on blades creep was investigated by Mohamed et al. [17]. Dependence of creep life on ambient and operating conditions was object of different studies [20, 21].

Degradation of multiple components and subsystems may be aggravated by components interaction. For example, degradation of one component can initiate or accelerate the failure of another one; if this aspect is ignored, failure risk can be underestimated. One reason is that a change in one component performance characteristic leads to a mismatch on the engine level, hence, the operating conditions vary affecting other components degradation. Studies on degraded components interaction in energy systems are limited. The effect of compressor fouling and operating conditions on creep of turbine blades was investigated showing that creep is accelerated in a machine with a degraded compressor [21]. Sun et al. analyzed interactive failures in mechanical systems, modelling the influence of multiple components [22].

In an mGT/SOFC hybrid system, coupling phenomena and interactions are complex. Components matching over the operability range is a delicate problem, to ensure system safe operations. Even in healthy conditions, small perturbations can be propagated and amplified in the system if not adequately controlled, causing for example compressor stall or excessive thermal stress in the SOFC stack [23]. The objective of this work is to assess the interdependent effects of components degradation in a hybrid system. Simultaneous fuel cell stack degradation and gas turbine degradation is studied to evaluate the impact on system lifetime and economic return compared to the case study of a previous work (where only fuel cell degradation was considered) [10].

METHODOLOGY

Cycle overview

In a directly coupled hybrid system, the pressurized SOFC stack replaces the traditional combustion chamber of a gas turbine, as shown in the diagram of Figure 1. The compressed air leaving the compressor is preheated by the turbine exhausts and sent to the fuel cell cathode side. On the anode side, fuel such as natural gas, syngas or biogas is supplied, and electrical power is generated through electrochemical reactions. Anode and cathode exhausts mix in a combustion volume (off-gas burner) where the unutilized fuel still present in the anode exit stream is oxidized with the excess oxygen from the cathode stream. Subsequently, the hot gas enters the turbine and additional electrical power is produced.

System model

The hybrid system model was developed in MATLAB Simulink and extensively described in previous publications [24, 25]. A degradation factor, function of fuel cell operating temperature, current density, and fuel utilization, increments the overpotential over time simulating a degradation in performance [25]. Since in previous work, a constant voltage operating mode was selected as the most economically beneficial [9], for comparison, the same operating strategy is applied in this study, summarized as it follows:

- Fuel cell current is decreased over time to offset degradation and keep constant voltage;
- Consequently, fuel cell power and fuel utilization decrease following the current;
- Gas turbine power is increased by incrementing the fuel flow through the anode and thus the thermal power transferred from the fuel cell system to the turbine;
- The total system power, sum of fuel cell and gas turbine power, is kept constant.

A size of 400 kW was selected for both the fuel cell stack and the micro gas turbine, while the system was designed to deliver a total of 500 kW of electric power. That means that, at the beginning of the fuel cell life, the turbine generates only 100 kW; as the fuel cell power degrades, the turbine load is increased to compensate the power loss, and when the design power is reached (i.e. the fuel cell degraded by 75%), the stack needs to be replaced with a new one. A curve of efficiency of the recuperated gas turbine cycle as function of load was built from available empirical data and is shown in Figure 2 [5, 26].

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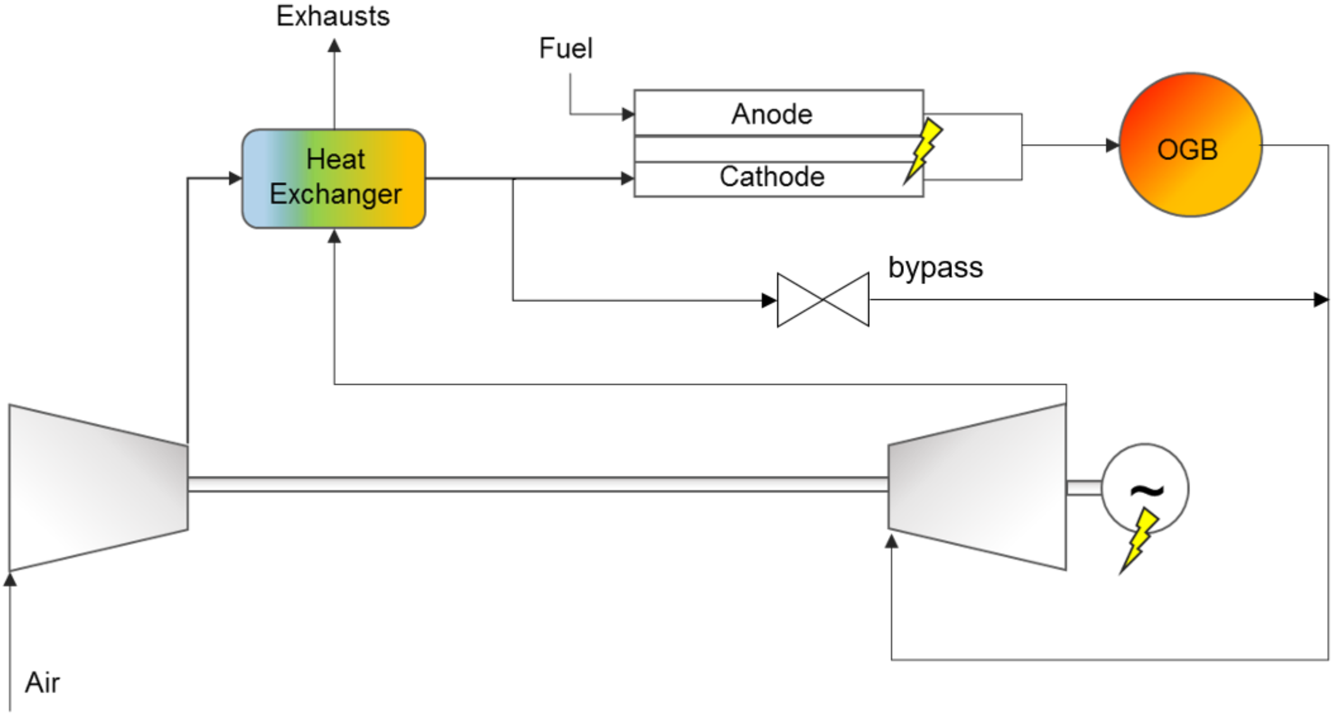

Figure 1. Schematic diagram of the hybrid system

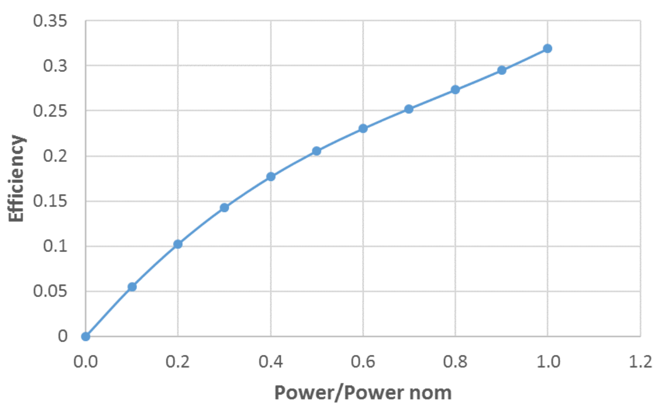

Figure 2. Gas turbine efficiency as a function of power

Degradation cases

Two parameters were considered to quantify gas turbine degradation: compressor pressure ratio (β) and overall gas turbine efficiency (η). Several phenomena from compressor fouling to blade erosion and increased tip clearance are known to decrease engine efficiency [11]. In a single-shaft machine, loss in compressor efficiency mostly reduces the pressure ratio, while the flow through the machine is usually not significantly affected [11]. Hence, only degradation of efficiency and pressure ratio was considered, also because these two parameters are expected to influence fuel cell performance.

The rate of performance deterioration over time can vary significantly from engine to engine and depending on operating conditions. For this reason, data available in the open literature are very limited. In particular, trends of degrading operating parameters in micro gas turbine are scarcely published. However, some estimations can be extrapolated from data of larger machines to assume reasonable case studies [27-29].

Looking at maintenance plans of commercially available micro turbines, a maximum of 30,000 hours of operation was assumed between overhauls [30]. Three cases were compared to evaluate the impact of gas turbine degradation on the fuel cell and system performance: 2% decay in 30,000 hours of compressor β and engine η, 5% decay, and 7% decay. Meanwhile, the fuel cell degraded always according to the degradation model presented in [25].

Turbine inlet temperature effect

Turbine inlet temperature (TIT) has a major effect on the performance of a hybrid system. Turbine power output and efficiency are obviously influenced by operating TIT, but also gas turbine degradation. As turbine inlet pressure and mass flow rate remained constant (with a slight increase of flow rate due to the fuel flow, from 2% to 3%), the increase in thermal energy released by the degrading SOFC incremented the TIT and hence the power output and efficiency. This effect, similar to those experienced by stand-alone micro gas turbine (in which rotational speed and thus mass flow rate are maintained constant) was modeled through the off-design performance curve of Fig. 2, taking into account the actual thermal energy entering the expander and its design value.

On the maintenance side, turbomachinery subject to continuous operation experiences several damaging mechanisms caused by high operating temperature (e.g. creep deflection, erosion, oxidation, corrosion). However, creep rupture of hot gas path components is the primary life limiter and is the mechanism that generally determines the maintenance interval [31].

The effect on the expander lifetime of a TIT exceedance above the design temperature can be assimilated to a peak load, with respect to parts life effect, as usually evaluated for heavy duty gas turbines. No increase in life was taken into account for firing temperature below design value. The case of a firing temperature above design condition was modeled with a creep law using the Larson-Miller Parameter (P) as in the creep formula of Equation 1.

$$P = TIT(20 + \log t) \cdot 10^{-3} \qquad (1)$$

For a design temperature of 950°C and a design life of 30,000 hours, P has a value of 29.94. This result was found in good accordance with peak load effects over maintenance prescribed by OEM of heavy duty gas turbines [31].

Fixing the value of P, a corrected time between overhauls t can be calculated depending on the operating TIT, when this latter exceeds 950°C. For example, for a TIT exceedance of 10°C above the design value, the TBO would be reduced to 19,000 hours. Three additional cases were thus analyzed by taking into account the effect of the TIT on gas turbine degradation; for comparison with the previous test cases, a maximum degradation of 2%, 5%, and 7% at the end of life was considered. The temperature-dependent degradation rate was then calculated as shown in Equation 2.

$$DR_{TIT} = DR_{design} \cdot \frac{30{,}000h}{TBO_{TIT}} \qquad (2)$$

Where DR_{design} was set at 2%, 5%, and 7%, respectively, and TBO_{TIT} was calculated from Equation 1.

Economic model

A simple economic model was used to calculate the impact of gas turbine replacements over the lifetime of the system. The same cost assumptions of a previous work were employed to have a comparison with the base case, and they are reported in Table 1 [10].

Table 1. Economic assumptions

Recuperated gas turbine [32, 33]	-159.7 * ln(mGT size) + 2089.2 [$/kW]
SOFC stack	1000 $/kW
Inverter [32]	10% stack cost
Gas turbine overhaul cost	80% gas turbine cost
Fuel cost	0.1 $/kg
Electricity price (feed-in tariff to favor SOFC market penetration)	0.14 $/kWh
Annual maintenance	3% capital investment
Discount rate	0.01

The economic parameter used to assess the maximum number of acceptable overhauls was the internal rate of return (IRR), calculated as shown in Equation 3.

$$\sum_{j=1}^{EOL} \frac{CFN_j}{(1+IRR)^j} - TCI = 0 \qquad (3)$$

Where TUO is the time until overhaul, i.e. the time elapsed between the beginning of life and subsequent gas turbine overhauls. The annual cash flow, CF, includes the sold electricity, the fuel consumption, and the annual maintenance cost.

RESULTS AND DISCUSSION

Three cases and different subcases were analyzed and compared:

- Case 0: only the fuel cell degrades, no gas turbine replacements
- Case 1: gas turbine replacement every 30,000 hours, constant degradation rate for β and η over time
  - Case 1a: 2% constant degradation rate
  - Case 1b: 5% constant degradation rate
  - Case 1c: 7% constant degradation rate
- Case 2: β and η actual degradation rate and gas turbine replacement time are function of TIT exceedance according to Eq. 1 and 2
  - Case 2a: 2% degradation at replacement time
  - Case 2b: 5% degradation at replacement time
  - Case 2c: 7% degradation at replacement time

Constant degradation rate

For Case 1, the micro gas turbine was replaced every 30,000 hours of operations, while the fuel cell stack lasted 20 years with the operating strategy previously discussed. Hence, the gas turbine was replaced 5 times during the fuel cell lifetime. Three constant degradation rates for β and η were considered to analyze the effect on the fuel cell performance and lifetime.

Figure 3 shows the system efficiency over time for Case 1a, 1b, 1c, and Case 0 (where gas turbine degradation and replacements are neglected). The overall trend is a decrease in system efficiency due to fuel cell performance deterioration, i.e. a decrement in power output at constant voltage. A further decrease over time is due to gas turbine efficiency degradation, which is recovered every 30,000 hours when the machine is replaced. A smaller contribution is due to the loss in fuel cell performance caused by a degradation in compressor pressure ratio.

Degradation in fuel cell inlet pressure is expected to slightly increase cell overpotential, thus aggravating fuel cell degradation. In contrast, degradation in gas turbine efficiency causes the control system to increase the fuel flow to maintained constant power; a higher flow rate through the anode is expected to lower the overpotential and mitigate degradation phenomena. However, both effects were negligible and the fuel cell life was not affected in either way: the maximum difference was a 3 months shorter life for the Case 1c compared with Case 0.

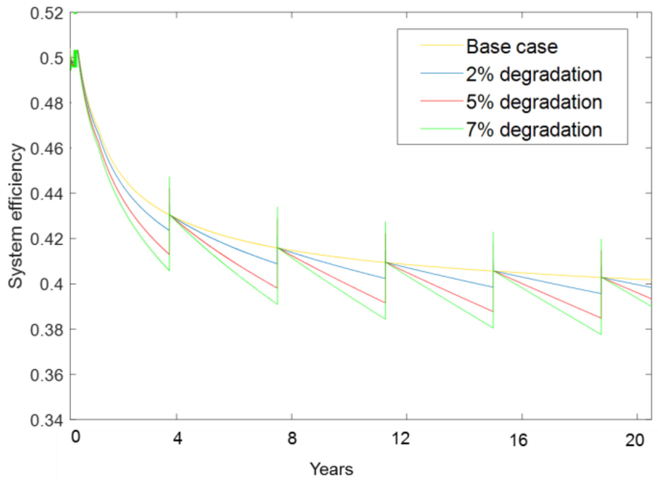

Figure 3. System efficiency trends with constant gas turbine degradation rate

An economic evaluation was performed by computing the IRR. The maximum value of IRR was always found at 20 years, therefore considering to operate the system until the fuel cell end of life and to replace the gas turbine when needed. Hence, the lifetime of the system was not affected by the rate of gas turbine degradation over time. The IRR values for the 4 cases are reported in Table 2. A not surprising reduction in IRR with increased implanted degradation rate was observed. Note that in Case 0, gas turbine replacements were not considered.

Table 2. IRR values comparison for Case 1 (constant degradation rates)

Case 0 – Base case	Case 1a – 2%	Case 1b – 5%	Case 1c – 7%
0.17	0.138	0.127	0.107

However, the effect of simultaneous degradation of fuel cell and gas turbine on the TIT was more evident, as shown in Figure 4. As the cell degraded, the TIT was increased to produce more power from the gas turbine. In absence of pressure ratio or gas turbine efficiency deterioration, the temperature reached the design value of 950°C after 20 years. Degradation of gas turbine components caused the temperature to rise more quickly between overhauls, which resulted in operating periods above the design temperature, in particular for the case at 7% degradation. Those peaks were expected to reduce blade lifetime and decrease the time between overhauls. Therefore, a TIT-dependent time between overhauls calculation was implemented as the second step to evaluate the interaction between degraded fuel cell and degraded gas turbine.

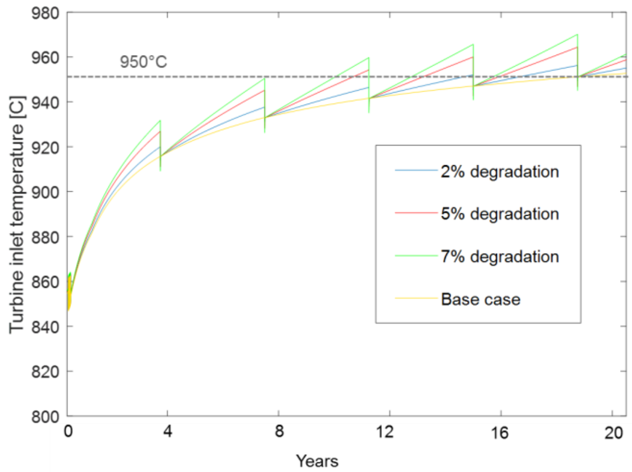

Figure 4. Turbine inlet temperature trends with constant gas turbine degradation rate

Turbine inlet temperature effect

In Case 2, degradation rates of β and η were calculated as function of TIT, as previously explained. When the TIT was below the design value (950°C), the TBO for the gas turbine was kept at 30,000 hours with a constant degradation rate over time. As the temperature exceeded the limit of 950°C, a correcting factor reduced the TBO, thus incrementing the instantaneous rate. For example, Figure 5 shows the Case 2c at initial degradation rate of 7% for efficiency and pressure ratio: during the first 60,000 hours, the TIT was below 950°C and β degraded at a constant rate in the same way as Case 1c. As the temperature rose, the TBO was shorter and the slope of β decay was not constant but dependent on the TIT (it was assumed that the gas turbine replacements always occurred when the total decay of β and η was 7% of the nominal values). This interaction caused a self-propagating effect because a higher degradation rate of β and η induced the temperature to rise faster.

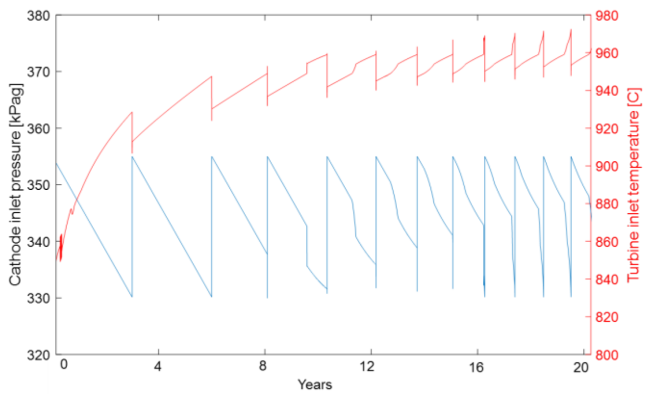

Figure 5. Cathode inlet pressure and turbine inlet temperature trends with 7% initial degradation rate and TIT-dependent time between overhauls

This case is a clear example of how the interaction between two degrading components (i.e. the fuel cell and the micro gas turbine) aggravates system performance degradation. As a matter of fact, in a traditional gas turbine cycle, the turbine outlet temperature (TOT) is normally used as control parameter. As the pressure ratio or the efficiency degrade, the TOT tends to rise; the control action to keep it constant is to decrease the fuel flow, actually decreasing the TIT. On the contrary, when the fuel cell degrades, more thermal power is transferred to the turbine and the TIT increases over time. Hence, the gas turbine is found to operate at harsher conditions when the fuel cell is more degraded.

Figures 6 and 7 present the system efficiency and TIT comparisons among the 3 cases and Case 0. With 2% initial degradation rate, the trends are exactly the same as per the Case 1a at constant degradation rate until the fourth replacement of the turbomachinery. After around 14 years, the TIT reached 950°C and the TBO started reducing accordingly. A total of 7 replacements was necessary during the plant lifetime. With 5% initial degradation rate, the TIT effect appeared after only 3 gas turbine replacements, and 9 overhauls were performed over the 20 years of operations. With 7% initial degradation rate, 11 overhauls were necessary over the plant lifetime.

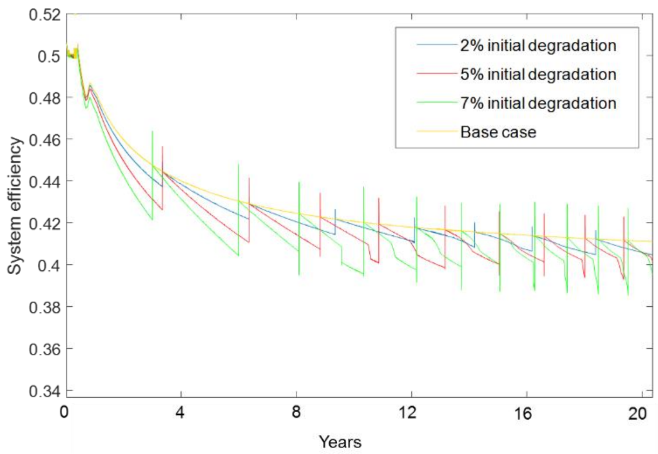

Figure 6. System efficiency trends with TIT-dependent time between overhauls

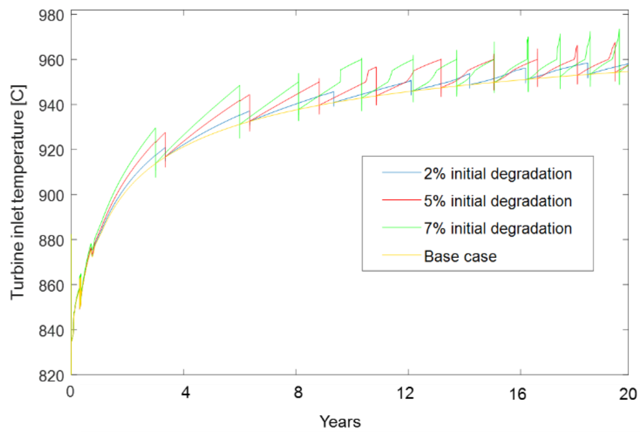

Figure 7. Turbine inlet temperature trends with TIT-dependent time between overhauls

It is clear that in this case there will be a maximum number of feasible overhauls to have the highest economic return, thus determining the total system lifetime. For Case 2a (2% initial degradation rate), the optimal IRR was found after 6 replacements; however, the plant lifetime was reduced to 19 years and the IRR was about 7% lower than for Case 1a and 20% lower than Case 0. Increasing the initial rate of degradation to 5%, the maximum IRR decreased and corresponded to a shorter system lifetime. A longer system lifetime and a higher number of replacements were observed for initial degradation rate of 7%. This trend is illustrated in Table 3 and Figure 8.

Table 3. IRR values comparison for Case 2 (TIT-dependent time between overhauls and degradation rate)

	Case 0	Case 2a 2%(TIT)	Case 2b 5%(TIT)	Case 2c 7%(TIT)
IRR	0.17	0.13	0.11	0.07
Replacements	1 (EOL)	6	6	7
System lifetime [yr]	20	19	17	18

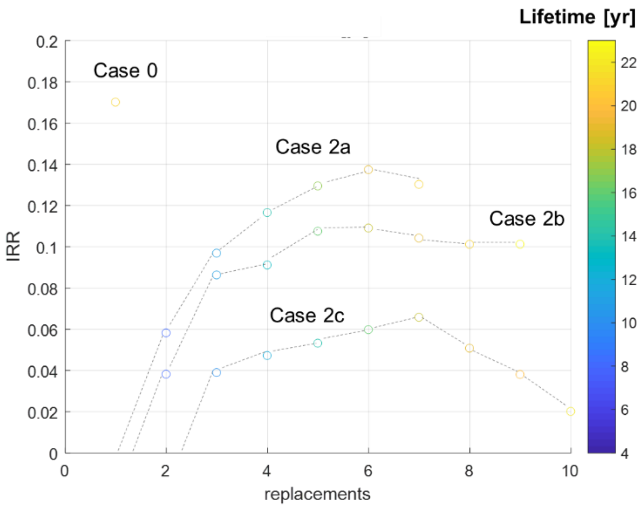

Figure 8. IRR comparison for Case 2, TIT-dependent time between overhauls

Interestingly, the decrease in IRR was not linear. Case 2a and 2b differ only for 2 points percentage, while Case 2b and 2c differ for 4 points percentage, although 2b exhibits the shortest system lifetime. For Case 2c, the extra replacement contributed more to the IRR reduction than the positive effect of longer lifetime compared to 2b. The small difference between the IRR of Case 2a and Case 1a (constant degradation rate) compared to the cases at higher degradation rates can be explained by the fact that the turbine was meant to reach design conditions after 20 years according to the employed operating strategy, and the closer the system lifetime is to 20 years, the more the gas turbine can be exploited close to design conditions. Comparing Case 1a and 2a, one additional replacement was necessary and the lifetime decreased by one year, which affected the IRR limitedly. In case of 5% and 7% initial degradation rate, the shorter lifetime meant power production at lower efficiency, which caused the IRR to decrease more than the sole contribution of extra gas turbine overhauls. After 7 replacements, the IRR in Case 2c dropped.

It is worth to notice that, even in the case with shorter lifetime, Case 2b, the gas turbine power at the end of life was 390 kW, very close to the optimal size of 400 kW. However, in general, system power share optimization should be performed considering the interaction between a degraded fuel cell and a degraded turbine, and the consequent reduction in useful lifetime depending on the expected degradation rate of β and η.

CONCLUSIONS

The effect of multiple components degradation on the performance of a micro gas turbine fuel cell hybrid system was analyzed. Two cases were taken into consideration: constant degradation of compressor pressure ratio and gas turbine efficiency over a fixed time between overhauls, and a TBO depending on the operating TIT. The impact on system efficiency, lifetime, and IRR was assessed by varying the degradation rate of the gas turbine components between 2% and 7%. The main conclusions are summarized by the following bullet points:

- With a constant TBO, the degradation rate of β and η did not impact the system lifetime. The maximum IRR was found for all cases at 20 years, considering 5 gas turbine overhauls over this period.
- With constant TBO, the plant IRR decreased linearly with increasing degradation rate of β and η from 2% to 7%.
- In all cases, the TIT exceeded the design value of 950°C before the end of life, indicating that a replacement strategy based on the TIT would be necessary to ensure system safe operations.
- When the TBO was considered as a function of the TIT, both system lifetime and IRR were strongly dependent on the assumption of design degradation rate.
- In this latter case, performance degradation of the fuel cell stack aggravated gas turbine degradation.
- With a design degradation rate of 2% for β and η, a 20% reduction in IRR was observed compared to the base case, due to the shorter system lifetime and the additional gas turbine replacement.
- With 5% design degradation rate, the larger decrement in lifetime reduced IRR more despite only one extra overhaul, resulting in a 14% lower IRR (35% lower than the base case).
- With 7% design degradation rate, a total of 7 gas turbine overhauls over 18 years resulted in an IRR 60% lower than the case without gas turbine deterioration.

Hence, when the interaction between degraded components is considered, system lifetime and economic return can change significantly. In designing the system (e.g. the optimal power share between fuel cell and gas turbine) and defining the operating strategy to mitigate degradation effect, the interaction aspect needs to be taken into account.

For future work, an improved operating strategy will be investigated, to regulate TIT and maximize the time between overhauls.

NOMENCLATURE

CF	Cash flow [$]
DR	degradation rate [%]
IRR	Internal rate of return
mGT	micro gas turbine
NDRES	non-dispatchable renewable energy sources
OEM	original equipment manufacturer
OGB	off-gas burner
P	Larson-Miller parameter
SOFC	solid oxide fuel cell
t	time [yr]
TBO	time between overhaul
TCI	total capital investment [$]
TIT	turbine inlet temperature [K]
TUO	time until overhaul [yr]
η	gas turbine cycle efficiency
β	pressure ratio

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