# Multi-objective Optimization of Solid Oxide Fuel Cell–Gas Turbine Hybrid Cycle and Uncertainty Analysis

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## Abstract:

Chemical process optimization problems often have multiple and conflicting objectives, such as capital cost, operating cost, production cost, profit, energy consumption and environmental impact. There are several conversion technologies that can convert Synthetic Natural Gas (SNG) into power, heat and electricity; of these, Solid Oxide Fuel Cell with Gas Turbine (SOFC-GT) has shown higher thermodynamic performance. In this study, design and operation of SOFC-GT is optimized for levelized electricity cost and annualized capital cost per kWh, simultaneously. The final selection of a solution from the obtained Pareto-optimal front depends on its sensitivity to the uncertain parameters, such as fuel and product prices, plant life and operating time. Practitioners are mainly interested in selecting one or few robust solutions which are less sensitive to the uncertain parameters, and so the uncertainty analysis of the obtained non-dominated solutions may help in identifying robust solutions. In this study, effect of several uncertain operating and market parameters namely, yearly operation, economic life time, interest rate, fuel cell capital cost factor, electricity price, oxygen price and SNG price, is studied on the performance of SOFC-GT system. The uncertainty analysis is able to idetify most promising non-dominated solutions, based on the levelized electriicty cost as main decision crieriton.

## Keywords:

Multi-objective Optimization, Solid Oxide Fuel Cell, Gas Turbine, Uncertainty Analysis.

# 1. Introduction

Many process optimization problems have multiple objectives, related to economics, energy, environment and safety (Sharma and Rangaiah, 2013). In such cases, Multi-objective Optimization (MOO) is useful in finding many optimal solutions, to understand the quantitative trade-offs among the objectives, and also to obtain the optimal values of decision variables. There are several conversion technologies that can convert Synthetic Natural Gas (SNG) into power, heat and electricity. SNG can be used in internal combustion engines, gas turbines or Solid Oxide Fuel Cell (SOFC). SOFC with Gas Turbine (SOFC-GT) has shown higher thermodynamic performance that leads to better utilization of natural resource, reduced environmental impact, and more profit.

Gasification can be used to convert biomass resource into SNG, which has methane, hydrogen, carbon dioxide as main component. Fuel cell can directly use the crude SNG without any carbon dioxide separation. Further, SOFC is a modern conversion technology, which has possibility of cogeneration, using natural gas (i.e., methane) or bio-gas (i.e., 0.62 mole fraction methane and remaining carbon dioxide) as fuel. The unconverted part of fuel from SOFC is generally combusted to recover low temperature heat. Hence, several researchers have used other technologies with SOFC, to achieve higher performance. Facchinetti et al. (2014) studied design and optimization of solid oxide fuel cell – gas turbine hybrid cycle, and achieved exergy efficiency higher than 65%. Performance of processes is highly influenced by operating and market conditions. Hence, effect of economic and operating conditions on process design has been investigated in literature. Tock and Maréchal (2015) have studied the sensitivity analysis of Pareto-optimal fronts obtained for $CO_2$ capture in power plant, and SNG production from biomass resource, with respect to several uncertain parameters.

In this study, design and operation of SOFC-GT is optimized for levelized electricity cost and annualized capital cost per kWh, simultaneously. For this, twelve important operating parameters are chosen as decision variables. The MOO is performed using OSMOSE, which has been mainly used for design and optimization of integrated energy system (Palazzi et al., 2007). The final selection of a solution from the obtained Pareto-optimal front for SOFC-GT system depends on its sensitivity to uncertain operating and market parameters. Decision makers are mainly interested in selecting a robust solution, based on levelized electricity cost as decision criterion, which should be less sensitive to the uncertain parameters. Hence, uncertainty analysis of selected non-dominated solutions, with respect to yearly operation, economic life time, interest rate, fuel cell capital cost factor, electricity price, oxygen price and SNG price, is studied. This uncertainty analysis is able to identify the best non-dominated solution.

The next section brefily describes the design and modeling of SOFC-GT system. Section 3 presents results for MOO of SOFC-GT system. Section 4 discusses distribution function for uncertain operating and market parameters, and also uncertainty analysis results for SOFC-GT system.

# 2. Solid Oxide Fuel Cell with Gas Turbine (SOFC-GT)

Fig. 1 presents a simplified schematic of SOFC-GT system, and it can be divided into five sub-systems: (1) fuel processing (SR), (2) fuel cell, (3) anodic gas turbine (GTA), (4) cathodic gas turbine (GTC), and (5) $CO_2$ compression. The SOFC-GT has been simulated in BELSIM-VALI (version 4.7.0.3) flowsheeting software. Fuel (crude SNG or bio-gas) used in SOFC-GT has 0.62 mole fraction methane and remaining carbon dioxide.

In the fuel processing sub-system, methane is partially converted into hydrogen inside a reformer. Both steam reforming reaction ($CH_4 + H_2O = CO + 3H_2$, $\Delta h = 206.11$ kJ/mol) and water gas shift reaction ($CO + H_2O = CO_2 + H_2$, $\Delta h = -41.16$ kJ/mol) are performed inside the reformer. The partially converted fuel enters the anode of a planner SOFC around 1,000 K, whereas hot air enters on the cathode side. In this study, SOFC model developed by Van Herle et al. (2003) is used, which also has possibility of internal reforming. The SOFC model assumes anode supported cells, composite lanthanum strontium cobaltite ferrite cathode and metallic interconnectors. Further, the electrochemical model for SOFC considers diffusion losses at anode and cathode, and polarization and ohmic losses.

As air is used at high temperature on the cathode side of SOFC, and so the unused air at high temperature can be used to produce electricity using cathodic turbine. The unconverted fuel from the anodic side of SOFC is combusted in a burner in the presence of oxygen, and then it goes to anodic turbine to produce electricity. The outlet stream from the anodic turbine has mainly carbon dioxide and some amount of water, and so water has to be removed before compression of carbon dioxide. Finally, carbon dioxide is compressed to a very high pressure (~ 125 bar) by a series of compressors and heat exchanges.

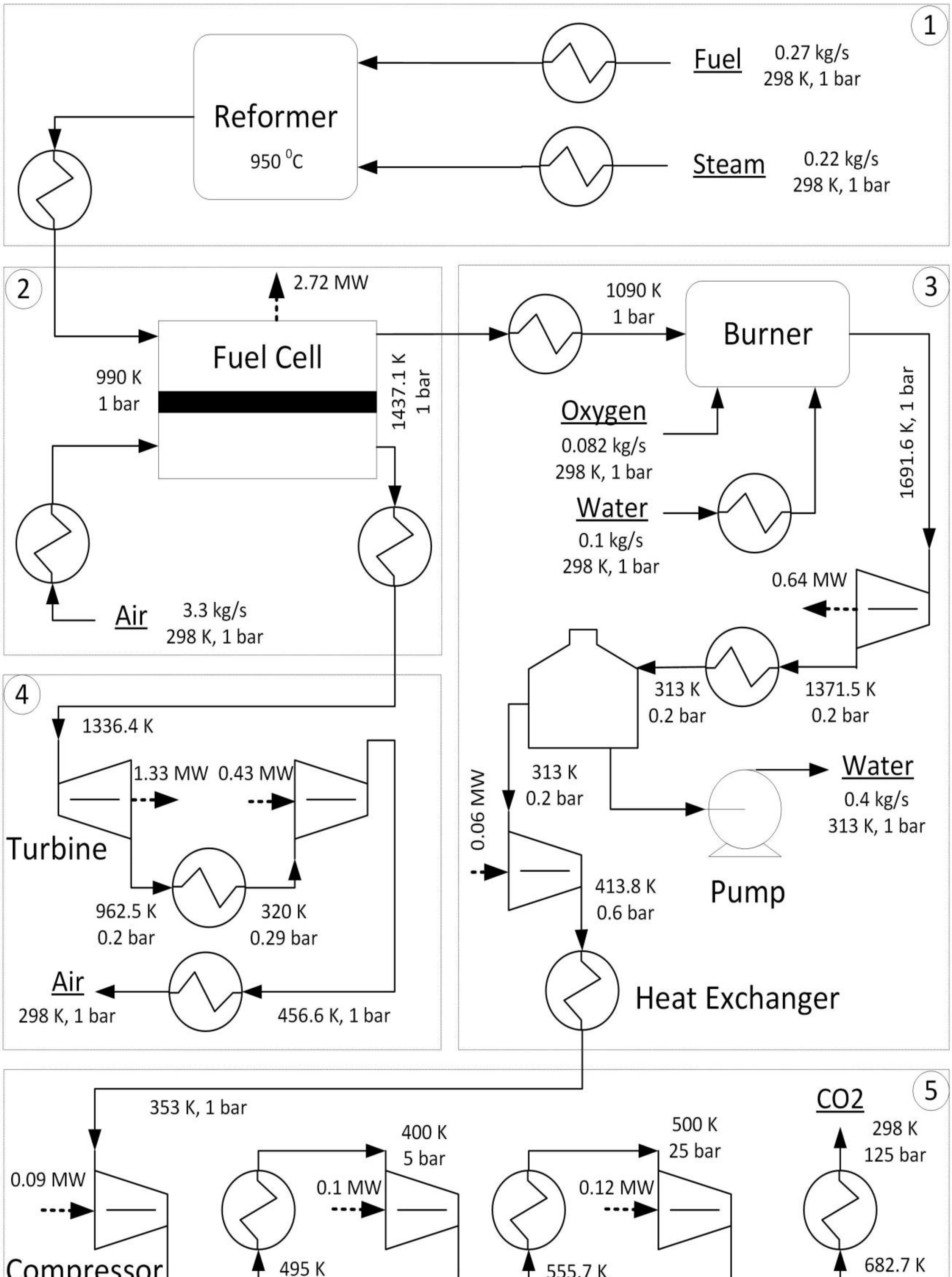


*Fig. 1. A simplified schematic of solid oxide fuel cell with gas turbine (1 - fuel processing, 2 – solid oxide fuel cell, 3 - anodic gas turbine, 4 - cathodic gas turbine, and 5 - $CO_2$ compression); stream data correspond to 5^th solution in Figure 4*

# 3. Multi-Objective Optimization of SOFC-GT

Table 1 presents the formulated MOO problem for SOFC-GT system. In this, minimization of both levelized electricity cost and annualized capital cost per kWh are two objectives. The MOO problem has 12 decision variables, from all five sub-systems of SOFC-GT. Ranges of all decision variables are decided based on the literature (Facchinetti et al., 2014) and preliminary analysis.

*Table 1. Multi-objective problem formulation for SOFC-GT system*

| **Objective Function** | | |
|---|---|---|
| Minimize Levelized electricity cost ($/kWh) | | |
| Minimize Annualized capital cost per kWh ($/kWh) | | |
| **Decision Variable** | **Lower Bound** | **Upper Bound** |
| Steam to carbon ratio for SR | 0.7 | 3.5 |
| Temperature outlet of SR (K) | 850 | 950 |
| Inlet temperature of the fuel cell reactor (K) | 950 | 1050 |
| Fuel utilization | 0.5 | 0.8 |
| Inlet temperature for GTC (K) | 1100 | 1500 |
| Pressure ratio GTC turbine | 3 | 5 |
| Pressure ratio GTC compressor | 3 | 5 |
| Pressure ratio GTA turbine | 3 | 5 |
| Pressure ratio GTA compressor | 3 | 5 |
| Pressure ratio for CO2 turbine 1 | 4 | 5 |
| Pressure ratio for CO2 turbine 2 | 4 | 5 |
| Pressure ratio for CO2 turbine 3 | 4 | 5 |

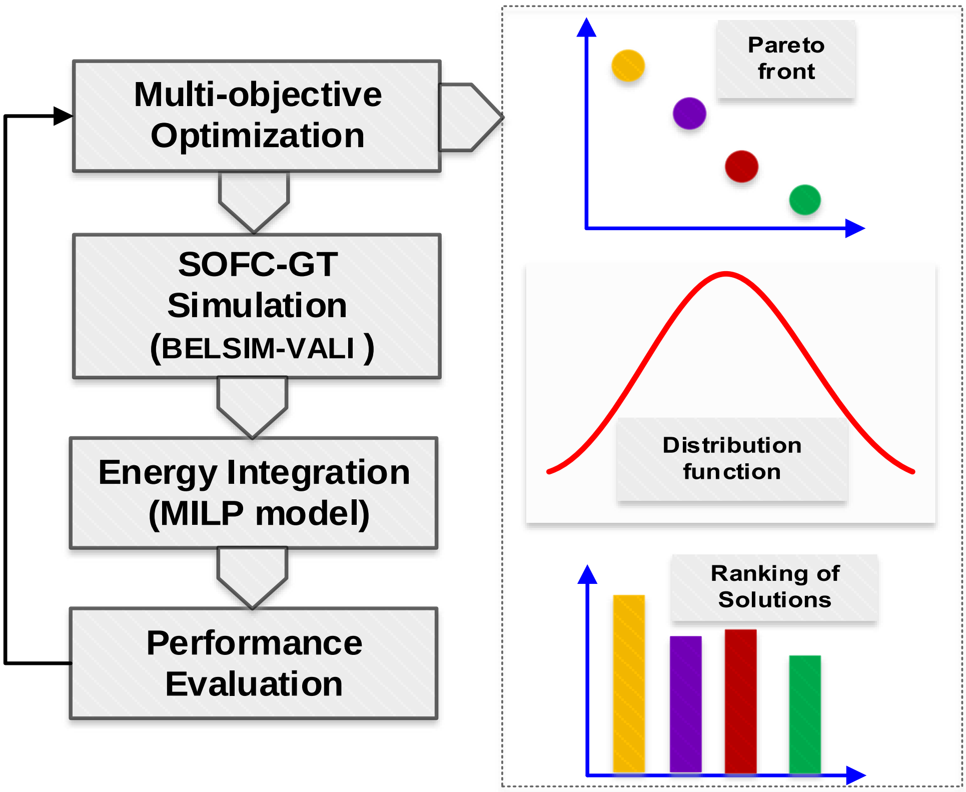


Fig. 2. MOO using OSMOSE which has four main parts: MOO, SOFC-GT simulation, energy integration and performance evaluation (uncertainty analysis part is inside the dotted box)

The MOO of SOFC-GT system is performed using OSMOSE, which has four important parts (see Fig. 2): (1) genetic algorithm based MOO program (where clustering technique maintains local optima) which provides the values of decision variables, (2) passes values of decision variables to BELSIM Vali for simulating SOFC-GT system, (3) obtains temperatures and flow rates of important streams from BELSIM Vali and perform heat integration, and (4) performance evaluation or calculations of objective functions for SOFC-GT system.

Annualized capital cost of SOFC-GT is calculated using correlations and data given in Pelster (1998), Maréchal et al. (2004) and Turton et al. (2009). In the MOO of SOFC-GT system, fixed values of uncertain operating and market parameters are used: yearly operation = 6592.9 (h/year), fuel cell life time = 5.9 (year), other equipment life time = 17.8 (year), interest rate = 0.059 (%), fuel cell capital cost factor = -0.016, electricity price = 0.16 ($/kWh), oxygen price = 1467 ($/3600 kg), and SNG Price (0.62 mole fraction methane and remaining carbon dioxide) = 672 ($/3600 kg). These values of operating and market parameters are average of 500 values, based on their distribution functions (see Table 3 and related discussion). The SOFC-GT system requires $6.4\times10^6$ (= 0.27×3600×6592.9) kg fuel per year.

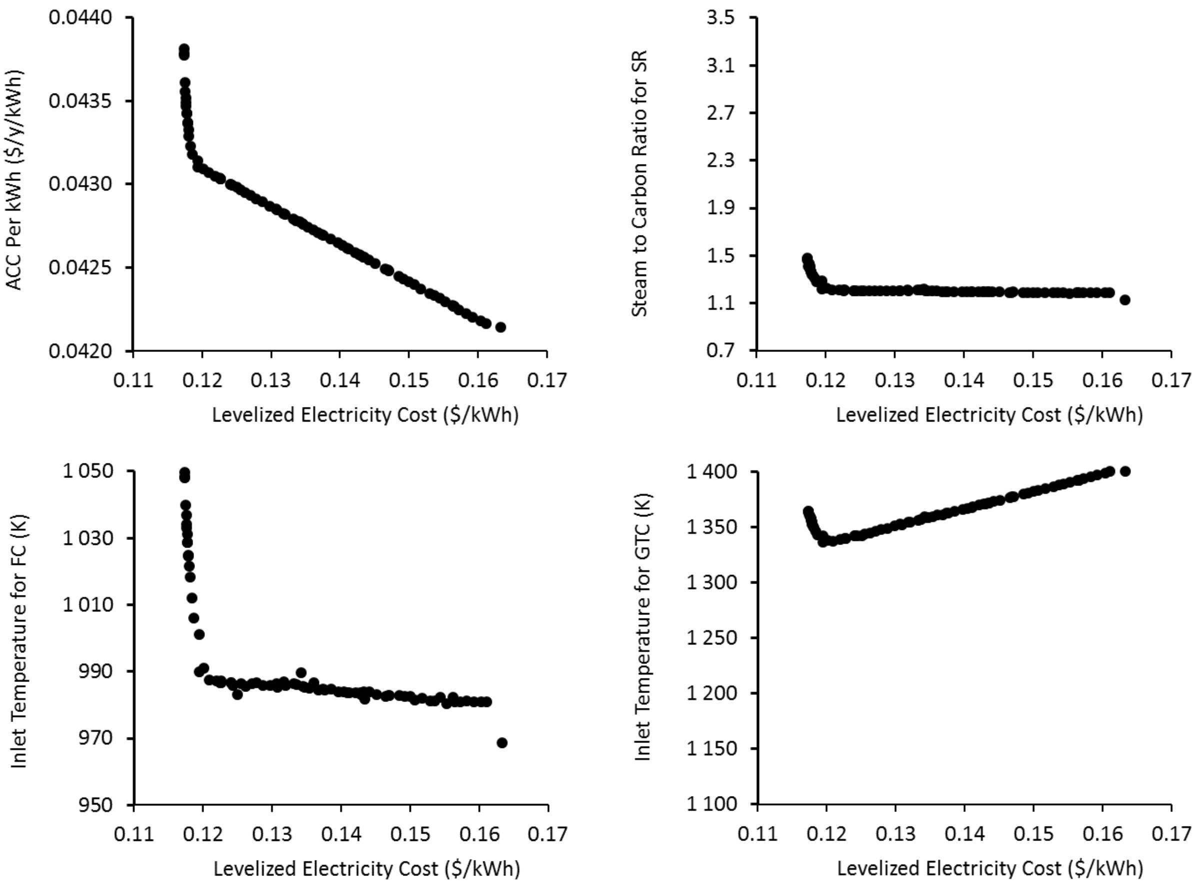


*Fig. 3. Trade-offs between levelized electricity cost and annualized capital cost per kWh for fixed values of operating and market parameters*

Fig. 3 presents the Pareto-optimal front for simultaneous minimization of both levelized electricity cost and annualized capital cost per kWh. These results are obtained with: population size = 100 and number of function evaluations = 10,000. As expected, levelized electricity cost is conflicting with annualized capital cost per kWh. Fig. 3 also shows variations of important decision variables with levelized electricity cost. Outlet temperature for SR, fuel utilization, pressure ratios for GTC and GTA turbines are close to their upper bounds. Finally, pressure ratios for all compressors (1 in GTC, 1 in GTA and 3 in $CO_2$) are close to their lower bounds, and these are not shown in Fig. 3 for brevity.

## 4. Uncertainty Analysis of Selected SOFC-GT Designs

It is worth mentioning that a corner solution on the Pareto-optimal front (e.g., solution 5 in Fig. 4) is an attractive choice, if decision maker wants to select a solution by just seeing the shape of Pareto-optimal front (i.e., no uncertainty analysis), as corner solution is generally most compromised solution. The selection of one solution from the Pareto-optimal front can be done based on the experience of engineers or using a Pareto ranking approach, which often requires preferences about objectives and their ranges (Rangaiah et al., 2015).

The uncertain operating and market parameters can be described by probability distribution functions. There are many uncertain operating and market parameters which can affect the performance of SOFC-GT system. In this study, eighth important operating and market parameters are considered, for studying their effects on the selected SOFC-GT designs (i.e., non-dominated solutions from Fig. 3). As different parts on the Pareto-optimal front (Fig. 3) represent different regions of decision variables space, so only some selected non-dominated solutions, covering all parts of the Pareto-optimal front, can be considered for uncertainty analysis. There are no integer variables in the optimization problem, and so the selection of some non-dominated solutions for uncertainty analysis is appropriate. Here, 25 non-dominated solutions are taken from the Pareto-optimal front for uncertainty analysis, and these are numbered and shown in Fig. 4.

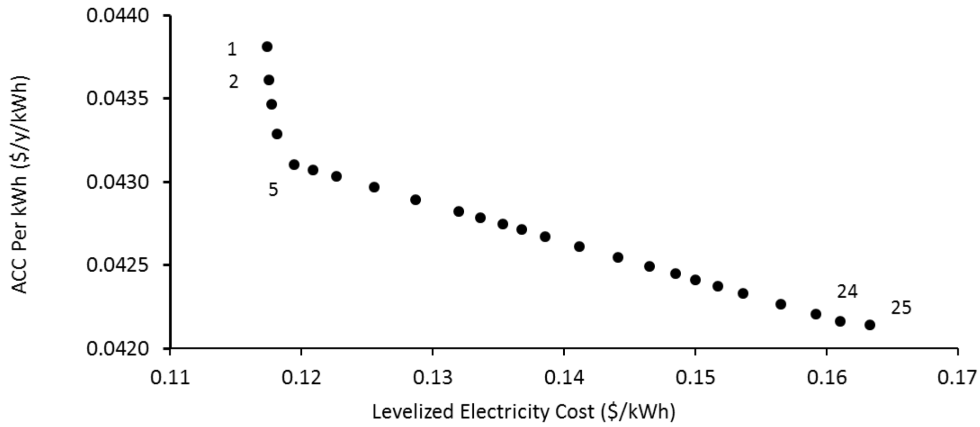


*Fig. 4. Selected SOFC-GT designs for uncertainty analysis*

Table 2 presents distribution functions for uncertain parameters. More details on distribution functions for yearly operation, economic life time, interest rate and fuel cell capital cost factor can be found in Tock and Maréchal (2015). Further, nominal electricity price is taken from Switzerland, oxygen price is calculated from Rao and Muller (2007), and SNG price (0.62 mole fraction methane and remaining carbon dioxide) is computed based on the natural gas price. Finally, normal distributions are assumed for electricity, oxygen and fuel prices, based on Tock and Maréchal (2015).

*Table 2. Definition of distribution functions for uncertain operating and market parameters*

| **Uncertain Parameters** | | **Distribution Functions** | |
|---|---|---|---|
| Yearly Operation | YO (h/year) | Beta | c = 8600, $\alpha$ = 3.9, $\beta$ = 1.2 |
| Interest Rate | IR (%) | Normal | $\mu$ = 0.06, $\sigma$ = 0.01 |
| Fuel cell Life Time | FCLT (year) | Beta | c = 10, $\alpha$ = 5.8, $\beta$ = 4 |
| Other Equipment Life Time | OELT (year) | Beta | c = 30, $\alpha$ = 5.8, $\beta$ = 4 |
| Fuel Cell Capital Cost Factor | FCCF | Uniform | a = - 0.3, b = 0.3 |
| Electricity Price | EP ($/kWh) | Normal | $\mu$ = 0.16, $\sigma$ = 0.02 |
| Oxygen Price | OP ($/3600 kg) | Normal | $\mu$ = 1476, $\sigma$ = 200 |
| SNG Price | SP ($/3600 kg) | Normal | $\mu$ = 670, $\sigma$ = 100 |

In order to perform the uncertainty analysis of selected non-dominated solutions, obtained via normal MOO approach, following steps are followed.

1. $LEC_i(FIX)$ is the levelized electricity cost for $i^{th}$ non-dominated solution, based on the fixed values of operating and market parameters.
2. Generate 500 economic scenarios (ES1, ES2,…, ES500) based on the distribution functions for uncertain operating and market parameters (see Table 3).
3. For ES1:

- For $i^{th}$ non-dominated solution, calculate levelized electricity cost value = $LEC_i(ES1)$
- For $i^{th}$ non-dominated solutions, calculate absolute relative change in the levelized electricity cost.

$$LEC_i(RC) = \left|\frac{LEC_i(ES1) - LEC_i(FIX)}{LEC_i(FIX)}\right| \quad (1)$$

- Lower value of $LEC_i(RC)$ means solution is less sensitive, and so identify best and top 5 solutions, based on $LEC_i(RC)$.

4. For ES2 to ES500: repeat Step 3, and identify best and top 5 solutions.
5. For 500 economic scenarios: calculate percentage to be best solution (= number of times a particular solutions was best solution / number of economic scenarios × 100) and percentage to be in top 5 solutions (= number of times a particular solutions was in top 5 solutions / number of economic scenarios × 100).

*Table 3. 500 economic scenarios, based on the distribution functions for uncertain operating and market parameters*

| **Uncertain Parameter** | **$ES_1$** | **$ES_2$** | | **$ES_k$** | | **$ES_{499}$** | **$ES_{500}$** |
|---|---|---|---|---|---|---|---|
| **YO** | $YO_1$ | $YO_2$ | … | $YO_k$ | …. | $YO_{499}$ | $YO_{500}$ |
| **IR** | $IR_1$ | $IR_2$ | … | $IR_k$ | … | $IR_{499}$ | $IR_{500}$ |
| **FCLT** | $FCLT_1$ | $FCLT_2$ | … | $FCLT_k$ | …. | $FCLT_{499}$ | $FCLT_{500}$ |
| **OELT** | $OELT_1$ | $OELT_2$ | … | $OELT_k$ | …. | $OELT_{499}$ | $OELT_{500}$ |
| **FCCF** | $FCCF_1$ | $FCCF_2$ | … | $FCCF_k$ | … | $FCCF_{499}$ | $FCCF_{500}$ |
| **EP** | $EP_1$ | $EP_2$ | … | $EP_k$ | …. | $EP_{499}$ | $EP_{500}$ |
| **OP** | $OP_1$ | $OP_2$ | … | $OP_k$ | … | $OP_{499}$ | $OP_{500}$ |
| **SP** | $SP_1$ | $SP_2$ | … | $SP_k$ | .. | $SP_{499}$ | $SP_{500}$ |

This uncertainty analysis of the selected SOFC-GT designs will help decision maker to select one final solution for the implementation purpose. Fig. 5 presents the ranking of non-dominated solutions, based on the percentage to be best and percentage to be in top 5, using 500 economic scenarios. It can be seen that solution 5 (with percentage to be best = 21.8) has minimum relative change in the levelized electricity cost. It can be noticed that this solution 5 is the best solution for 109 economic scenarios (or 21.8%), out of 500 economic scenarios. Non-dominated solutions near to the corner (solutions 3, 5, 7, 8 and 9) and on the extreme sides of the Pareto-optimal front (solutions 1 and 25) seem to be more robust solutions compared to others. Further, solutions 1-5 have nearly same percentage to be in top 5 solutions. Hence, solution 5 can be selected for implementation purpose, based on this uncertainty analysis.

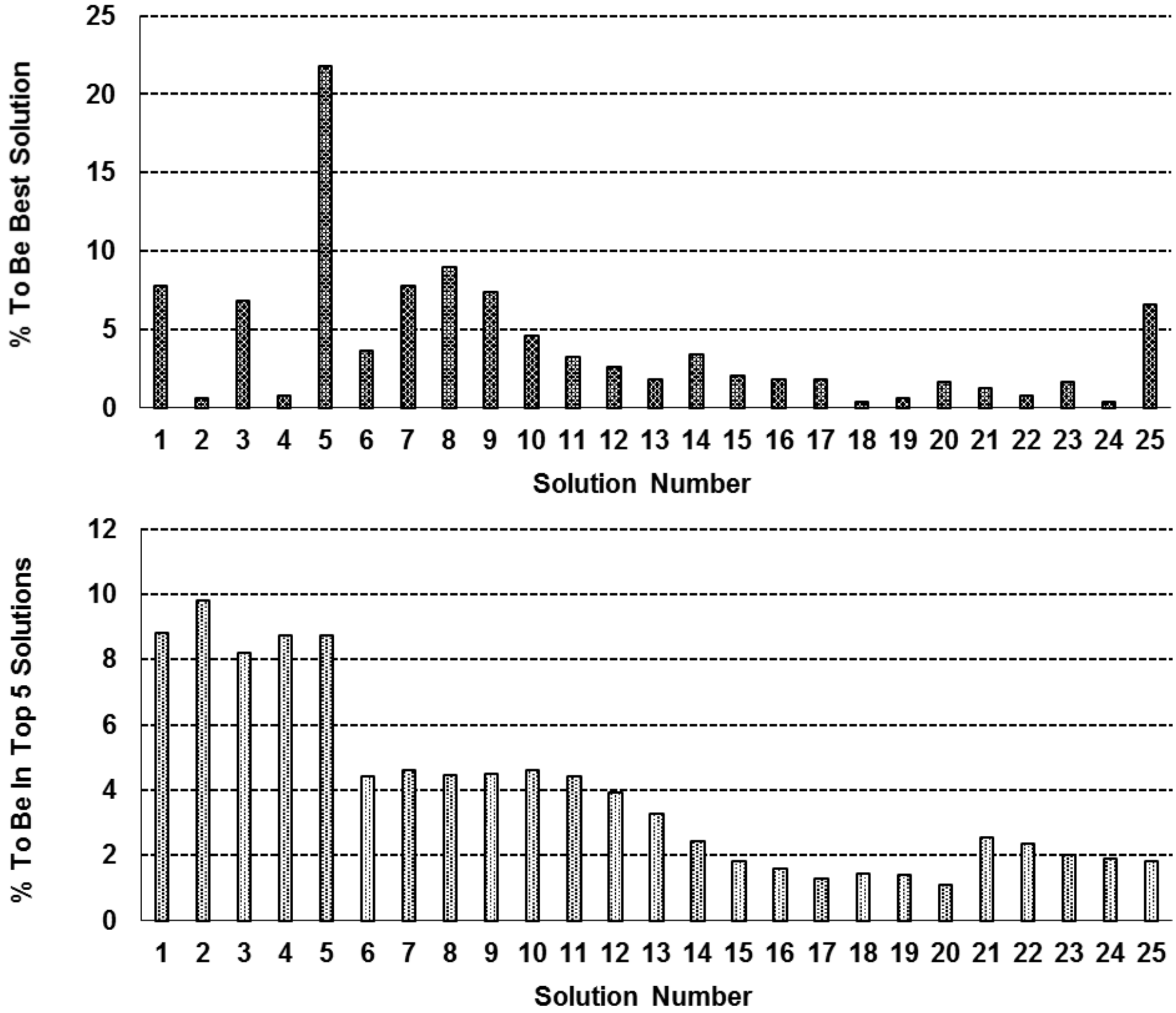


*Fig. 5. Ranking of selected SOFC-GT designs via uncertainty analysis*

# 5. Conclusions

This study optimizes performance of SOFC-GT system for minimization of both levelized electricity cost and annualized capital cost per kWh, simultaneously. In this optimization, steam to carbon ratio for reformer, inlet temperature for fuel cell and inlet temperature for cathodic gas turbine are mainly affecting the performance of SOFC-GT system. Finally, selected SOFC-GT designs are ranked based on the percentage to be best and percentage to be in top 5 solutions, using 500 economic scenarios. It was found that corner and extreme solutions from the Pareto-optimal front are more robust solutions, and so one of these can be selected for the implementation purpose.

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