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Fuel Cells
FROM FUNDAMENTALS TO SYSTEMS

ORIGINAL RESEARCH PAPER

Evaluating the influence of requirements in fuel cell system design using Design Requirement Maps

Alexander Fladung[1,2] | **Hannes Scholz**[1] | **Oliver Berger**[1] | **Richard Hanke-Rauschenbach**[2]

[1] Volkswagen AG, Group Innovation Fuel Cell, Wolfsburg, Germany

[2] Institute of Electric Power Systems, Gottfried Wilhelm Leibniz University Hannover, Hannover, Germany

Correspondence
Alexander Fladung, Volkswagen AG, Group Innovation Fuel Cell, Berliner Ring 2, 38440 Wolfsburg, Germany.
Email: alexander.fladung@volkswagen.de

Abstract

Finding a combination of design variables for an optimized design target is the main aspect in fuel cell system design. Beside that, it has to be ensured that all requirements, on component and vehicle level, are met. Using a visualization approach, called Design Requirement Map, as a graphical presentation of the design target and the requirements of two degrees of freedom, helps to answer certain design questions and enable an estimation of the influence of requirements and operating points on the optimal system design. In this paper, first, the general fuel cell system design problem is formulated and, second, the Design Requirement Map is used to study the influence of requirements on the optimal combination of humidifier scale and air compression ratio. Designs with too small or too large humidifiers reveal as designs, which are constrained by at least one of the considered requirements. In addition, the influence for a multi-objective design target and different ambient temperatures and pressures are addressed. For certain design questions using Design Requirement Maps can be very helpful to evaluate the impact of requirements on the system design especially when considering different operating points.

KEYWORDS

ambient operating conditions, automotive requirements, PEM fuel cell system, system design, vehicle application

1 | INTRODUCTION

This paper is dealing with the design of fuel cell systems for automotive application, whose interest increases due to the fact of reduced environmental impact of fuel cell electric vehicles (FCEVs) regarding CO_2-emissions compared to conventional internal combustion engine vehicles [1, 2]. For the commercialization of FCEVs, the design of the fuel cell system has to be optimized to minimum costs as well as maximum efficiencies. The challenge is to match the design of several components to meet the system requirements at optimal design target.

Main focus of this paper are the formulation and numerical evaluation of fuel cell system design problems with the specialty of consideration of external and internal requirements, a multi-objective design target, and several operating point operations due to ambient conditions with the particularl consideration of the influence of certain requirements.

In general, there are three different levels of the considered system boundary of FCEV design: vehicle level, system level, and component level. On vehicle level the overall vehicle propulsion system design with focus on optimal control and optimal design of fuel cell system, hydrogen tank, battery system and electric motor is investigated [3, 4]. In contrast, on component level a more detailed design of single components of the systems is addressed [5–8].

Reviews of designing fuel cell systems on system level where this paper is classified can be found in Wang et al. [9] and Secanell et al. [10]. Typical investigations are analyses of the influence of the internal operating conditions like operating pressures or operating temperatures on the system efficiencies [11] and furthermore the optimization of those ([12–15]).

Many studies optimize performance [16, 17], costs, durability or emissions [18, 19] as design objective. In Chen et al. [14], a multi-objective evolutionary algorithm is used to study the pareto front of the maximum efficiency and the maximum system power. Ang et al. [15] use a multi-objective optimization to investigate the design trade-off between efficiency and size, represented by the area of the membrane electrode assembly.

Less found in the literature is the consideration of vehicle requirements and specific component constraints (e.g., minimum membrane humidity) as well as different operating points of the fuel cell system due to lower ambient pressures and higher ambient temperatures in the design problem. In Ahluwalia et al. [20] at least a heat rejection constraint of 1.45 kW K^{-1} for an 80 kW fuel cell system is limiting the operating pressure and operating temperature. The influence of the behavior of the fuel cell system at different ambient conditions with focus on the efficiency and net power is discussed by Haraldsson et al. [21] but without direct feedback to prior design.

A general formulation of the design problem under consideration of i) requirements, ii) multi-objective design function, and iii) several operating points and a method for evaluation of their feedback on the system design is missing. In this paper the general design problem and additionally a useful illustration method to evaluate the influence of (i), (ii), and (iii) on two exemplary design variables is discussed. The advantages of the methodology are the easy generation and helpful visualization of the combination of design variables and design constraints with the possibility to choose the optimal value of the design variable and therefore system design. With use of the so-called Design Requirement Map (DRM) the optimal selection of the design variables can be obtained with regard to the requirements.

This paper is arranged as follows: In Section 2, the general design problem of a PEM fuel cell system for vehicle application is formulated and an introduction to the used methodology is shown. In Section 2, also the considered example system and example design problem is described. The possibilities of the approach and several analyses are presented in Section 3 starting with a reference case and extended cases by a multi-objective design target and then evaluating the influence of different ambient conditions on the specific design case.

2 | FUEL CELL SYSTEM DESIGN PROBLEM, DRM AND EXAMPLE FUEL CELL SYSTEM

2.1 | General design problem of fuel cell systems

Figure 1 shows a schematic overview of the general design problem of a fuel cell system for automotive applications. The elements of the general design problem and the consequential interconnections are individual shown in Figure 1 and are explained in the following.

The aim of designing is to find the best combination of values for the degrees of freedom of design (also called: design variables (DV)) with regard to an optimal design target fulfilling all requirements. The system degrees of freedoms (see Figure 1, box I) can be divided into two different types. On the one hand, there are design variables of the components (component design variables (CDV)) based on geometric aspects of the components or the number of used fuel cells. On the other hand, there are design variables which can be controlled (controlled variables (CV)), for example, rotation speed of a pump, and therefore can differ in different operating points (OP). The operating point of a fuel cell system is defined by one partial load determining controlled variable (the current density is used in fuel cell system applications) and also external operating conditions; here: ambient conditions (AC)) like ambient temperature and ambient pressure (see Figure 1, box II).

Depending on the external operating conditions and the degrees of freedom of design the system will be operated under certain internal operating conditions (IOC, see Figure 1, box III) defined by process and state variables (e.g., pressures, temperatures, relative humidities, concentrations, but also cell voltages, heat flows, and mass flows).

Based on these internal operating conditions and the values of the design variables certain Key Performance Indicators (KPI) can be derived (see Figure 1, box IV). Key Performance Indicators are values of the system specification with special interest. There are two types of

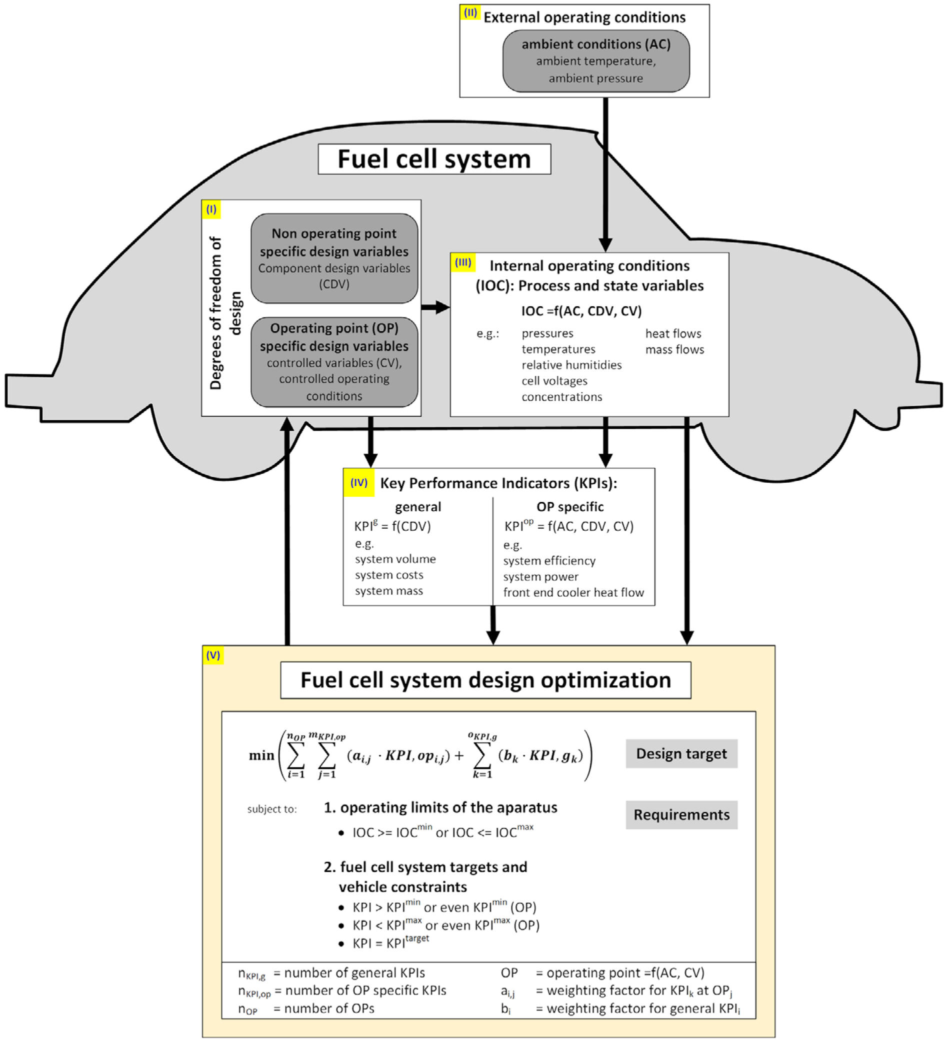

FIGURE 1 Schematic description of the design problem of fuel cell systems, classified by (box I) degrees of freedoms, (box II) external operating conditions, (box III) internal operating conditions, (box IV) key performance indicators and (box V) design optimization

KPIs: General KPIs and OP specific KPIs. General KPIs are only based on the CDV whereas OP specific KPIs depend on the OP and its ambient conditions and CVs. Typical general KPIs are volume, cost, and mass of the fuel cell systems. Typical KPIs related to specific OPs are the system efficiency, the system power and the temperature difference related heat flow of the front-end cooler, which is an important boundary condition for the integration of fuel cell systems into automotive applications due to the design of the front end cooler.

Finally, in the fuel cell system design optimization (see Figure 1, box V) the design variables are determined under minimization of a design target made up from weighted KPI as a multi-objective design target. The multi-objectivity of the design function is characterized by weightings of general KPIs and weightings of OP specific KPIs. As a special characteristic in this design problem the design is constrained by requirements of two different types. First type requirements originate from certain apparatus used in the fuel cell system like membranes, which maximum operating temperature is limited. Second type requirements originate from in the design target not implemented KPI. In general, there are three possible options of consideration of KPI as a requirement. First and second, the design is constrained by a inequality constraint (minimum/maximum values of the KPI or even constrained by minimum/maximum values of the KPI) depended on different operating point. Third option is the formulation of the constraint as equality constraint for exact achievement of a value of its KPI.

Typical example is a maximum heat rejection possibility of a vehicle formulated in the design process as a heat rejection constraint.

2.2 | Introduction of DRMs

To discuss influences of requirements (section 3.1), design targets (section 3.2), and ambient conditions (section 3.3), a methodology referred to as DRM in the following is used and presented in this paper. This methodology as graphical presentation method of the design target and the requirements is especially suitable for design problems reduced to two design variables. Design problems reduced to two design variables can be very helpful with regard to evaluation of influences to get certain knowledge and understanding about coupled design questions. In cases where specific state variables in the fuel cell system or in the fuel cell can be reached on two different ways, the consideration of their combination is recommended by use of DRMs. Another advantage of the use of DRMs is the possibility of a visual approach of determining the values of the design variables and the visualization of the requirements in form as marked regions where requirements are not met.

Figure 2 illustrates schematically the procedure for creating a DRM. To create a DRM it is necessary to have a suitable model of the fuel cell system which has to be designed and which influence towards the requirements shall be analyzed. In a first step two degrees of freedom have to be selected from a set of degrees of freedom. Their design is of special interest to answer certain design questions.

As a second step, external operating conditions (ambient temperature, ambient pressure), i.e. the operating point has to be fixed. As third step, the degrees of freedom will be varied in a certain range and with a certain discretization. The determination of the grid of discretization is carried out so that simulation effort and accuracy of the DRM are in a rational relationship to each other. Each simulation result of combination of the two design variables is a single element of the DRM. By the fourth special visualization step with the use of a tool like Matlab the DRM will be created. In this step mainly two different helpful approaches of the visualization of the design problem will be done. Firstly the design target is shown as height lines in the diagram. From this diagram the best values for the degrees of freedom can be concluded from an optimal value of the design target.

Secondly, the values of the requirements are compared to the targets of the requirements. Areas on the diagram that do not meet certain requirements will be colored.

With this approach it is possible to choose the best combination of the degrees of freedom due to the design target with respect to the fulfilment of requirements and for example robust system design. But beyond that the effects of the different requirements on the design of the fuel cell system can be simply concluded. Questions like how is the design of the fuel cell system changed when it is possible to enable other targets of the requirements can be answered. Therefore, the sensitivities of the design towards the requirements can be considered.

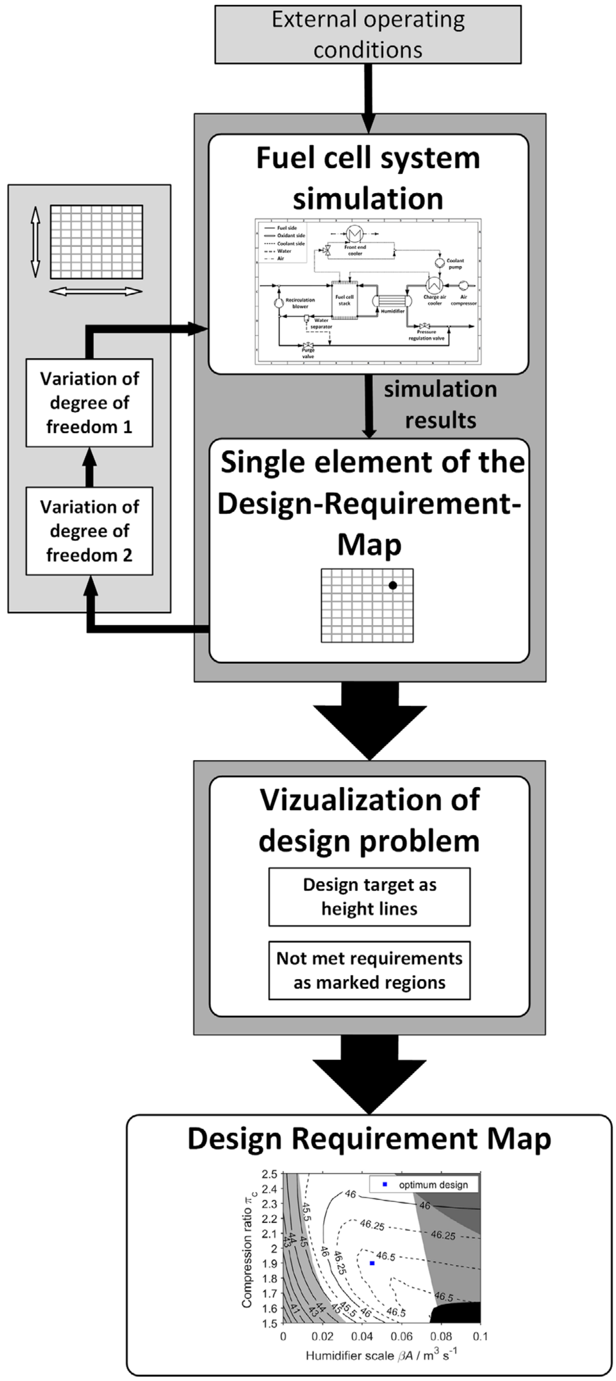

FIGURE 2 Creation process of Design Requirement Maps

2.3 | Example system and example design problem

2.3.1 | Fuel cell system

The architecture and flow sheet of the considered fuel cell system is shown in Figure 3. The system consists of several components of which the most important are

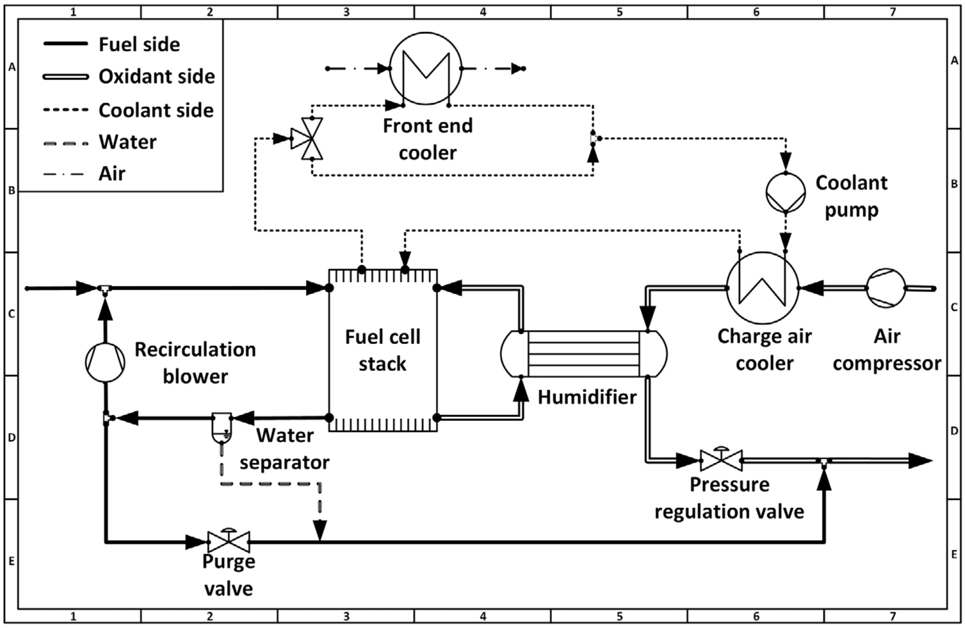

FIGURE 3 Schematic flow sheet of considered fuel cell system

considered in the model, namely fuel cell stack, air compressor, charge air cooler, humidifier, pressure regulation valve, anode recirculation blower, water separator, purge valve, and coolant pump. Also shown is the front-end cooler and thermostat of the vehicle which is necessary for simulation of the system but not directly part of the fuel cell system and therefore out of the system boundary. Components like air or coolant filters are neglected here.

To feed the cathode of the fuel cell ambient air will be sucked from the air compressor and compressed with a certain compression ratio. In the charge air cooler, the air will be cooled by the coolant for the conditioning of an air temperature which will flow next in the humidifier. Since the membrane proton conductivity rises with higher membrane humidities and because low membrane humidities lead to failures and defects in the membrane a humidification of the inlet air is helpful [22]. For the humidification of the inlet gas the cathode outlet gas is used. With the use of a membrane the water of the wet cathode outlet gas diffuses to the dry cathode inlet gas. By sizing the humidifier, a specific air humidity of the cathode inlet gas can be reached. For generation of back pressure of the cathode gas a pressure regulation valve will be used.

The main task on the anode side is to feed the fuel cell with hydrogen gas. The hydrogen will be supplied by the hydrogen tank system which includes valves and a heat exchanger for the throttling and temperature conditioning of the high-pressure hydrogen from the tank. Because of diffusion of water and nitrogen over the membrane in the fuel cell also water and nitrogen appear at the anode gas outlet of the fuel cell stack. With the water separator the liquid water will be removed.

A recirculation of the anode gas helps to increase the efficiency of the fuel cell and the fuel cell system due to the use of higher hydrogen flow rates that increases the diffusion from the gas channel to the catalyst combined with the use of the non-reacted hydrogen. For the recirculation a recirculation blower is used.

The cooling of the fuel cell stack is done by a liquid coolant which is circulated in a coolant circuit with the use of a coolant pump.

The modeling of the fuel cell system is done in Dymola (modeling language Modelica). The internal solver “Dassl” of Dymola is used. Because this paper focusses on expanding the usage of system models by analyzing the design problem regarding design target and requirements with the DRM, the system simulation model is shortly described but no detailed equations or parameters are listed. Consequently references are given. The fuel cell stack model is based on spatially distributed control volumes (along the channel) of a parametric bipolar plate and the consideration of detailed kinetic, diffusion and thermal effects in the functional layers of anode and cathode GDL, anode and cathode catalyst layer (CL), PEM, and bipolar plate (BPP). Detailed aspects about the used fuel cell model have been described in Tang et al. [23]. The models of the air compressor, coolant pump and recirculation blower are efficiency based models which are defined by isentropic efficiencies for the calculation of their power demand. Heat and mass transfer components namely humidifier and charge air

TABLE 1 List of design variables (DV) separated by (i) component design variables (CDV) and (ii) controlled variables (CV) specified for the example design problem

Design variable	Value	Unit
(i) CDV:		
n_{cells}	160	-
βA_{hum}	varied	$m^3\ s^{-1}$
kA_{cac}	68	$W\ m^{-2}\ K^{-1}$
(ii) CV:		
i_{fc}	1.5	$A\ cm^{-2}$
π_c	varied	-
Δp_{cross}	0.51	bar
$T_{cool,in}$	70	°C
ΔT_{cool}	8.2	K
λ_{ca}	1.61	-
λ_{an}	1.4	-
$c_{H2,an,out}$	66	%

cooler are modeled with respect to [24] by means of the calculation the number of transfer unit (NTU) for cross flow apparatus in relation to their scaling units. The adaption of such an approach to humidifiers is published in [25].

2.3.2 | Example design problem

For application of the concept described in the previous subsections an example design problem will be presented with specification of the design variables, external operating conditions, fuel cell system model, design target and requirements, structured in the same way as the general design problem (Figure 1).

The design variables of the fuel cell system (cf. Figure 1, box I) are listed in Table 1, column 1 and are: (1) component design variables: number of single fuel cells (n_{cells}), product of mass transfer coefficient and mass transfer area of the humidifier (βA_{hum}), hereinafter referred as βA) as humidifier scale and product of heat transfer coefficient and heat transfer area of the charge air cooler (kA_{cac}) as charge air cooler scale. (2) controlled variables: fuel cell current density (i_{fc}), air compressor compression ratio (π_c), anode-cathode cross inlet pressure (Δp_{cross}), coolant stack input temperature ($T_{cool,in}$), coolant temperature difference (ΔT_{cool}), cathode stoichiometry (λ_{ca}), anode stoichiometry (λ_{an}) and hydrogen anode stack outlet concentration ($c_{H2,an,out}$).

The controlled variables will be described shortly. The current density of the fuel cell defines the load point of the fuel cell and the fuel cell system. In this paper, the design problem is reduced to a single load point consideration at maximum current density, that means that all considerations are at a constant current density, which is chosen before as the design current density of the fuel cell system. The pressure difference between the anode gas input pressure and the cathode gas input pressure is called cross pressure for a design of a stack which is operated in co-flow of anode and cathode gas. The mass and heat flow are mainly dependent on the coolant stack input temperature and the temperature difference between the coolant at the stack input and the coolant at the stack output. A measure of the flow rates of anode and cathode gas is their stoichiometry. The stoichiometry is a calculation of the ration of the flow rate to the reaction mass flow rate. A stoichiometry of one means that all the incoming hydrogen or oxygen will be consumed in the reaction. Due to diffusion of nitrogen trough the membrane a small amount of the anode gas has to be removed by a purge valve so that a certain volumetric hydrogen concentration exists.

As mentioned before, the focus of this paper is the consideration of design questions in particular the influence of requirements with the use of DRMs under coupled effects of two design variables. Not focused is the overall and complete design of the fuel cell system. The advantage of the here described method compared to a mathematical system optimization method is the visualization of the influence and thus the limitation of the design towards requirements. Along with this, the possibility of recognizing the potential that a change in the requirements on the system design has, is an advantage of the proposed methodology. The fact that the problem is reduced to two design variables supports this approach if internal operating conditions can be achieved through various design variables.

Due to a significant effect of the humidity of the membrane on the cell performance and therefore overall system the coupled effect of the scale of the humidifier *vs.* the cathode pressure, which both have an impact on the stack cathode inlet humidity and therefore the membrane humidity, will be analyzed. The used parametric scaling of the humidifier is done by different values for the product of mass transfer coefficient and mass transfer area βA. The second degree of freedom characterizes the design of the air compressor by varying the compression ratio π_c of the compressor. The compression ratio is defined as ratio of the compressor outlet $p_{c,out}$ and inlet pressure $p_{c,in}$

$$\pi_c = p_{c,out} / p_{c,in} \tag{1}$$

The values for the non-varying design variables are fixed. In Table 1, column 2 the values of the fixed design variables are listed separated by components design variables and controlled variables.

Next, the external operating conditions (ambient temperature and ambient pressure; cf. Figure 1, box II) have to

TABLE 2 External operating conditions (ambient temperature and ambient pressure) of the example design problem for different design cases

Case	Ambient temperature	Ambient pressure (cor. height)
1 (ref)	20°C	1.013 bar (0 m)
2	25°C	1.013 bar (0 m)
3	27°C	1.013 bar (0 m)
4	30°C	1.013 bar (0 m)
5	20°C	0.945 bar (600 m)
6	20°C	0.882 bar (1200 m)
7	20°C	0.804 bar (2000 m)

be classified. For the reference case standard ambient conditions with 20°C and 1.013 bar are used. In section 3.3, the influence of different ambient conditions on the DRM and therefore system design will be analyzed. For this study, there will be used three higher ambient temperatures and three lower ambient pressure levels, which are related to a certain operational height (Table 2). The selection of the variation of ambient conditions was made with the knowledge that higher ambient temperatures and lower ambient pressures reduce the valid range restricted by requirements and are therefore to be understood as a kind of example for the influence of environmental conditions. The cases are numbered from case 2 to 7.

With use of the fuel cell system simulation (described in section 2.3.1) the internal operating conditions (process and state variables, cf. Figure 1, box III) are calculated. Based on the simulation results the KPIs of the fuel cell system can be obtained.

The considered KPIs (cf. Figure 1, box IV) of fuel cell system in the example design problem are the system efficiency η, the system box volume V_{sys} and the temperature difference depending heat flow $\dot{Q}/\Delta T$ which has to be transferred via the frontend cooler. The system efficiency for the fuel cell system is defined as the net fuel cell power divided by the provided hydrogen energy flow, which can be calculated by the product of the hydrogen mass flow from the hydrogen storage $\dot{m}_{\text{H2}}$ and the lower heating value of hydrogen LHV_{H2} (Equation 2). The fuel cell system power is the difference of the power of the fuel cells (P_{fc}) and power of the additional electric devices: air compressor (P_{c}), hydrogen recirculation blower (P_{hrb}) and coolant pump (P_{pump})

$$\eta = \frac{P_{\text{fc}} - P_{\text{c}} - P_{\text{hrb}} - P_{\text{pump}}}{\dot{m}_{\text{H}_2} \cdot LHV_{\text{H}_2}} \tag{2}$$

The system box volume is the sum of volumes of the main components of fuel cell system, here fuel cell stack V_{fc}, air compressor V_{c}, humidifier V_{hum} and charge air cooler V_{cac} (see Equation 3)

TABLE 3 List of design targets and their KPIs of the example design problem used in the analysis

KPIs	Design target
System efficiency	$\max(\eta)$
System efficiency and system box volume	$\max(x \cdot \eta - (1-x) \cdot V_{\text{sys}})$

$$V_{sys} = V_{\text{fc}}\ (n_{\text{cells}}) + V_{\text{c}}\,(P_{\text{c}}) + V_{\text{hum}}\,(\beta A) + V_{\text{cac}}\,(kA) \tag{3}$$

The volume of the fuel cell stack is calculated from parametric data of BPP, GDLs and CCM and the number of single fuel cells (n_{cells}). Therefore, areas for sealing and gas distribution are included. For the air compressor an approach with regard to similarity laws of compressors is used where the volume of the compressor is mainly dependent on the motor diameter and therefore a function as the maximum power of the compressor $V_{\text{c}} = \text{f}(P_{\text{c}})$. The volumes of the humidifier and the charge air cooler are linearly related to the mass transfer area times the mass transfer coefficient βA and the volume of the humidifier respectively heat transfer area times heat transfer coefficient (kA).

The temperature difference depending heat flow $\dot{Q}/\Delta T$ is the heat flow transferred via the frontend cooler $\dot{Q}_{\text{fec}}$ divided by the inlet difference of coolant temperature ($T_{\text{cool,in}}$) and air temperature ($T_{\text{air,in}}$) (see Equation 4). The air inlet temperature of the frontend cooler is equal to the ambient temperature

$$\frac{\dot{Q}}{\Delta T} = \frac{\dot{Q}_{fec}}{T_{\text{cool,in}} \;--T_{\text{air,in}}} \tag{4}$$

As described in subsection 2.1, the KPIs can be used in the design problem in two different ways (cf. Figure 1, box V). First, all or some KPIs are part of the design target. Second, the KPIs are limiting the design variables formulated as requirements. In the specific design problem used for the paper the system efficiency is declared as main design target for the fuel cell system, in section 3.2 the system box volume is used as second KPI for a multi-objective design target. Concluded in Table 3, there are two variants for the design target of the fuel cell system in this paper, where x defines the weighting factor between the weighing of system efficiency and system box volume.

The requirements of the design problem are based on (a) the general design problem specific component requirements due to their specific apparatus character, or (b) vehicle constraints formulated of constraints of KPIs. On (a): Two essential component requirements coming from the

TABLE 4 Requirements of the example fuel cell system design problem separated by component limits and vehicle constraints

Requirement	Value	Referred as
Component limits:		
T_{PEM}^{max}	95°C	constraint_T_PEM_max
RH_{PEM}^{min}	60 %	constraint_RH_PEM_min
T_{hum}^{max}	95°C	constraint_T_hum_max
Vehicle constraints:		
V_{sys}^{max}	25 dmş	constraint_V_max
$\dot{Q}/\Delta T^{\ max}$	1450 W K^{-1}	constraint_Q/ΔT_max

operating limit of the membrane of the fuel cell. The maximum allowed temperature of the membrane T_{PEM}^{max} is limited to 95°C and the minimum local membrane humidity RH_{PEM}^{min} is confined to 60 %. Both limits are requirements for safe operation of the fuel cell and therefore failures in the membrane. In the used fuel cell stack parametrization, the anode and cathode gases flow in parallel in the same direction, for this case the minimum humidity of the membrane is at the entrance of the gas inlet. Because of similar membranes in the humidifier the operating temperature limit T_{hum}^{max} is also 95°C. On (b): Requirements of vehicle constraints are formulated by KPIs and are for the design problem of the reference case (section 3.1), the maximum system box volume V_{sys}^{max} and the maximum temperature difference related heat flow through the front-end cooler of the vehicle $\dot{Q}/\Delta T^{\ max}$.

The requirement of a maximum system box volume is important because it must be ensured that the fuel cell system can be used in a specific space of a vehicle. Here the maximum box volume (see Equation 3) is limited to 25 dm^3 (=25 liter). In addition to the design of fuel cell systems for vehicles, particular care must be taken to ensure that the waste heat from the fuel cell can be rejected. Especially at different ambient temperatures this must be even possible. The maximum temperature difference related heat flow ($\dot{Q}/\Delta T^{max}$) is limited to 1450 W K^{-1}. The requirements of the example fuel cell system design problem are summarized in Table 4, additionally the referred name in the figures of section 3 are presented.

The effect of the different requirements on the system design under variation of design target and ambient conditions is focus of the following analysis.

3 | RESULTS AND DISCUSSIONS

3.1 | Reference Design Case and Multi-Objective Design Problem

Now, the concept from section 2.1 and 2.2 is applied on the example design problem, sketched in section 2.3. First the reference design case is considered. It is characterized by standard ambient conditions (see Table 2, case 1) and system efficiency-based design function (see Table 3). Figure 4 shows the DRM of the reference design problem.

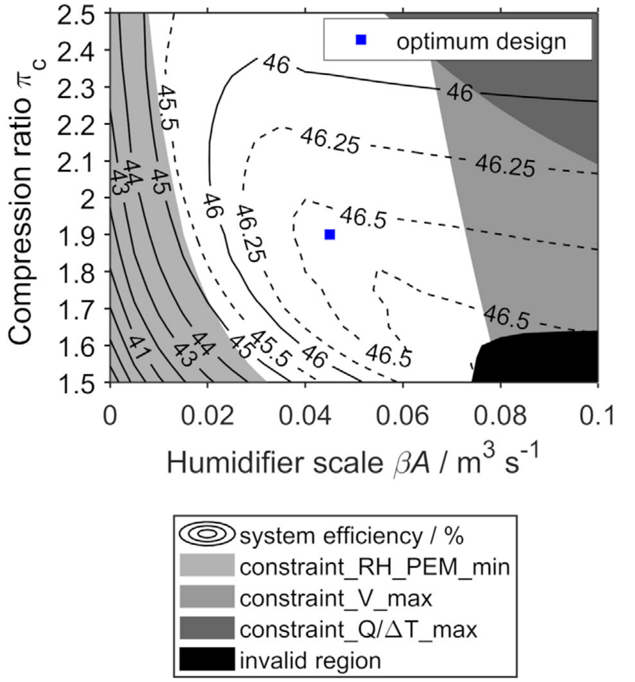

FIGURE 4 Design Requirement Map for the design of humidifier scale (βA) and compression ratio (π_c) of the reference design problem

Contour lines and different colored areas depending on the two design variables, the humidifier scale (βA) and compression ratio (π_c) can be seen. The contour lines are constant values of the system efficiency (Equation 2) of the fuel cell system, the colored regions mark combinations of the design variables where certain requirements are not achieved. The benefit of the DRM is the answering of following two questions:

(i) How the system design is constrained by the requirements?
(ii) Regarding the design variables, how does the optimum system design under consideration of vehicle and component requirements looks like?

First question will be answered by consideration of the colored areas in the DRMs. Four different regions are recognizable: (1) constraint_RH_PEM_min, (2) constraint_V_max, (3) constraint_Q/ΔT_max and (4) invalid region. These regions characterize the different requirements (Table 4) for combinations of the design variables which do not satisfy the requirements and therefore influence the system design with the exception of the region (4). Before the influence of the requirements will be discussed the invalid region will shortly explained: In certain cases of combinations of the design variables it is possible that the pressure drop of the cathode gas along the cathode side Δp_{ca} is higher than desired pressure increase in the air compressor, which is calculated by the compression ratio π_c times the ambient pressure p_{amb} minus the ambient pressure. This situation/state is not a real thermodynamic state of the system. For valid regions condition (Equation 5) must be met

$$\pi_c \cdot p_{amb} \geqslant \Delta p_{ca} \tag{5}$$

Requirement regions: (1) The minimum membrane humidity constraint is not reached at small humidifiers scales. Without humidifier ($\beta A = 0$ m^3 s^{-1}) a valid system design even by increasing the compression ratio at analyzed limits due to the minimum membrane humidity requirement could not be found. But for example, at relatively small humidifiers (e.g., $\beta A = 0.02$ m^3 s^{-1}) increasing the pressure ratio is a possibility to meet the requirements, but maybe not intended due to the design target. (2) The area which is constrained by the maximum allowed system volume is characterized by greater influence of the humidifier scale than the compression ratio or compressor scale on the system volume. For humidifiers larger than $\beta A = 0.08$ m^3 s^{-1} the system volume constraint is not met. (3) The maximum heat constraint of the vehicle is constraining the design of the humidifier and compressor in a way that a combination of high pressure ratios and large humidifier scales lead to high waste heat, so that in these regions the constraint is not met. First aspect is that with higher pressure ratios the inlet temperature of the charge air cooler is higher and therefore more heat is transferred from the cathode side to the coolant. Second aspect is because of the generation of liquid water in the stack which leads to latent heat that is also transferred to the coolant. That leads to less waste heat which is removed from the stack by the cathode gas leaving the stack.

For answering the second question a more detailed consideration of the height lines of the design target in Figure 4 is carried out. In general: The values of the system efficiency are in a range of 38–47 %. That seems to be a small variation but considering the relative influence choosing the optimal combination of the values of the humidifier scale and compression ratio, the system efficiency is influenced by about maximum of 19 %.

In detail: The system efficiency at small humidifiers (smaller than $\beta A = 0.01$ m^3 s^{-1}) is very sensitive to the humidifier scale and less sensitive to the compression ratio. At larger humidifier scales (greater than $\beta A = 0.06$ m^3 s^{-1}) it is the opposite case. Further increasing the humidifier scale does not increase the system efficiency and due to higher liquid water existence, the system efficiency slightly decreases. In between small humidifiers and large humidifiers there is a transition area where both effects increase the system efficiency. In this area it can be seen that an increase of the compression ratio increases the system efficiency but the absolute value of the system efficiency is only increasing mainly at the first decimal place.

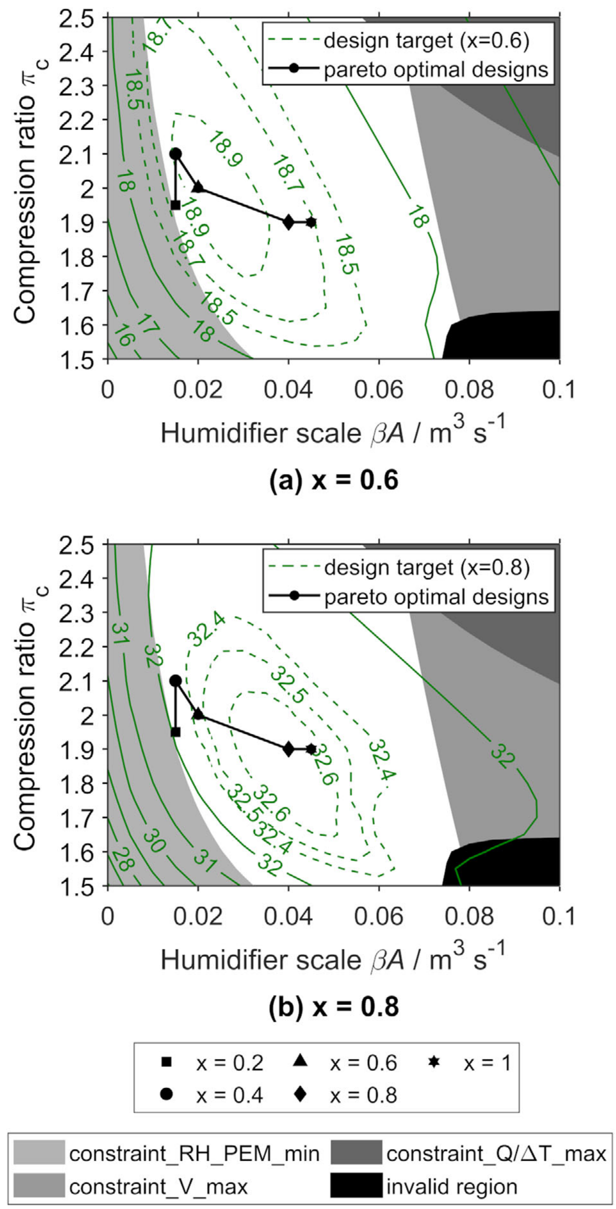

FIGURE 5 Design Requirement Maps with multi-objective design target with weighting factor (a) x = 0.6 and (b) x = 0.8 according to design target of Table 3. The black line characterizes the pareto optimal multi-objective designs for x = 0.2, 0.4, 0.6, 0.8, 1

Overall, for answering question 2 following three criteria have to be considered:

Criterion 1: All requirements are met (non-marked region).

Criterion 2: Optimal value of design target (system efficiency).

Criterion 3: Distance to requirement constraint in terms of robustness of design.

The first and the second criteria are significant for an efficient system design process. In other words, the best combination of the design targets has to be chosen which meets all requirements and in this left design space the best value for the design target has to be found. The third criterion helps to choose a combination of the design variables under consideration of the distance to a limit of requirements. It is not a necessary condition but is an example of the advantage of the use of Design Requirement Maps in contrast to straight mathematical design optimizations. Another advantage of the DRM where the optimization problem will be visualized is the possibility to get knowledge about the optimal design constraining requirement. For example, if the optimal value of the design target is not in a region where all requirements are met, the potential of a change of the requirement can be derived. In this design problem used in this paper this is not the case, therefore the optimal designs are a humidifier scale of 0.045 $m^3\ s^{-1}$ and compression ratio of 1.9. The best combination of the design variables is marked. In a next step the influence of the design target on the optimal values with respect to a multi-objective design target is considered.

3.2 | Multi-Objective Design Problem

The design target of fuel cell systems for vehicle application can be also formulated as multi-objective design problems. The usage and effect of the DRM for multi-objective design targets is addressed in this section.

Besides the system efficiency for the multi-objective design problem the system volume is included in the design problem (cf. Table 3).

The system volume depending on the two design variables is characterized by parallel lines mainly depending on the humidifier scale (see Figure 7b in the appendix). Using the DRM the influence of the weighting factor x, weighting the system efficiency and the system volume in the design target, can be analyzed.

Figure 5 shows the DRM with different weighting factors ($x = 0.6$ and 0.8). In general it should be noted that the values of the design targets of $x = 0.6$ and $x = 0.8$ does not permit comparisons among each other. Comparable are the optimal design of humidifier and air compressor for different weightings x of system efficiency and system volume which characterizes the pareto front. Shown as the black markers are the optimal designs of the design variables for weighting factors $x = 0.2, 0.4, 0.6, 0.8, 1.0$.

In Figure 5 can be seen that with increasing weighting of the system efficiency (increasing of x) the optimum of the design target shifts towards larger humidifiers and first higher then smaller compression ratios.

The design of the humidifier for the weighting factor of 0.6 would lead to $\beta A = 0.02\ m^3\ s^{-1}$ and compression ratio of $\pi_c = 2$ in contrast to $\beta A = 0.04\ m^3\ s^{-1}$ and $\pi_c = 1.9$ for a weighting factor of 0.8. The increase of the humidifier with less weighting of the system volume is obvious due to the greater impact of the humidifier scale on the system volume, but the trend of the optimum compression ratio, which according to the results has a greater impact on the system efficiency improvement than on the system volume reduction, is an interesting fact.

3.3 | Influence of Ambient Conditions on the System Design

Typical for fuel cell systems in vehicle applications is the operation of vehicles under different ambient conditions for example at different ambient pressures, in the mountains, or different ambient temperatures, in the summer or winter. Important for the design is the fact, that the KPIs have to meet the requirement constraints even under different ambient conditions. In this context, it is of special interest to get knowledge about the crucial requirements which affect mainly the system design by variation of ambient temperature and ambient height. For this purpose the DRM are calculated for different ambient conditions and serve as example of the consideration of the influence of ambient conditions on the requirements and therefore optimal design of humidifier and compressor. The choice of the chosen values is described in Table 2.

Ambient temperature variation: For the reference case of section 3.1, ambient conditions of 20°C, 0 m (1.013 bar) were used. In Figure 6a–c, the ambient temperature according to Table 2 (cases 2–4) is varied.

Higher ambient temperatures have two main effects on the fuel cell system. First, higher gas temperature at the compressor inlet and second smaller temperature difference between coolant and ambient gas.

The effect of a higher gas inlet temperature is essentially also a higher gas outlet temperature. Constant charge air cooler dimensioning as assumed in this paper leads then to slightly higher stack cathode input gas temperature, which also affects the gas humidity. For a more detailed analysis, these effects can be seen in separate contour lines of the stack gas input temperature and humidity attached in the appendix. Their effect can be seen in the DRM by consideration of different system efficiencies with increasing

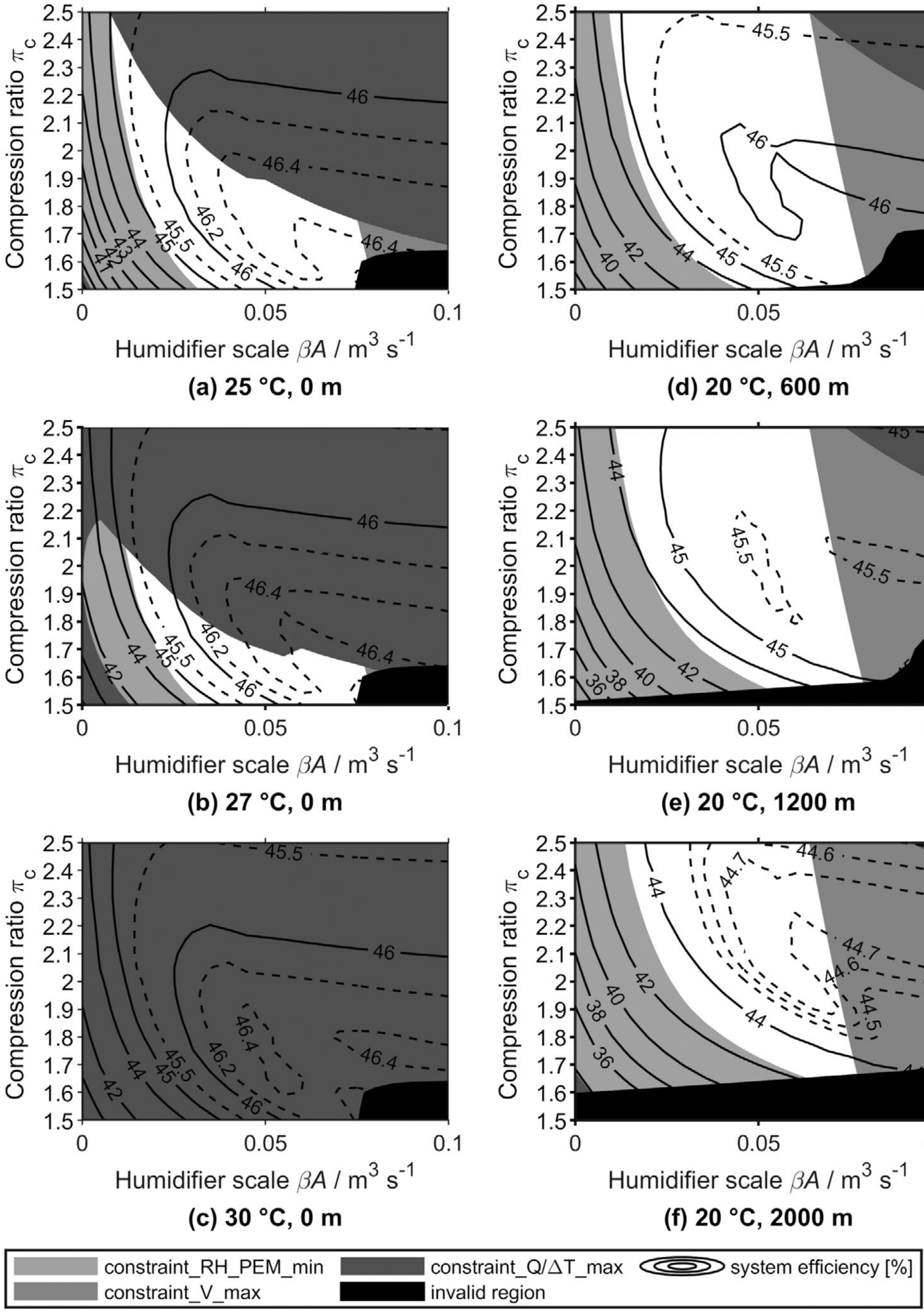

FIGURE 6 Design Requirement Map at 0 m and a) 25°C, b) 27°C, and c) 30°C, Design Requirement Map at 20°C and d) 600 m, e) 1200 m, and f) 2000 m (cases 2–7 of Table 2)

ambient temperatures. Considering the absolute values of the height lines of the system efficiencies, only a small influence of the system efficiency is determined. Considering the influence of different ambient conditions on the regions of the requirement constraints, the great influence on the heat constraint due to the second effect is recognizable. The heat constraint, characterized by the heat flow related to the temperature difference of coolant and ambient air (see Equation 4), is mainly affected by the smaller temperature difference. On the one hand, the valid region is getting more limited from top right of the DRM due to combination of high compression ratios and high humidifier scales, with the same reason as described in the reference case, but on the other hand obvious in the DRM for 27°C (b), from small humidifiers and low compression ratios due to very low system efficiencies and therefore more waste heat of the fuel cell stack which has to be removed by the coolant. This effect even leads so far that in

Figure 6c the waste heat rejection constraint is constraining all considered combinations of the design variables.

In general, lower system efficiencies with increasing ambient temperatures intensify this effect. A significant effect of increasing ambient temperatures on the minimum membrane humidity constraint and volume constraint isn't observed.

Ambient pressure variation: Similar consideration is done for evaluation of the effect of different ambient heights on the design of the fuel cell system. The ambient heights and their correlated ambient pressures are listed in Table 2. The DRM with variation of ambient pressure are shown in Figure 6d–f.

Considering the change of the DRM the increasing area of the invalid region is especially noticeable. The main reason for that is the previously described fact, that with lower compressor inlet gas pressure and the same compression ratio the outlet pressure is lower (see Equation 5). This leads to lower pressure increases in the air compressor and therefore to a larger region where the condition in Equation 5 is not satisfied due to higher pressure drop on the cathode side compared to the pressure increase in the air compressor.

Lower ambient pressures mainly lead to lower pressures of the inlet gas of the compressor and that implicates lower cathode gas stack inlet pressures at same compression ratios. Due to constant pressure difference between anode gas inlet and cathode gas inlet also the pressure of the anode gas at stack inlet is affected. Lower gas pressures in the fuel cell have primarily two effects, first less relative humidity of the gas and second influences the kinetics of the fuel cell reaction. Both effects decrease the system efficiency. It can be seen that the maximum level of the system efficiency decreases with increasing ambient height and the optimal combination of the design variables characterized by the maximum value of the design target function change. The optimal system efficiency will be reached by increasing ambient heights with increasing compression ratios but the optimal value for the humidifier scale is not significantly affected. The effect of the change of the optimal combination of the design variables on the system design will be discussed later. The maximum value of the system efficiency for ambient heights at 0 m to 2000 m decreases from 46.65 % to 44.80 %.

The operation of the fuel cell system at lower ambient pressures also affects the requirements. The most affected requirement is the minimum membrane humidity due to lower pressures and relative humidity of the cathode gas at stack inlet. The area where this requirement is not met is significantly increasing with increase of the ambient height. Less influence can be considered for the waste heat rejection constraint.

4 | CONCLUSIONS

In this paper, the general design problem under consideration of a) requirements, b) multi-objective design target, and c) several operating points is formulated and a useful approach for specific design questions of fuel cell systems is provided with the advantage of visualization of the design problem with respect to the design target and the influence of the design requirements.

With use of the DRM, the influence of the design target and the requirements for a design problem characterized by the scale of the humidifier and the air compression ratio as an example is discussed. Combinations with small and large humidifiers reveal as designs, which do not meet the requirements. The design target shows a flat efficiency based optimum. The selection of optimal combinations of the design variables under different criteria and different design functions is shown by application of different weightings of efficiency and system volume as multiple design target. With increasing weighting of the system volume the optimal combination is shifted towards smaller humidifiers and higher compression ratios.

The influence of ambient conditions like ambient temperature and ambient pressure with usage of the DRM is shown. By variation of the ambient temperature the waste heat constraint is getting more significant due to constraining the design variables towards low compression ratios. No significant effect on the system efficiency is observed. By variation of the operational height and therefore ambient pressure the most effected requirement is the minimum membrane humidity, which requires with increasing ambient height larger humidifiers and higher compression ratios. In contrast to the variation of the ambient temperature, the variation of the ambient pressure is greatly affecting the system efficiency.

In general, the DRM in fuel cell system designs help to identify and visualize the influence of requirements in regard to the optimal design variables.

ABBREVIATIONS

AC	Ambient conditions
CDV	Component design variable
CV	Controlled variable
DRM	Design requirement map
DV	Design variable
EC	Environmental conditions
FCEV	Fuel cell electric vehicle
IOC	Internal operating conditions
KPI	Key performance indicator
LHV	Lower heating value

OC	Operating conditions
OP	Operating point
PEMPolymer electrolyte membrane	Polymer electrolyte membrane Symbols βA Exchange area times

Symbols

βA	mass transfer coefficient of humidifier
c	Volumetric concentration
kA	Exchange area times heat transfer coefficient of charge air cooler
n_{cells}	Number of fuel cells
P	Power
p	Pressure
$\dot{Q}$	Heat flow
RH	Relative humidity
T	Temperature
U	Voltage
V	Volume
x	Weighting factor
ΔT	Temperature difference
Δp	Pressure difference

Greek

β	Mass transfer coefficient of humidifier
η	System efficiency
λ	Stoichiometry
π	Compression ratio

Subscripts and Superscripts

an	Anode
amb	Ambient
c	Compressor
cac	Charge air cooler
ca	Cathode
cool	Coolant
fc	Fuel cell
fec	Front-end cooler
g	General
H_2	Hydrogen
hum	Humidifier
hrb	Hydrogen recirculation blower
in	Inlet flow
max	Maximum
op	OP specific
out	Outlet flow
pump	Coolant pump
sys	System

ORCID

Alexander Fladung https://orcid.org/0000-0002-9047-3930

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APPENDIX

In this appendix, height lines of selected variables (system power, system box volume, $\dot{Q}/\Delta T$, single cell voltage, minimum membrane humidity, cathode gas inlet humidity) depending on the two design variables, humidifier scale βA and compression ratio π_c, for three selected operating points (Reference case (Figure 7), 27°C and 0 m (Figure 8); 20°C and 1200 m (Figure 9)) are presented as additional support for understanding of certain correlations and described and compared shortly in this Appendix.

First, considering the height lines of the system power for the reference case, it can be noticed, that the height lines correlate to the height lines of the system efficiency (see Figure 4) and the height lines are dependent on the operating point. In contrast to that, the height lines of the system volume (Figures 7b, 8b, and 9b) are not depending on the operating point regarding the external operating conditions. Comparing the heat rejection of the fuel cell system transferred via the front-end cooler, a combination can be identified with a maximum heat rejection. This

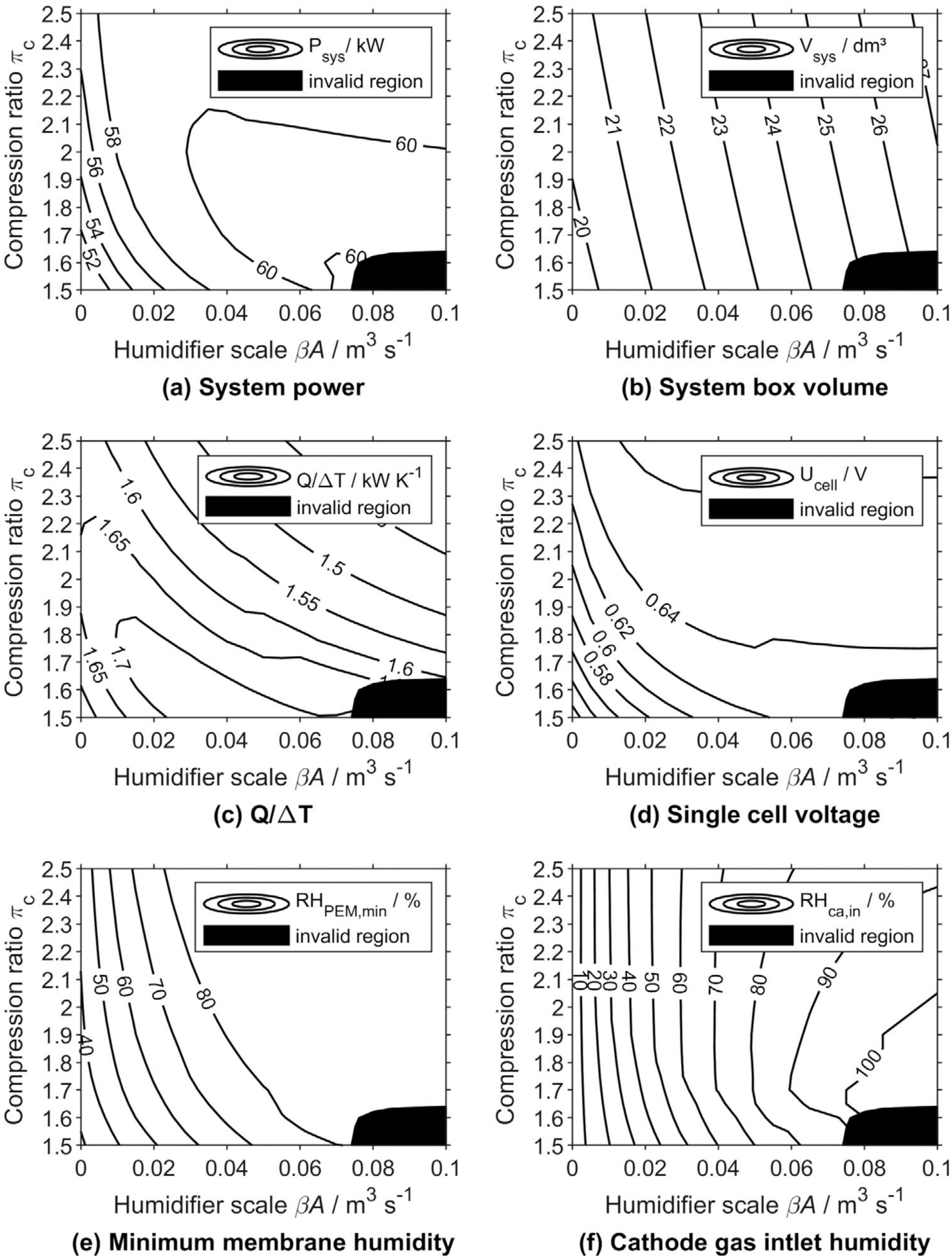

FIGURE 7 Height lines of selected variables for the reference case (Figure 4) of (a) system power, (b) system volume, (c) $Q/\Delta T$, (d) cell voltage, (e) minimum membrane humidity, and (f) stack inlet relative humidity of cathode gas

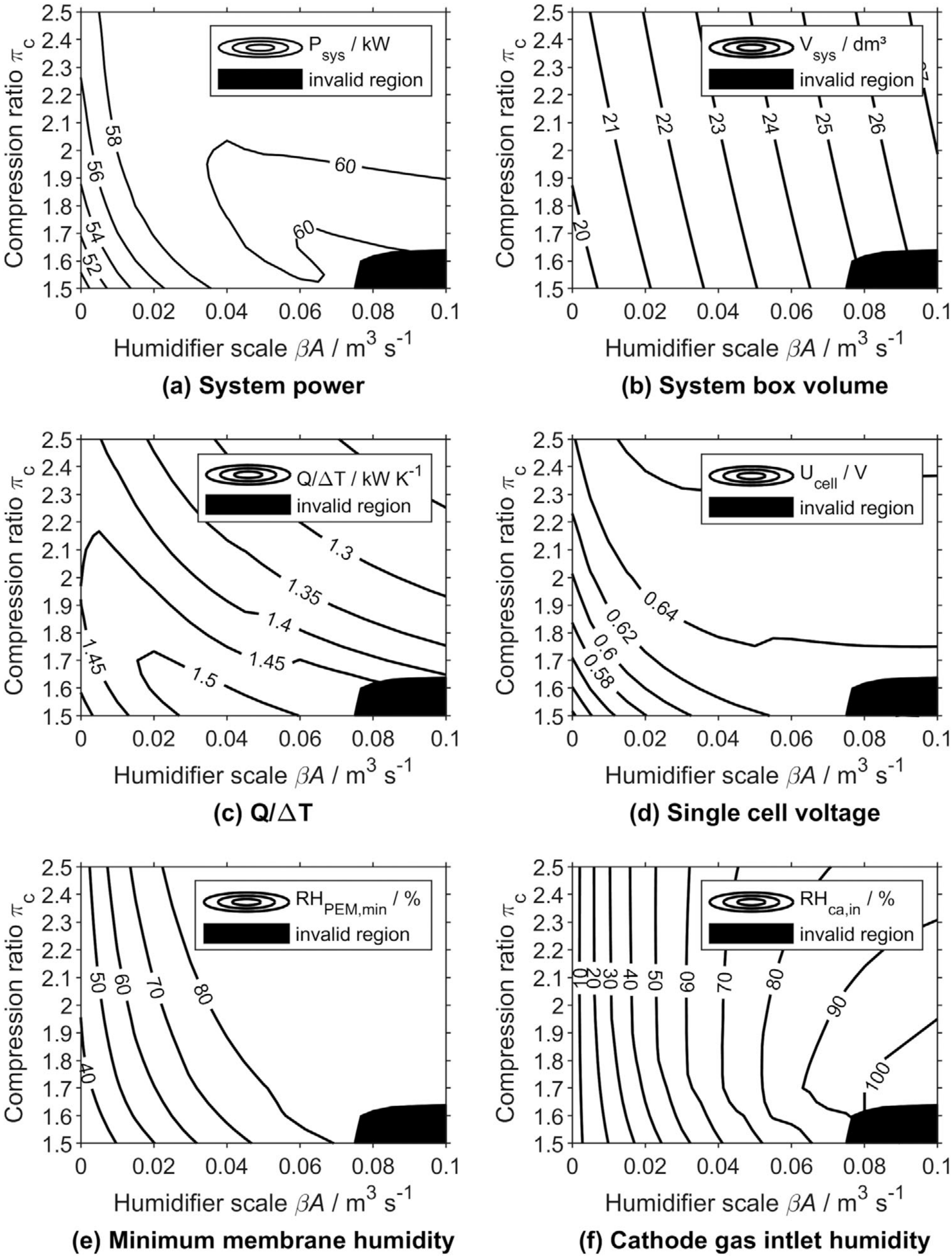

FIGURE 8 Height lines of selected variables for the design case of 27°C and 0 m (Figure 6b) of (a) system power, (b) system volume, (c) $Q/\Delta T$, (d) cell voltage, (e) minimum membrane humidity and (f) stack inlet relative humidity of cathode gas

maximum as well as combination of the design variables which have the maximum heat rejection are influenced by the ambient temperature and the ambient pressure.

As a helpful operating condition for understanding the behavior of the fuel cell, the cell voltage depending on the design variables is presented in Figures 7d, 8d, and 9d. The significant influence of the gas humidity and thus the design of the humidifier can be seen by considering the lower cell voltages at smaller humidifiers and lower compression ratios. The correlating minimum membrane humidity as a design requirement is shown in Figures 7e, 8e, and 9e. To get an understanding of the impact of the humidifier scale and compression ratio of the humidity of the cathode gas at fuel cell stack inlet the possible humidities for the three ambient conditions are presented in Figures 7f, f, and f.

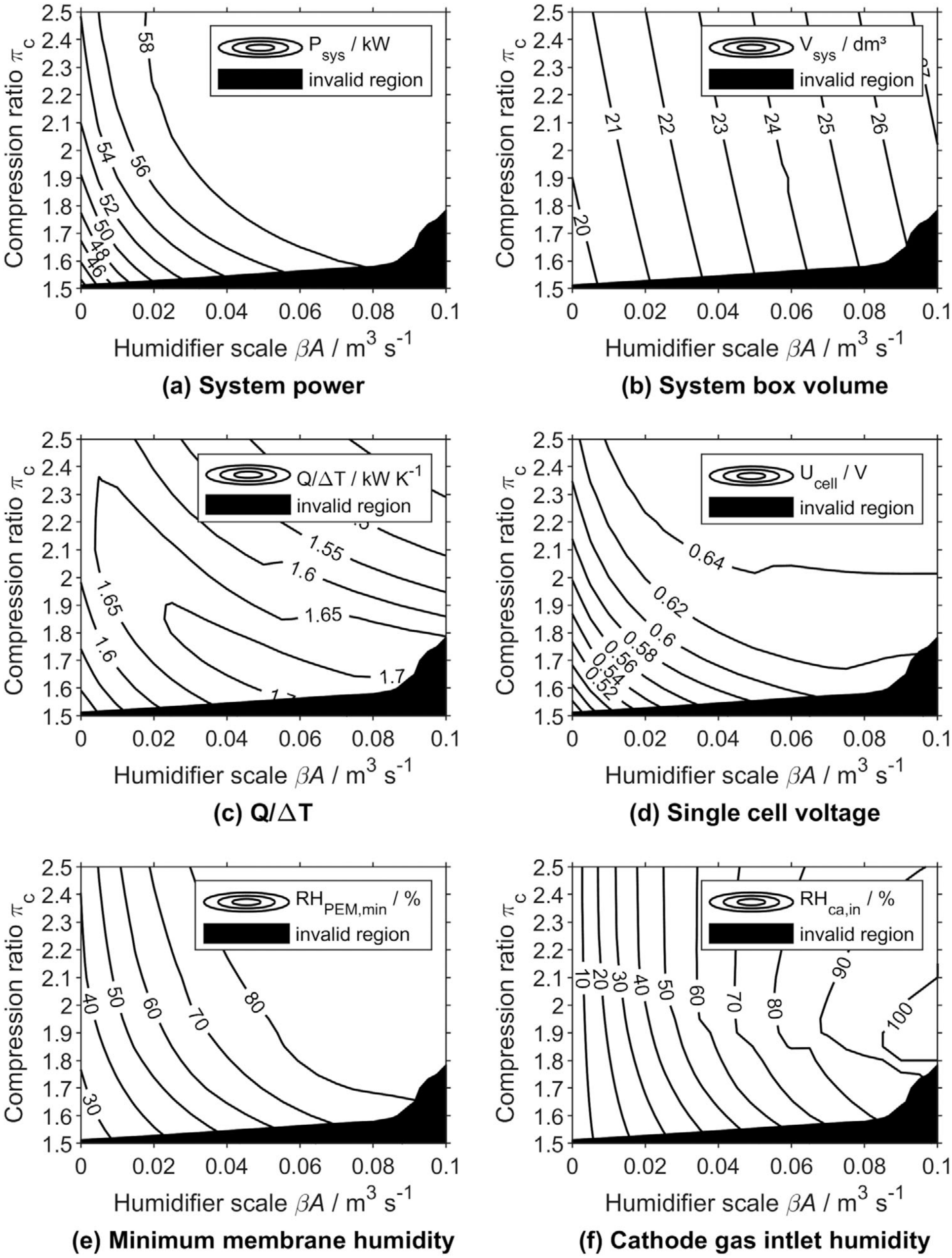

FIGURE 9 Height lines of selected variables for the design case of 20°C and 1200 m (Figure 6e) of (a) system power, (b) system volume, (c) $Q/\Delta T$, (d) cell voltage, (e) minimum membrane humidity and (f) stack inlet relative humidity of cathode gas