9th International Conference on Applied Energy, ICAE2017, 21-24 August 2017, Cardiff, UK

Modeling fuel cells in integrated multi-energy systems

Paolo Gabrielli, Matteo Gazzani and Marco Mazzotti*

Institute of Process Engineering, ETH Zurich, Sonneggstrasse 3, 8092 Zurich – CH

Abstract

This contribution investigates how different technology modeling methodologies affect the design of decentralized multi-energy systems, especially when fuel cell and energy storage are considered. First, thermoelectric models based on a first-principle approach are implemented to determine the performance and dynamic behavior of a set of conversion technologies. Then, as such nonlinear models are intractable within mixed-integer linear programming for the optimal design of multi-energy systems, simplified linear models suitable are developed. In particular, an affine and a piecewise affine approximations of the conversion efficiency are compared, and a linear description of the system dynamics is implemented. An optimization problem is formulated to investigate the impact of these modeling approximations on the design of integrated residential systems.

Keywords: Energy conversion; Energy Efficiency; Energy storage; Cogeneration; Linear programming; Optimization.

1. Introduction

In recent years, the necessity of reducing the environmental impact and increasing the flexibility of the energy sector led to increasing penetration of intermittent renewable energy sources (RES), and the shift from centralized to decentralized generation. In this context, distributed multi-energy systems (MES) is a new paradigm of energy generation, and the optimal design and operation of such systems have been widely investigated in the last years. Among others, Mancarella presented a comprehensive reviews of the model formulations used for the design and analysis of multi-generation systems [1]. The problem of the optimal design and unit commitment of multi-energy systems started being investigated by Marnay et al. [2] and Hawkes and Leach [3], whereas Keirstead et al. [4] studied the impact of cogeneration on the planning of urban energy systems. Methods for the multi-objective design

* Corresponding author.
  E-mail address: marco.mazzotti@ipe.mavt.ethz.ch

of this type of energy systems were proposed by Fazlollahi et al.[5], while approaches accounting for energy distribution among different nodes of residential multi-energy systems were presented, e.g., by Mehleri et al. [6] and Omu et al. [7] for the Greek and British energy sector, respectively. In all these past studies, a very simplified description of the conversion technologies, featuring constant efficiency, was implemented. More recently, Bischi et al. used a piecewise affine approximation to model part-load efficiency of the conversion units[8]. Similarly, Bracco et al. distinguished between maximum and rated efficiency for some of the conversion units [9].

This paper evaluates the impact of modeling approximations performed when simulating fuel cell (FC) technologies on the optimal design of residential multi-energy systems. First-principle models describing the part-load performance of two types of fuel cells are implemented and used to derive simplified models, suitable for an optimization framework. In particular, the effects of linear conversion efficiency and conversion dynamics are evaluated .

2. Development of linear models of fuel cells

A systematic modeling procedure is implemented, which merges process simulation for steady-state operation (Aspen software®) and dynamic modelling for transient investigation (Matlab-Simulink®). A first-principle, lumped approach is developed to describe the behavior of various fuel cells, resulting in nonlinear models accounting for electrochemical features and transport phenomena within the cell, including mass transport across the membrane as well as heat transfer. Then, such models are inserted in a wider process simulation to reproduce the steady-state operation of commercial products at various operating conditions. Finally, the main characteristics of conversion dynamics are modeled to capture the typical delays in power generation and system operation.

The following fuel cell technologies are considered in this work: (i) a solid oxide fuel cell (SOFC) using natural gas (NG) as a fuel and air as an oxidant based on the BlueGen system by SolidPower (1.6 kW) [10], and (ii) a NG-air proton exchange membrane fuel cell (PEMFC) based on Panasonic/ENE-FARM systems (1.5 kW) [11]. For both of them, the model is validated against available manufacturer data. The modeling methodology is based on [12–14] and references therein.

2.1. Conversion efficiency

The developed first-principle models describe the part-load efficiency of the considered FC systems in various operating conditions, e.g. temperature and pressure. In particular, with the linear models we aim at retaining the power and size dependencies of the conversion efficiency at design phase. Such dependencies, typically nonlinear, are linearized for use in an optimization framework: for any of the underlying conversion units, the outlet power P is expressed as a linear function of the inlet power F, and the size of the technology S, i.e. the maximum inlet power. In the following, P and F refer to generated electrical power and inlet thermal power (fuel LHV), respectively. Here, a linear and a piecewise affine (PWA) approximations are implemented. In both cases, the convex hull of the original efficiency curve is selected. The PWA approximation is generated by choosing the optimal position of n breakpoints to solve the optimization problem described in [14]. Differently from [14], the first and last breakpoints are forced to stay on the first and last point of the original efficiency curve, respectively. For all time instants $t \in \{1,\ldots,T\}$, the generated power can be generally expressed in the linear and PWA case, respectively, as

$$P_t = \gamma_1 F_t\, \gamma_2 S x_t\, \gamma_3 x_t \tag{1}$$

$$P_t \leq \alpha_1^i F_t + \alpha_2^i S x_t + \alpha_3^i x_t, \forall i \in \{1, \ldots, n-1\} \tag{2}$$

where the coefficients γ and α express power and size dependencies of the generated power, with i referring to the i-th approximating line segment; $x_t \in \{0,1\}$ is a binary variable specifying whether the device is turned on, producing power but also incurring in the balance-of-plant consumption. In other words, when the device is in operation, a minimum power is absorbed, according to

$$F_t \geq \beta_1 S x_t + \beta_2 x_t \tag{3}$$

where $\boldsymbol{\beta}$ is the proportional coefficient defining size limitations. It is worth noting that due to the concavity of the efficiency curve, no additional integer variables are required in the PWA approximation, Eq. (1), to select the active line segment. However, the inequality constraint in Eq. (1) allows the device to generate an amount of power lower than the minimum threshold, i.e. it allows to dissipate the generated power. Therefore, the following constraint is also imposed:

$$P_t \geq (\beta_1 \alpha_1^1 + \alpha_2^1) S x_t + \beta_2 \alpha_1^1 x_t \tag{4}$$

Due to the modular nature of fuel cells, the size of the unit does not significantly affect the system performance, translating in $\gamma_3 = \alpha_3 = \beta_2 = 0$.

Moreover, fuel cells are cogenerative systems, i.e. they generate electricity and heat at the same time. Since the two outputs are related, the generated heat Q is expressed for all time steps $t \in \{1,\dots,T\}$ as

$$Q_t = P_t(\delta - 1) \tag{5}$$

where δ is the average first-principle-to-electrical efficiency ratio. All coefficients in Eqs. (1) – (5) are reported in Table 1.

2.2. Conversion dynamics

The dynamic behavior of the conversion units is considered in terms of (i) start-up/shut-down power trajectories, (ii) ramp-up/ramp-down limitations, and (iii) ramp-up/ramp-down transients. Start-up/shut-down and rump-up/rump-down trajectories are modeled following Eqs. 1-12 in [15]. However, a time parameter σ, based on manufacturer and literature data, is introduced here to handle start-up and shut-down operations shorter than the discretization time, i.e. one hour. Thus, the input powers at the h-th period of start-up and shut-down processes are constrained, respectively, as

$$\frac{\sigma F^{\min h}}{SU} \leq F_h^{SU} \leq \frac{F^{\min h}}{SU} + (1 - \sigma)RU \tag{6}$$

$$\frac{\sigma F^{\min (SD+1-\ )}}{SD} \leq F_h^{SD} \leq \frac{F^{\min (SD+1-\ )}}{SD} + (1 - \sigma)RD \tag{7}$$

where SU and SD indicate the duration of start-up and shutdown processes, respectively; RU and RD indicate the ramp-up and ramp-down limits, respectively; $F_{\min}$ and $F_{\max}$ represents the minimum and maximum power, respectively. Also, the maximum number of start-ups in one year is limited by

$$\sum_{t=1}^{T} y_t \leq N_{SU} \tag{8}$$

where $y_t \in \{0,1\}$ is a binary variable indicating whether the unit is started-up during period t. The rump-up/rump-down transients are modeled as energy losses, due to delays in power generation. A time parameter ω based on the first-principle models is used to describe such losses. For all time instants $t \in \{2,\dots,T\}$, both electrical and thermal generated power can be expressed as

$$E_t = [P_t(1 - \omega) + P_{t-1}\omega]\Delta t \tag{9}$$

where E_t is the energy actually generated at the net of transient losses and Δt is the length of the t-th time step.

2.3. Investigated multi-energy system

An exemplary multi-energy system consisting of a SOFC, a PEMFC and hot water sensible thermal storage (TS) is investigated. The storage system is modeled through the linear dynamics described in [9] and it is included to

Table 1. Parameters needed for the reduced order models of the conversion technologies.

Parameter	Units	SOFC	PEMFC
		Energy conversion efficiency	
n		5	5
α_1		{0.71, 0.61, 0.51, 0.41}	{0.54, 0.47, 0.41, 0.36}
α_2		{-0.05, -0.02, 0.04, 0.11}	{-0.04, -0.01, 0.02, 0.06}
β_1		0.14	0.18
γ_1		0.56	0.45
γ_2		-0.04	-0.03
δ		1.46	2.01
		Energy conversion dynamics	
N_{SU}	yr^{-1}	10	1000
RU, RD	kW/hr	$(F_{max} - F_{min}) / 3$	$F_{max} - F_{min}$
SU, SD	hr	8	1
σ	hr	1	0.25
ω_e	hr	0.004	0.003
ω_t	hr	0.021	0.014

satisfy thermal demands lower than the minimum level that can be provided by the fuel cells. The system provides electricity and heat to a neighborhood requiring a peak electricity demand of 0.43 MW and a peak thermal demand of 2 MW. The demand profiles are based on a neighborhood in Zurich, Switzerland. Here, we consider a single energy hub that satisfies the heat and electricity demands; therefore, the energy is converted and stored in a central node and then delivered to the buildings.

3. Optimization framework

A mixed integer linear program (MILP) is formulated to determine the minimum annual cost design of the multi-energy system described in Section 2.3. Accordingly, inputs to the optimization problem are (i) the expected prices of electricity and gas, (ii) the expected electrical and thermal demand profiles, and (iii) the set of available conversion and storage technologies with the corresponding performance and cost coefficients. Inputs (i)-(ii) are assumed to be known without uncertainty at every hour of the year. Outputs of the optimization problem are the design and operation strategy which yield to the minimum total annual cost. In particular, the following decision variables are returned: (i) the size of the installed technologies, (ii) the on/off status of the conversion units, (iii) the input/output energy of both conversion and storage technologies, (iv) the amount of energy in the storage units, and (v) the imported/exported energy from/to electricity and gas grids. The optimization problem can be generally expressed as

$$\min c^T v + d^T w$$

s. t.

$$Av + Bw = z \tag{10}$$

$$v \geq 0 \in \mathbb{R}^{N_v}, \ w \in \{0,1\}^{N_w}$$

where c and d represent the cost vectors associated to continuous and binary decision variables, v and w, respectively; A and B are the corresponding constraint matrices and z is the constraint known-term; N_v and N_w indicate the dimension of v and w, respectively. The objective function is the total annual cost of the system, given by the sum of capital, operation and maintenance contributions. The constraints of the optimization problem include (i) the performance of conversion and storage technologies as described in Section 2, and (ii) the energy balances within the energy system, requiring that the sum of imported and generated power equals the sum of exported and used power for all the involved energy carriers.

In this framework, the year time horizon is modeled through typical design days, which are defined based on input data (i)-(ii) through the Matlab®-embedded clustering algorithm *kmean*. Such design days are optimized independently from each other. A detailed description of the optimization problem can be found in [16,17].

4. Results and discussion

Three different scenarios are investigated to evaluate the impact of linear conversion efficiency and conversion dynamics on the system design: (i) base scenario (BS), with PWA approximations of the conversion efficiency and conversion dynamics, (ii) linear conversion scenario (LCS), with linear approximations of the conversion efficiency and conversion dynamics, and (iii) no dynamics scenario (NDS), with PWA approximations of the conversion efficiency and no conversion dynamics. The results of the simulations are summarized in Fig. 1. On the right hand side, the total annual costs of two different systems, one implementing a SOFC and one implementing a PEMFC as conversion technologies are compared. On the left hand side, the size of a SOFC-based system, i.e. including a SOFC and the HWTS, is presented. Although not shown here, similar results are obtained for a PEMFC-based system. Note that if both technologies are considered at the same time, the optimizer only selects the PEMFC as the more convenient alternative. Thus, different simulations are needed to analyze the effects of the modeling approximations on the different technologies.

For both fuel cells, the total annual cost of the system is overestimated when considering linear conversion performance (LCS) and it is underestimated when neglecting the conversion dynamics (NDS). The following considerations can be drawn with respect of the SOFC: (i) The linear conversion scenario translates in about the same sizing of conversion and storage units. The higher total annual cost is due to the concavity of the part-load efficiency curves. In fact, the convex hull approximation of concave curves implies an underestimation of the conversion efficiency which, in its turn, implies a greater amount of imported natural gas. (ii) Neglecting the conversion dynamics translates into a bigger SOFC and a smaller TS, turning into a lower overall annual cost. This is because the slow start-up/shut-down dynamics forces the fuel cell to be always switched on, requiring a smaller device to comply with the minimum threshold of generated power. At the same time, when no thermal energy is required by the end user the minimum generated power must be stored in the thermal storage, which must therefore be bigger. Similar considerations can be drawn with respect of the PEMFC. In this case, a smaller impact of both modeling approximations is observed. This is due to a less pronounced nonlinearity of the conversion curve and to a faster conversion dynamics, which is less limiting the operation of the PEM device. Furthermore, while neglecting
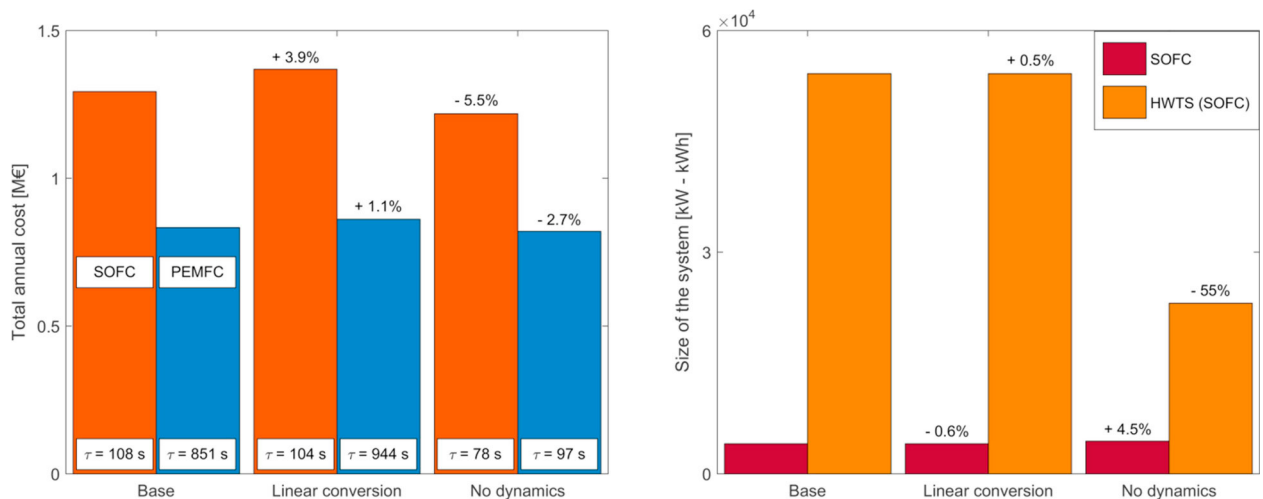

Fig. 1. Impact of different modeling approximations on the total annual cost (left), and size (right) of the multi-energy system: (I) base scenario, (II) linear conversion scenario, (III) no dynamics scenario. Percentage deviation with respect of the base scenario (top of the bars), and computational time (bottom of the bars). Only the size of the SOFC-based MES is shown.

the conversion dynamics provides a significant benefit in terms of computational time, no advantages are observed when implementing a linear conversion efficiencies instead of a PWA approximations.

Finally, the analysis of the results indicates that the PEMFC is significantly more convenient than the SOFC. This is due to the higher thermal efficiency of the PEM fuel cell, which is favored in a residential context where the thermal demand is predominant over the electrical load, as well as to the faster dynamics of the PEMFC, which allows more frequent start-up and shut-down operations.

5. Conclusions

This paper studied the impact of modeling approximations on the design of integrated multi-energy systems including fuel cell technologies and storage systems. Simplified linear correlations suitable for an optimization framework were determined based on first-principle models. A linear and a PWA approximations of the conversion efficiency were considered, together with a linear description of the system dynamics. A MILP optimization framework was used to evaluate the impact of (i) linear conversion efficiency and (ii) conversion dynamics on the minimum-cost design of the integrated multi-energy system. Findings showed that assuming linear conversion efficiency and neglecting the conversion dynamics turns into deviations in the total annual cost of the system in the range of 5% for SOFC and 2% for PEMFC, due to the different features of the conversion devices. Moreover, while a shorter computational time is observed when neglecting the conversion dynamics, no computational benefit is obtained through a linear approximation of the conversion efficiency. Findings also show that conversion units with a better balance between electric and thermal efficiency are favored in the context of residential generation.

Acknowledgements

References

[1]   Mancarella P. MES (multi-energy systems): An overview of concepts and evaluation models. Energy 2014;65:1–17. doi:10.1016/j.energy.2013.10.041.

[2]   Marnay C, Venkataramanan G, Stadler M, Siddiqui A, Firestone R, Chandran B. Optimal Technology Selection and Operation of Commercial- Building Microgrids. IEEE Trans Power Syst 2007;23:1–10.

[3]   Hawkes AD, Leach MA. Modelling high level system design and unit commitment for a microgrid. Appl Energy 2009;86:1253–65. doi:10.1016/j.apenergy.2008.09.006.

[4]   Keirstead J, Samsatli N, Shah N, Weber C. The impact of CHP (combined heat and power) planning restrictions on the efficiency of urban energy systems. Energy 2012;41:93–103. doi:10.1016/j.energy.2011.06.011.

[5]   Fazlollahi S, Mandel P, Becker G, Maréchal F. Methods for multi-objective investment and operating optimization of complex energy systems. Energy 2012;45:12–22. doi:10.1016/j.energy.2012.02.046.

[6]   Mehleri ED, Sarimveis H, Markatos NC, Papageorgiou LG. Optimal design and operation of distributed energy systems: Application to Greek residential sector. Renew Energy 2013;51:331–42. doi:10.1016/j.renene.2012.09.009.

[7]   Omu A, Choudhary R, Boies AM. Distributed energy resource system optimisation using mixed integer linear programming. Energy Policy 2013;61:249–66. doi:http://dx.doi.org/10.1016/j.enpol.2013.05.009.

[8]   Bischi A, Taccari L, Martelli E, Amaldi E, Manzolini G, Silva P, et al. A detailed MILP optimization model for combined cooling, heat and power system operation planning. Energy 2014;74:12–26. doi:10.1016/j.energy.2014.02.042.

[9]   Bracco S, Dentici G, Siri S. DESOD : A mathematical programming tool to optimally design a distributed energy system. Energy 2016;100:298–309. doi:10.1016/j.energy.2016.01.050.

[10]   SolidPower. http://www.solidpower.com/en/home/ n.d. http://www.solidpower.com/en/home/.

[11]   Panasonic Fuel Cells. http://panasonic.co.jp/ap/FC/en_about_01.html n.d. http://panasonic.co.jp/ap/FC/en_about_01.html.

[12]   Barelli L, Bidini G, Gallorini F, Ottaviano a. An energetic-exergetic analysis of a residential CHP system based on PEM fuel cell. Appl Energy 2011;88:4334–42. doi:10.1016/j.apenergy.2011.04.059.

[13]   Barelli L, Bidini G, Gallorini F, Ottaviano PA. Design optimization of a SOFC-based CHP system through dynamic analysis. Int J

Hydrogen Energy 2013;38:354–69. doi:10.1016/j.ijhydene.2012.09.162.

[14] Gabrielli P, Flamm B, Eichler A, Gazzani M, Lygeros J, Mazzotti M. Modeling for optimal operation of PEM fuel cells and electrolyzers. 2016 IEEE 16th Int. Conf. Environ. Electr. Eng., IEEE; 2016, p. 1–7. doi:10.1109/EEEIC.2016.7555707.

[15] Arroyo JM, Conejo AJ. Modeling of start-up and shut-down power trajectories of thermal units. IEEE Trans Power Syst 2004;19:1562–8. doi:10.1109/TPWRS.2004.831654.

[16] Gabrielli P, Gazzani M, Martelli E, Mazzotti M. Optimal design of multi-energy systems with seasonal storage. Appl Energy 2017. doi:http://dx.doi.org/10.1016/j.apenergy.2017.07.142.

[17] Gabrielli P, Gazzani M, Martelli E, Mazzotti M. A MILP model for the design of multi-energy systems with long-term energy storage. Comput. aided Chem. Eng., vol. 40, Elsevier; 2017, p. 2437–42.