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Optimal design of a district energy system including supply for fuel cell electric vehicles

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HIGHLIGHTS

- Analysis includes energy demand for individual mobility in design of a district energy system.
- Analysis includes future technologies such as solid oxide fuel cells and PEM electrolyzer.
- Uniform modeling and systematic analysis of economic influences.
- Analysis shows under which economic conditions the different configurations and operation modes become feasible.
- Especially the feed-in tariff and PV investment costs determines the application of electrolyzer and batteries.

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ABSTRACT

In the context of increasing use of renewable energy sources, residential energy supply systems are changing as well. In this paper, a techno-economical model for the energy supply of a district including both electrical and thermal demand as well as renewable energy generation is developed. Furthermore, a high penetration of fuel cell electric vehicles is assumed and the hydrogen has to be provided by the energy supply system as well. The single components of the energy system are optimal sized, with respect to the total cost of ownership of the system, while the systems operation strategy is defined by a fixed ranking list. A reference case is defined by actual or near future techno-economical assumptions of the components. In the resulting optimal system, the most important components are a large PV system, a SOFC for heat and power generation and a PEM electrolyzer for hydrogen production. The produced hydrogen is used solely to refuel the fuel cell electric vehicles. On this basis, the influences of the components investment costs and the energy purchasing costs on the system configuration are investigated. It is shown that, the PV investment costs as well as the feed-in tariff can cause qualitative differences in the system configuration. Moreover, interactions between all conversion devices with respect to the optimal sizing are identified. Finally, it is shown that if the PV investment costs and the feed-in tariff decreases in the future, a reconversion of the self produced hydrogen in the SOFC becomes economically feasible, even for small natural gas purchasing costs.

1. Introduction

The energy demand of residential households is dominated by the demand for electricity, hot water and space heating. Additionally, the energy demand for individual mobility could be taken into account, since it is needed locally as well. In general, these energy demands are supported by the public electricity grid, for heating and for hot water from individual boilers, which are mainly fueled with oil or natural gas. Individual mobility is achieved through cars with combustion engines which are fueled by a large network of filling stations. However, this energy supply structure is changing, due to the decreasing investment costs of renewable energy (RE) sources, such as photovoltaic systems and wind turbines. Additionally, in several countries different laws enforce the installation of RE sources. In all, the electricity generation costs of RE power plants as well as revenues for feeding electricity into the grid decrease while purchasing costs for electricity increase. Thus, direct consumption of the self-produced electricity becomes increasingly profitable. Nevertheless, in most cases, storing renewable excess

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Nomenclature

Acronyms

Bat	battery storage system
Comp	compressor
El	electrical
Ely	electrolyzer
FCEV	fuel cell electric vehicles
GA	genetic algorithm
GCB	gas condensing boiler
HHV	higher heating value
HPH_2	high pressure hydrogen
HRS	hydrogen refueling station
HWT	hot water tank
LHV	lower heating value
LPH_2	low pressure hydrogen
KPI	key performance indicator
MFH	multi-family house
NG	natural gas
PEM	proton exchange membrane
PV	photovoltaic system
RE	renewable energy
ref	reference
SFH	single-family house
SOFC	solid oxide fuel cell
TCO	total cost of ownership
Th	thermal
TRNSYS	transient systems simulation

Latin symbols

C_{an}^{i}	annualized investment costs of component *i*
C_{anv}^{j}	annuity value
C_{I}^{i}	investment costs of component *i*
C_{LCOE}^{j}	mean energy purchasing costs
C_{LCOE,a_0}^{j}	energy purchasing costs at the beginning of the investment
C_{op}^{j}	energy purchasing costs
C_{RI}^{i}	reinvestment costs of component *i*
C_{RV}^{i}	residual value of component *i*
C_{TCO}	total cost of ownership
E	energy amount
f_{an}^{i}	annuity factor of component *i*
$f_{P/E}^{i}$	power to rated energy content ratio of component *i*
$F^{i}(t_k)$	filling level of component *i* in timestep t_k
h_α	specific enthalpy of species α
n_{RV}^{i}	number of reinvestments for the investigated period of component *i*
$\dot{M}_\alpha^{i}(t_k)$	massflow of component *i* in timestep t_k
$\dot{M}_\alpha^{L}(t_k)$	mass flow load demand
Q_v^{i}	power loss of component *i*
r_i	discount rate
r_{inf}	inflation rate
$r_{O\&M}^{i}$	rate for operation and maintenance costs of component *i*
r_p	energy purchasing costs increasing or decreasing rate
r_r	real interest rate
r_{el}^{ss}	electrical self sufficiency rate
r_{el}^{sc}	electrical solar coverage rate
r_{HRS}^{sc}	solar coverage rate of the hydrogen refueling station
r_{SOFC}^{sc}	solar coverage rate of the overall fuel consumption of the SOFC
r_{th}^{sc}	thermal solar coverage rate
T	Temperature
T	depreciation period of the system
T^{i}	lifespan of component *i*
$T^{i,depr}$	calendrical lifespan of component *i*
$T^{i,tech}$	technical lifespan of component *i*
$T_{RI}^{\alpha,i}$	year of the reinvestment component *i*
p	pressure
$P^{i}(t_k)$	power input/output of component *i* in timestep t_k
$P_{loss,el}^{i}$	electrical power loss of component *i*
$P_{loss,th}^{i}$	thermal power loss of component *i*
$P_{el}^{L}(t_k)$	electrical load demand in timestep t_k
$P_{th}^{L}(t_k)$	thermal load demand in timestep t_k
$P_{PV}(t_k)$	electrical power generation of the PV system in timestep t_k
$\dot{P}^{i}(t_k)$	power flow of component *i* in timestep t_k
w_t	specific work

Greek symbols

Δt	constant timestep
ε_{EER}	energy efficiency ratio
η	efficiency
τ^{i}	self discharging rate of component *i*
φ_{FU}^{SOFC}	fuel utilization of the SOFC

Indices

ABu	afterburner SOFC
char	charging
dchar	discharging
dyn	dynamic
H_2	hydrogen
HW	hot water
L	load demand
max	maximum value
min	minimum value
R	rated (capacity/power)
set	desired
SH	space heating
α	species

energy, e.g. in batteries, is not yet economically reasonable. However, with respect to batteries, a significant cost decrease can be expected in the near future. Moreover, there are further developed technologies such as fuel cells and electrolyzers for which a strong cost decrease is forecasted [1]. Thus, these technologies can become components for residential energy supply systems as well. Within the present article, the structure of future household energy systems is analyzed. Thereby, especially the economic boundary conditions such as the investment costs of the system devices and energy purchasing costs are analyzed.

The system of interest could be classified as a hybrid energy system, consisting of multiple energy sources, especially renewable and non-renewable, and storage units (e.g. Krishna and Kumar [2]). Several articles in literature focus on similar systems. Thereby, either the operation strategy of the different components is analyzed (e.g. Fischer and Madani [3], Salpakari and Lund [4]) or an optimal configuration including the dimensions of the components is determined (e.g. Beck et al. [5], Wakui et al. [6], Al Moussawi et al. [7]). From these, there is one group focusing only on the electrical power generation (e.g. reviews of Upadhyay and Sharma [8], Chauhan and Saini [9], Mahesh and Sandhu [10] and Krishna and Kumar [2]). A large variety of different systems consisting of photovoltaics, wind turbines, fuel cells, diesel engines as well as energy storage components such as batteries, flywheels and supercapacitors are considered. Furthermore, different setups can be distinguished, namely grid connected and stand-alone