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# Transition path towards hybrid systems in China: Obtaining net-zero exergy district using a multi-objective optimization method

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ABSTRACT

A hybrid energy system including both off-site and distributed energy sources, energy conversion technologies and operation methods, is a necessary step on a transition path towards a sustainable energy system. The challenge is to identify such a combination of design options that result in minimum life cycle cost (LCC) and maximum exergy efficiency (EE) at each phase of the transition path. In this paper, a time-effective multi-objective optimization method based on genetic algorithm (GA), is proposed for the transition path problem. The proposed model makes use of a fitness function approach to reduce the model into one objective function and to reduce the computational time. In a case study, the model is applied to a potential net-zero exergy district (NZEXD) in Hangzhou, China. Here, three possible hybrid energy scenarios and three preference treatment strategies are analyzed. The study suggests that the proposed approach is workable for the identification of the most feasible options to be gradually integrated in an NZEXD in a multi-stage process. In the Hangzhou case, with the reduction of investments in distributed energy components and escalating market prices of fossil fuels, distributed energy system (DES) may have more feasibility in the near future.



## 1. Introduction

With the development of society, energy needs have become a key focus in the considerable aspects of human life. The level of concern regarding the total energy consumption in both buildings and districts has increased recently. A significant proportion of energy is used by the building sector, i.e. about 38.9% of the total primary energy requirement (PER) in the U.S. was consumed by buildings [1]. Likewise, in China over 35% of the PER was used for satisfying building energy demand [2]. With rising living standards, building energy consumption has significantly increased over the past decades. For instance, energy used for buildings in China has been increasing at more than 10% per year over the past 20 years [3]. Nowadays, increasing price of fossil fuels and impending climate catastrophe compels researchers to apply innovative methods to control the growth of energy use. In the future, when the availability and the penetration of renewable energy presumably increase, challenges such as reducing the capital and maintenance costs of the energy system and avoiding thermal pollution will call for novel ways of thinking in defining and improving the overall energy efficiency.

The concept energy quality, also known as exergy, provides an attractive direction for managing energy use in the future. Exergy is the measure of the maximum useful work that can be done by a system interacting with a reference environment at a constant pressure and a constant ambient temperature. This concept was initially used in the context of energy generation systems, such as solar power system, micro-turbine CHP, geothermal power plant and bio-energy system [4–7]. During the past five years, exergy

*Abbreviations:* NZEXD, net-zero exergy district; DES, distributed energy system; GA, genetic algorithm; LCC, life cycle cost; EE, exergy efficiency; BCHP, bio-fuel micro-turbine combined heat and power; WT, small scale wind turbine; PV, solar photovoltaic; TC, solar photovoltaic thermal; CEG, centralized electricity grid based on the traditional fossil fuel power generation technologies; STH, solar thermal heater; HP, air source heat pump; DH, district heating; AC, air conditioner; EH, electricity heater; GB, biogas boiler; WHU, waste heat (produced by electricity generation process) utilization; SAC, solar absorption cooling; EL, electricity; SH, space heating; DHW, domestic hot water; CC, cooling capacity; OED, off-site energy system dominated; DED, distributed energy system dominated; DEO, distributed energy system only.

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**Nomenclature**

| | |
|---|---|
| $\dot{E}x$ | exergy (MJ) |
| $F_Q$ | Carnot factor |
| $T_0$ | constant ambient temperature (K) |
| $T$ | thermal source temperature (K) |
| $E$ | energy (MJ) |
| $C_0$ | cost of component (c€/kW h) |
| $C$ | cost (c€/kW h) |
| $PW$ | present worth (c€/kW h) |
| $Pr$ | present worth factor |
| $i$ | inflation rate |
| $d$ | discount rate |
| $P$ | power (kW) |
| $Q$ | energy demand (MJ) |

*Subscripts*

| | |
|---|---|
| out | output |
| in | input |
| heat | thermal energy |
| ele | electricity |
| ke | kinetic energy |
| int | installation |
| ope | operation |
| rep | replacement |
| man | maintenance |
| recy | recycling |
| supply | energy supply |
| demand | energy demand |
| stor | energy storage |

had been connected with buildings in several contexts. Björk [8] mentioned "exergy" in energy management and established a rational exergy management model (REMM) for individual buildings, whereas, Weber and Lu enlarged the utilization range of energy quality from individual building to building clusters and districts [9,10].

Since building coupled with exergy, a new concept called "net zero exergy building (NZEXB)" was defined as a building that equates the exergy delivered from the power or gas grid with the exergy exported to the grid during a given period of time [11]. The International Energy Agency (IEA)'s Annex 49 strengthened the position of exergy to the community level [12]. To that end, NZEXB was expanded as net zero exergy district (NZEXD). NZEXD is a district whose energy relations are linked with distributed energy sources (solar, wind, biomass, etc.) and has a sum of net-zero exergy transfer across the district boundary. Here, the energy demands of NZEXD are presumed to be satisfied by the distributed energy system (DES) completely [11]. A gradual process is suggested to replace the existing energy system by a DES. Hence, a hybrid energy system, which includes both off-site and distributed systems, is a necessary step on a transition path towards the sustainable energy system for NZEXD. The boundaries of the hybrid energy systems on the path would be varied along with the transition process, from both centralized energy system and DES to only DES.

Prior to the formation of the transition path, it is challenging to find out the suitable hybrid energy systems comprised in the path. Identifying the recommended combination of system options, an optimization approach is needed. Here, parallel to maximizing exergy performance, another key objective is to minimize cost. The cost analysis calls for determining the investment cost, operational costs, maintenance costs and recycling costs [13]. Therefore, life cycle cost (LCC) analysis, which refers to the estimation of the cost of a product during its life span, has been widely used for evaluation of various energy systems over the past decades [14,15]. Accordingly, a multi-objective optimization approach based on genetic algorithm (GA) is proposed. GA is suited to handling complicated optimization problems with nonlinear, discrete and constrained search spaces and it had been applied to a diverse range of scientific and engineering problems [16,17]. During past years, researchers began to implement GA optimization approach to present economic studies of hybrid energy systems for residential application [1,18–20]. However, for the community level, practical applications in terms of exergy and economic analysis related to GA optimization are hardly found.

Hence a case study is finally presented, where the proposed methodology has been applied to provide transition path on a realistic district located in Hangzhou, China. The initial work is to confirm the appropriate hybrid energy systems included in the path. Three types of energy scenarios are presented: off-site energy system dominated, DES dominated and DES only. Each scenario includes three preference treatment strategies: LCC and EE are equally important, LCC oriented and EE oriented. Based on these solutions, a transition path in hybrid energy systems for the case is taken into analysis. The path is performed as a multi-stage process that distributed energy sources are gradually integrated into the energy system.

## 2. Methodology

### 2.1. Optimization algorithm: Genetic algorithm (GA)

GA is a powerful general purpose stochastic optimization method which has been inspired by the Darwinian evolution of a population subject to evolution operators in a selective environment where the fitness survives [21]. The basic evolution operators of GA are selection, crossover and mutation.

In this paper, a multi-objective optimization approach based on genetic algorithm (GA) is proposed for the identification of optimal hybrid energy systems at each phase of the transition path. GA is suitable for the exploration problem due to some reasons. The most important advantage of GA is that the calculation of the objective function can be placed in a black box. GA only needs to confirm the combination of the input values and the resulting objective function values. With this knowledge, this algorithm can search for optimized input values according to required objective function values. Additionally, the advantage of being able to code infinite numbers of parameters on a chromosome makes it suitable for sizing hybrid energy supply system.

GA was experiencing a blooming period in past decades and had been applied for many aspects including buildings and energy systems. Such types of optimization problems are relatively complicated; therefore, numbers of objectives need to be considered. Wang used a novel multi-objective GA, which combined with life cycle analysis, in green building design process. Life cycle analysis methodology was employed to evaluate for both economic and environmental criteria [22]. Hamdy [23] also implemented GA as main methodology to find economic and environmental solutions towards nearly-zero-energy building. It focused on exploring the possible combination of energy saving measures (envelopes, heat recovery system) and energy supply systems (PV, wind turbine) [23]. Lu [10] proposed a novel multi-objective design optimization scheme that minimizes the global warming potential during the life-cycle and maximizes the exergy performance, while the maximum allowable level of the loss of power supply probability (LPSP) is predefined by the user as a constraint. The purpose of study was to search for the reliable, efficient and environmental friendly energy system for building clusters and districts. A fictitious case located in Norway was used to prove that the proposed approach achieves