Optimized Energy Management of Electric Drive Vehicles in a Green Residential Building

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ABSTRACT:
During the extremely-hot weather or transient heat waves, air conditioners are the main contributors to highest peak electricity demand which may lead to the widespread blackouts or brownouts. Meanwhile, electric drive vehicles are rapidly gaining popularity due to the global warming and energy crisis. Hence, this paper schedules on optimal charge and discharge decisions of plug-in electric vehicles (PEV) in a residential cooling and power microgrid that is driven by a solar Stirling engine. In the presented microgrid, the solar dish Stirling heat engine is employed as an external combustion engine to supply the electricity requirement of compressor, evaporator and condenser fans and charge the PEVs in the off-peak cooling-load hours. During the on-peak periods, optimal discharge of PEVs increases total energy and emission savings, significantly. A thermodynamic based mixed integer nonlinear programming (MINLP) problem is solved to minimize total electricity cost for a benchmark residential building located in a tropical region taking into account the operational constraints of the Stirling engine and the refrigeration cycle. Simulation results demonstrate that this micro-cogeneration system can be introduced as a near-zero energy building with zero-carbon footprint in the presence of PEVs.

KEYWORDS: Combined cooling and power (CCP) system, Solar Stirling engine, Plug-in electric vehicles (PEVs), Mixed integer non-linear programming (MINLP).

1. INTRODUCTION

1.1. Motivation and Literature Review

Nowadays, plug in pure and hybrid electric vehicles are growing in popularity due to the major concerns about the excessive emissions and global energy crisis [1, 2]. During extremely hot weather or transient heat waves, air conditioners are the main contributors to highest peak electricity demand which may lead to interconnected power system's instability, uncontrolled islanding and widespread blackouts or brownouts [3-5]. Meanwhile, charging and discharging of plug in electric vehicles (PEVs) and use of renewables are instrumental in the transportation and smart homes to reduce the electricity bills and on-peak CO_2 emissions [6].

Recently, many scholars have introduced several remarkable strategies for energy management of smart homes, such as energy management modeling in a mixed-integer linear programming (MILP) framework [7], [8], Markov decision process [9], demand side management technique based on the time-varying pricing model taking into account the uncertainties in household appliance operation time [10], rolling horizon algorithm for renewables based smart grid [11], and Monte Carlo approach to estimate electric vehicles' possible states regarding their demand, location and grid connection periods [12]. In [13], load shifting and use of renewables such as fuel cell, battery, solar panel and wind turbine is implemented as two energy management schemes on a smart home. By shifting the electricity demand from on-peak hours to off-peak periods, total load supplied by wind and solar increased approximately 2.5% and 2%, respectively. As the load is supplied more from renewables, annual energy supplied by fuel cell is reduced about 4%.

Authors of [14] used lithium-ion batteries as a storage medium for residential buildings with photovoltaic panels to minimize load-generation mismatch and monthly energy bill. Total energy sent and consumed from local electricity grid and monthly energy bill are respectively reduced in 76%, 78%, and 87.2%. Marzband et al. investigated a day-ahead optimal stochastic programming model for grid-connected residential buildings integrating the uncertain and dispatchable distributed energy sources and flexible and non-responding electricity loads [15]. A MILP problem is solved to minimize hourly power system operational cost. Use of controllable generation sources and responsive loads caused a reduction in power procurement cost by almost 21% in comparison with conventional energy management systems. Authors of [16] incorporated the operational priority of different appliances in the price-based home energy management (HEM). In [17], an artificial bee colony based central energy management system is developed for home microgrids to maximize overall efficiency and minimize energy cost under variable nature of generation sources and plug-and-play structure of storage devices. Iwafune et al. controlled a battery storage that is connected to a rooftop photovoltaic system considering electricity demand and photovoltaic generation prediction errors [18]. Forecasting approach is investigated by real home energy management system data from 160 households.

1.2. Contributions

As mentioned, PEVs are promising technologies that can be used to reduce the global warming and environmental pollutants of fossil fuel based transportation infrastructure and residential energy hubs. Hence, this paper presents a mixed integer nonlinear programming framework for short-term optimal scheduling of charge and discharge patterns of PEVs and minimizing total energy procurement cost of a combined cool and power plant during extremely-hot summer days. The contributions of current paper can be listed as follows:

- Optimal charge and discharge decisions of PEVs are scheduled over a 24-hour period with the aim of energy management in building cool and power system and transportation sector considering their daily driving patterns.
- Two cases are studied in the absence and presence of PEVs to prove their economic-environmental benefits for participating in summer cooling and power.

1.3. Paper Organization

The reminder of this paper is set out as follows: Section 2 presents the problem formulation. Afterwards, simulation results and discussions are drawn in Section 3. Finally, concluding remarks appear in Section 4.

2. MATHEMATICAL FORMULATION

2.1. Combined cooling and power system

The small-scale cogeneration system which can be used for the residential sector is shown in Fig. 1. More details of this cooling cycle can be found in Refs. [19-21]. In this combined cooling and power system, total energy requirement of electrical demand (P_{EL}^t), compressor (P_{comp}^t), inside (P_{in-fan}^t) and outside ($P_{out-fan}^t$) air fans is supplied either by a solar Stirling engine ($P_{Gen}^t = \eta_{elec} P_{M_{SE}}^t$) or by purchasing from the upstream electricity grid (P_{grid}^t).

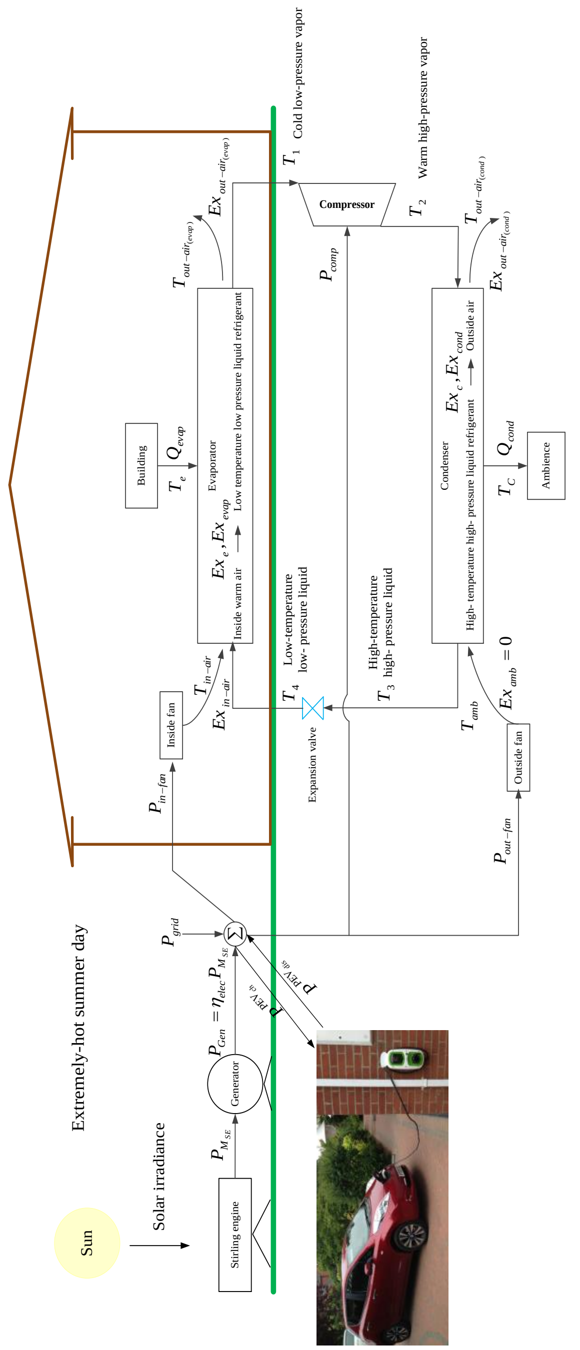

Fig. 1. Capability of PEVs for charging/discharging power from/into solar cogeneration microgrid.

2.2. Optimal charge and discharge of plug-in electric vehicles

Plug-in electric vehicles (PEVs) can participate in supplying total energy requirements of transportation and residential districts. In this paper, equality and inequality constraints (1)-(7) are used to optimize the charge and discharge decisions of PEVs [22]. Their charging and discharging rates are captured in constraints (2)-(3), respectively. Constraint (4) enacts the level of energy stored in PEVs. Constraint (5) imposes that PEVs are not charged and discharged at the same time. The constraint (6) forces the power balance criterion in PEVs at time *t*. Finally, constraint (7) shows that PEVs are charged and discharged only in plugged times.

$$SOC_{t_0}^{PEV_i} = SOC_0^{PEV_i} \;; \quad \forall i \tag{1}$$

$$P_{PEV_{ch}}^{\min}(i)\times U_{t,i}^{PEV_{ch}} \le P_{t,i}^{PEV_{ch}} \le P_{PEV_{ch}}^{\max}(i)\times U_{t,i}^{PEV_{ch}} \;;\; \forall t \;,\forall i \tag{2}$$

$$P_{PEV_{dis}}^{\min}(i)\times U_{t,i}^{PEV_{dis}} \le P_{t,i}^{PEV_{dis}} \le P_{PEV_{dis}}^{\max}(i)\times U_{t,i}^{PEV_{dis}} \;;\; \forall t \;,\forall i \tag{3}$$

$$SOC_{PEV_i}^{\min} \le SOC_t^{PEV_i} \le SOC_{PEV_i}^{\max} \;;\; \forall t \;,\forall i \tag{4}$$

$$U_{t,i}^{PEV_{ch}} + U_{t,i}^{PEV_{dis}} \le 1 \;;\; \forall t \;,\forall i \tag{5}$$

$$SOC_t^{PEV_i} = SOC_{t-1}^{PEV_i} + \chi\times P_{t,i}^{PEV_{ch}} - \frac{P_{t,i}^{PEV_{dis}}}{\eta} - E_{t,i}^{PEV} \;;\; \forall t \;,\forall i \tag{6}$$

$$P_{t,i}^{PEV_{ch}}, P_{t,i}^{PEV_{ch}} = 0 \;;\left\{\forall t \;,\forall i \mid E_{t,i}^{PEV} \ne 0\right\} \tag{7}$$

where,

$SOC_t^{PEV_i}$: Stored energy in i^{th} PEV at time *t*

$P_{t,i}^{PEV_{ch}}, P_{t,i}^{PEV_{dis}}$: Charging/discharging power of i^{th} PEV at time *t* (kW)

$SOC_{PEV_i}^{\min}, SOC_{PEV_i}^{\max}$: Minimum/maximum energy level of i^{th} PEV

$U_{t,i}^{PEV_{ch}}, U_{t,i}^{PEV_{dis}}$: Binary decision variables, 1 if i^{th} PEV charges/discharges at time horizon *t*; otherwise 0.

χ, η : Efficiency of charge and discharge of i^{th} PEV

$E_{t,i}^{PEV}$: Energy requirement for transportation of i^{th} PEV at time *t*

2.3. Objective function and constraints

As mentioned before, the battery pack of plug-in electric vehicles can exchange electricity with electrical loads of residential buildings. In this research, total cost of purchased electricity from local power system should be minimized taking into account the operational constraints of electric drive vehicles. In the optimization process of this combined cooling and power microgid, it is assumed that building electrical and cooling demands are known parameters. Therefore, the value of compressor power (P_{comp}^t), evaporator fan (P_{in-fan}^t), condenser fan ($P_{out-fan}^t$) which depend on building cooling load or inside and outside air temperature will be known. In addition, the electrical demand of benchmark residential building (P_{EL}^t) will be known at each hour of study horizon. Hence, the decision variables of the optimization problem can be considered as follows:

Decision variables: P_{grid}^t , $U_{t,i}^{PEV_{ch}}$, $U_{t,i}^{PEV_{dis}}$, $P_{t,i}^{PEV_{dis}}$, $P_{t,i}^{PEV_{ch}}$; $\forall t$, $\forall i$

Applying the charge and discharge powers of plug-in electric vehicles, the power balance criterion can be given by equation (8).

$$\begin{aligned} P_{grid}^t + \sum_{i=1}^{N_{PEV}} P_{t,i}^{PEV_{dis}} + P_{Gen}^t &= (P_{comp}^t + P_{in-fan}^t + P_{out-fan}^t) \\ &\quad + P_{EL}^t + \sum_{i=1}^{N_{PEV}} P_{t,i}^{PEV_{ch}} \end{aligned} \tag{8}$$

where,

N_{PEV} : Number of vehicles

P_{grid}^t : Electrical power purchased from the upstream grid (kW)

P_{Gen}^t : Electrical power produced by Stirling engine [23-25] and generator set (kW)

P_{EL}^t : Electrical demand (kW)

The following objective function is defined to minimize total energy procurement cost taking into account the operational constraints of Stirling engine and cooling cycle [19-21]:

$$\text{Min}\left(\sum_{t=1}^{24} \lambda_t P_{grid}^t\right) \tag{9}$$

where, λ_t is the electricity rate at time t in $\$/\text{kWh}$.

3. SIMULATION RESULTS

In this section, the optimal short-term scheduling of PEVs is applied on a benchmark residential building and solved as a mixed integer non-linear programming (MINLP) problem using CONOPT [26] tool under general algebraic modeling system (GAMS) [27] environment. The specifications of Stirling engine and refrigeration cycle have been reported in Refs. [19-21].

Daily variations of cooling and electrical demands, hourly electricity rates, ambient and inside air temperatures during a sample summer day have been depicted in Figs. 2-5, respectively.

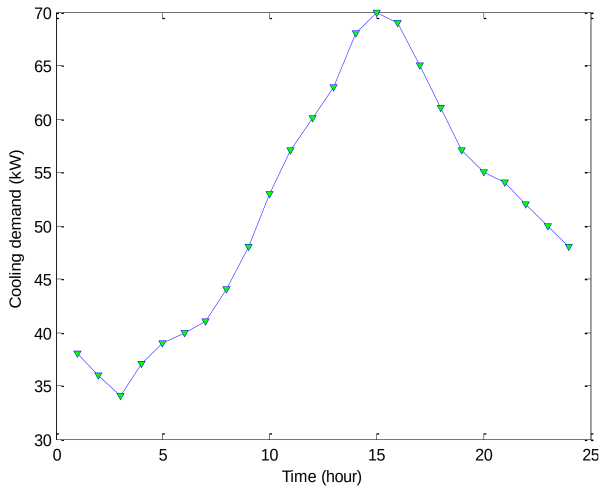

Fig. 2. Cooling demand of residentil building.

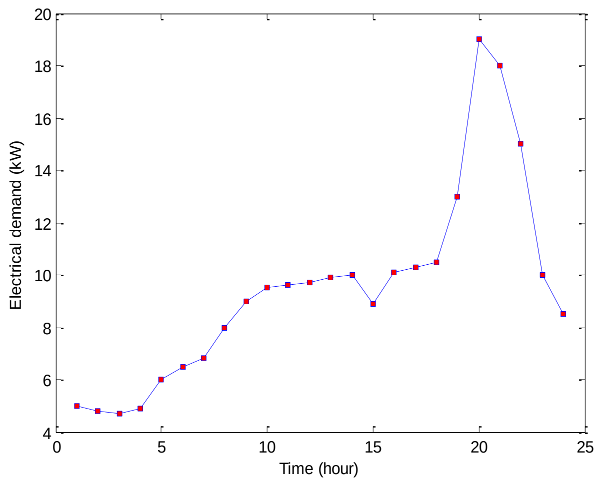

Fig. 3. Electrical demand of residentil building.

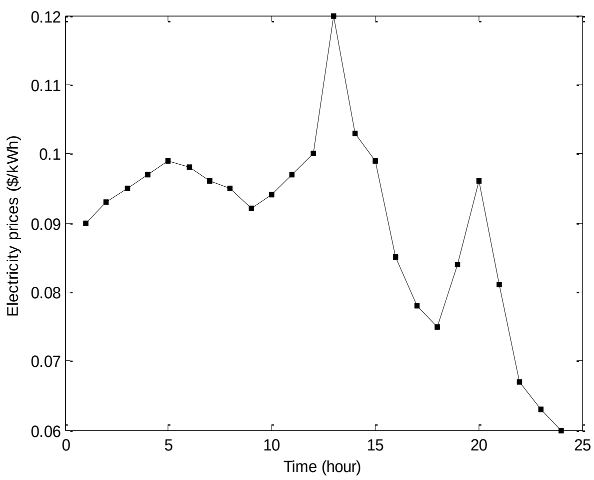

Fig. 4. The hourly electricity rates.

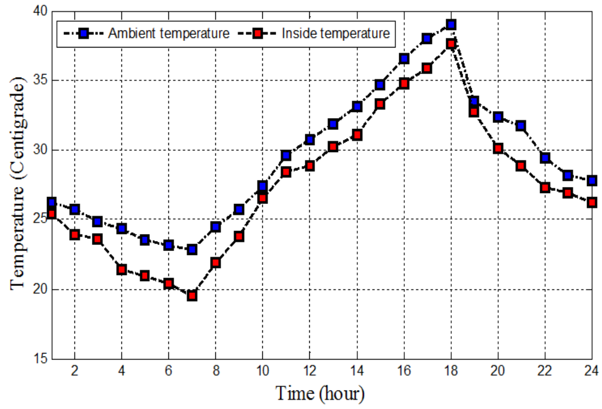

Fig. 5. Ambient and indoor air temperatures during a sample summer day before installing the cogeneration system

In this study, a set of three new PEVs with different daily driving patterns presented in Fig. 6, are considered. Other parameters of electric drive vehicles used in two cases are presented in Table 1. To demonstrate the feasibility and the applicability of the presented system, two cases are studied. Case 1 evaluates the performance of a combined cooling and power system without participation of PEVs. In case 2, the optimal short-term scheduling of cogeneration microgrid is conducted considering the participation of PEVs.

The optimal charge and discharge decisions of PEVs obtained from solving the mixed integer non-linear programming problem have been shown in Fig. 7. Moreover, the mechanical power output of Stirling engine and the electrical power purchased from the upstream electricity grid in two cases with and without considering PEVs are presented in Fig. 8. As obvious from Figs. 7-8, total electricity requirement of cooling process increases as the value of cooling demand increases and vice versa. In other words, on-peak electricity demand occurs in operating time interval $t=12^{noon}$ to t=19, as shown in Fig. 2. Besides, total electrical power consumed by refrigeration cycle increases at this time period, as shown in Fig. 8. According to this figure, from t=1 to t=12 and t=19 to t=24 which is related to the off-peak cooling demand hours, total electricity consumption of building is less than that of other periods. Hence, solar powered Stirling heat engine can supply it. During extremely hot hours with on-peak cooling load from t=12 to t=9, Stirling engine cannot provide total energy requirement of building. Therefore, optimal participation of plug-in electric vehicles in plugged times can procure this not-supplied demand.

Simulation results demonstrates that PEVs charge from the Stirling engine (which is integrated with the heat storage tank) during the off-peak cooling-demand hours with lower ambient air temperature or lower electricity rates from t=1 to t=12 and from t=19 to t=20, and discharge over the high-price time intervals with on-peak electrical demand at midday or from t=12 to t=16, as shown in Figs. 7-8. Figs. 6 and 7 proves that PEVs can charge or discharge energy only in plugged times with zero energy requirement. As it is obvious from Fig. 8, the use of PEVs results in an energy procurement cost reduction from 11.887$ to 6.991$.

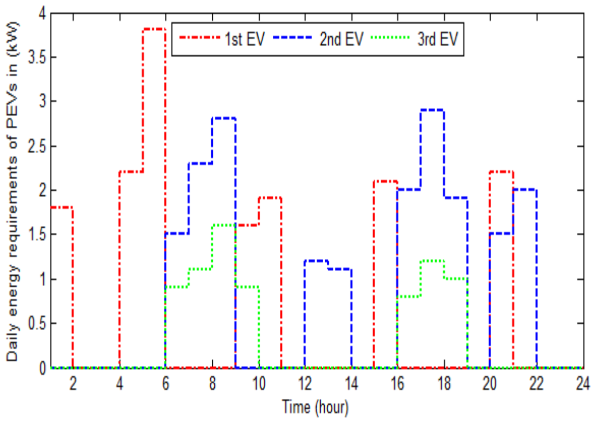

Fig. 6. Daily driving patterns of three different PEVs.

Table. 1. The parameters of PEVs

Parameters	Values
$P_{PEV_{ch}}^{max}, P_{PEV_{dis}}^{max}$	8.5 kW
$P_{PEV_{ch}}^{min}(i), P_{PEV_{dis}}^{min}(i)$	0
SOC_{PEV}^{min}	0
SOC_{PEV}^{max}	25.5 kWh
χ	0.9
η	0.8

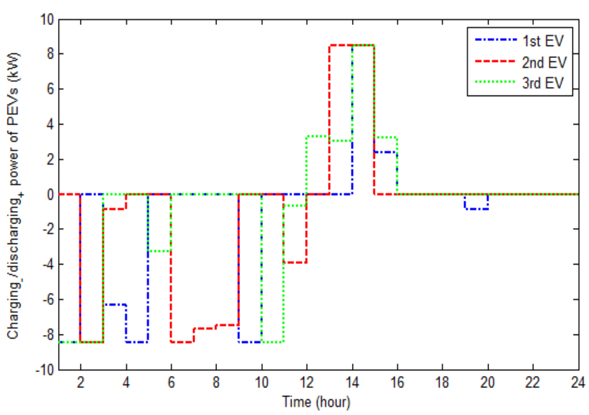

Fig. 7. Charging and discharging patterns of PEVs.

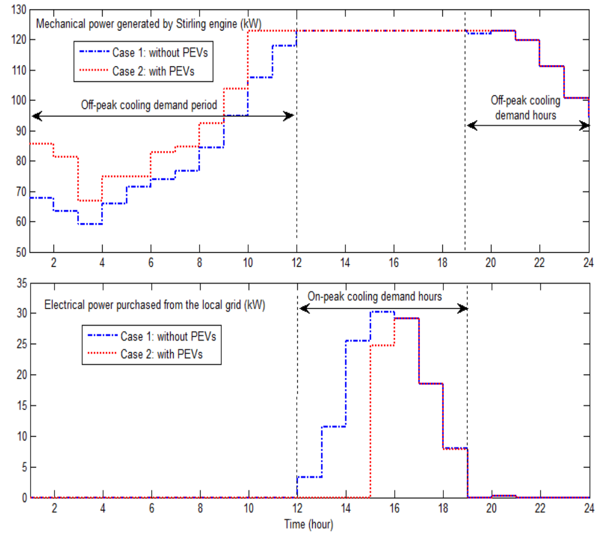

Fig. 8. Mechanical power generated by Stirling engine and electrical power purchased from the upstream grid.

4. CONCLUDING REMARKS

In this research, participation of electric drive vehicles in the residential-district level combined cooling and power system was investigated on a benchmark residential building which consists of 12 flats from an energetic-economic standpoint. Finally, concluding remarks can be summarized as follows:

- Total energy requirement of cooling cycle during extremely-hot summer days, increases as the value of cooling demand or ambient temperature increases and vice versa.
- During on-peak cooling demand hours from t=12 to t=19, Stirling engine cannot supply total electricity consumptions of building cooling and power system. Hence, optimal charge and discharge of plug-in electric vehicles is an effective way in shaving the peak load and reducing the amount of electrical power purchased from local power grid.
- It is found that optimal short-term scheduling of charge and discharge decisions of plug-in electric vehicles only in plugged times results in 41% lower electricity costs and zero-carbon footprint in comparison with the conventional combined cooling and power systems.
- It is demonstrated that PEVs can participate in both residential cooling and power and transportation sector.

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