A scheduling optimization model for minimizing the energy demand of a building using electric vehicles and a micro-turbine

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Abstract— **High energy demand in corporate and/or public buildings is nowadays one of the main reasons of excessive energy consumption. At the same time, electric vehicles (EVs) have become very popular worldwide being a considerable alternative power source when parked. In this work we propose a scheduling mechanism which optimizes the control of the charging-discharging schedule of an altered but finite number of EVs arriving at a university building for a typical load-day in February aiming at the minimization of the energy demand and the electricity cost of the building. In the aforementioned framework, a parallel operation of a small sized gas turbine generator (GGT) is considered. To this end, a mixed integer linear programing (MILP) model containing binary and continuous variables has been developed to optimize the control process and minimize energy cost. Results showed that the use of the EVs as an alternative energy source can significantly contribute to the reduction of the building's energy demand leading to important cost decrease. The exploitation of the energy produced by the GGT further contributed to the minimization of the total energy consumption of the building and the total electricity cost.**

***Index Terms-E*lectric vehicles; energy management system; optimization; building; micro-turbine**

I. INTRODUCTION

Buildings have become the major energy consumers over the world as they consume around 40% of total end-use energy [1]. This percentage could reach even 90% in some advanced countries like Hong-Kong [2]. Especially corporate/public buildings contribute to a great extent in excessive energy consumption. The incorporation of smart technologies in buildings is considered crucial on the roadmap towards increasing energy efficiency, integration of renewable energy sources (RESs) and reduction of pollutants emissions. To ensure environmental sustainability and promote the relatively new concept of Net Zero Energy Buildings (NZEBs), the development of novel infrastructures under the combination of Information and Communication Technologies (ICT) and energy management systems (EMS) is required. The main advantages of nZEBs have been identified to be the integration of renewable energy sources; the integration of energy storage mechanisms such as plug-in electric vehicles and the implementation of zero-energy concepts such as net zero source energy, net zero energy costs and net zero emissions [3].

The use of smart technology through comprehensive and efficient facility management functions characterize the smart buildings which are a vital part of smart grids. By smart technology we mean advanced technologies including smart meters, home and building energy management systems, smart controllers/sensors that can be actually involved in energy and communication coordination between the smart grid and buildings. Smart meters can be used to investigate, analyze and schedule the priorities of house appliances for power demand-response. This is the reason why such systems are often utilized to predict the next day energy consumption/production [4].

Energy management and optimal control systems are key factor for accomplishing the NZEB goals. A high building performance can only be guaranteed by a well-managed and controlled energy system [5]. A main challenge for the efficient control of the energy systems is the integration of on-site energy production and storage systems. Electricity storage (batteries) has been a proven technology used for shifting electricity demand and power peak shaving. But batteries still remain an expensive technology which can sometimes increase up to 50% the total cost of the power system [6]. On the other hand, electric vehicles (EVs) of all types are gaining popularity and are now commercially available from a number of car manufacturers worldwide. The V2G concept could contribute to the increase of the quality and performance of a supply grid it terms of system efficiency, stability and reliability while it plays an important role in NZEB concepts [7].

EVs including hybrid electric vehicles (HEVs), battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) have been experiencing considerable development in recent years [8]. The benefits of using vehicle energy have urged many researchers to work on modeling several EVs concepts. Special attention has been given to charging and discharging algorithms for grid-able vehicles (i.e. BEVs or PHEVs with grid capacity), optimal scheduling for vehicle-to-grid (V2G) operation [9] and the impact of plug-in EVs on power systems [10]. EVs can act either as distributed storage devices delivering power to a grid at peak hours or serve as load.

The time-based electricity schemes can have many different forms. The most common but not limited to are the time-of-use pricing (TOUP), the critical peak pricing (CPP) and the real-time pricing (RTP) [11]. The power load could be managed by charging the plugged-in PHEVs when the electricity price received from the utility is lower and discharge the PHEVs batteries injecting energy to the grid when prices are higher.

In this study, we examine the effect of different PHEVs fleets in combination with the operation of a small-sized gas generator turbine (GGT) on the electricity demand profile of a university building in Mons, Belgium under a dynamic price scheme. Our goal is on one hand to optimize the charging-discharging process of the PHEVs so as to minimize the energy demand and thus the electricity cost of the building and on the other hand to optimize the operation of the GGT in order to maximize revenue according to a given pool price. Finally, a scenario on which the GGT does not inject the produced energy to the grid but instead contributes its energy to cover the building's demand is considered.

The remainder of this paper will be organized as follows. In Section II the mathematical formulation of the model is described along with the considered assumptions. In Section III the results of both the optimization process for the charging-discharging PHEVs control and the GGT's optimal operation are presented while in Sections IV and V the discussion and the conclusions follow accordingly.

II. ASSUMPTIONS AND MODELLING

A. *Building Load and Used Pricing*

A load profile of a typical winter day has been selected from an available set of building load measurements. The load profile covers 10 hours, from 8 am to 6 pm, and the energy consumption is available on a 15-min time base as shown in Fig. 1.

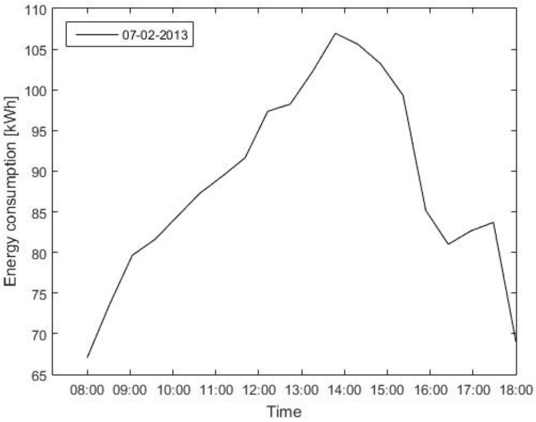

Figure 1 University building load during a typical day in February 2013

We have considered this timetable taking into account the usual working hours of the university. The PHEVs charging-discharging optimization and the operation of the GGT takes place during these hours. Fig.2 shows the spot price tariff for electricity cost and the pool price data used for the operation of the GGT.

Electricity cost reaches its peak value between 4 pm and 7 pm while the pool price data indicate that energy to the grid is mostly required between 12 pm and 3 pm and 4.30 pm and 6 pm.

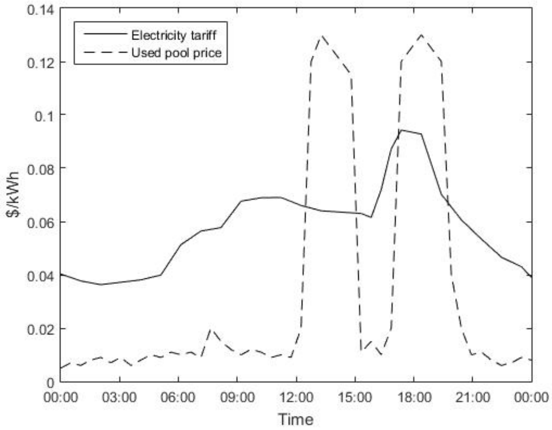

Figure 2 Electricity tariff (spot price) and pool price [12]

B. *Specifications of the PHEVs*

Each PHEVs battery is equipped with a maximum capacity of C^{PHEV} = 10.15 kWh and is characterized by its all-electric range (AER). AER is the total distance that the PHEVs can cover running on an all-electric mode. Different PHEVs require different amounts of energy based on their type. The energy required to accomplish their AER is called electrical energy per kilometer. In this work, it is selected equal to 0.37 kWh/km [13]. Assuming an energy conversion efficiency η^{EV} = 0.88 from the AC energy absorbed from low voltage (LV) to DC energy stored in the battery of the vehicle, a full charge would require 11.53 kWh. Among the different available standards and codes for the EVs charging, we have chosen the SAE J1772. More specifically the AC level-1 has been selected which defines single phase charging at 120V, 16A and 1.92 kW of power. This standard defines a common EV and supply equipment vehicle conductive charging method. Although this standard defines only the charging process (thus, a unidirectional flow of energy), in this study we have considered a bidirectional energy flow of energy. The reason behind this assumption is that a bidirectional energy flow ensures the ability of the system not only to allow PHEVs charging but also to exploit the energy coming from the PHEVs when discharging. The bidirectional operation of converters or/and EVs battery chargers has been addressed in literature (see, e.g., [14]). Moreover, in this work, it has been assumed that the discharging rate is equal to the charging rate for simplicity reasons. The authors acknowledge the necessity of considering the charging-discharging rates as variables (their values being determined by the optimization model) and current research is heading that way. Finally, fast charging was not considered as it requires higher voltage levels and a higher short-circuit power which induces extra investments increasing the total implementation costs.

C. *PHEVs Arrivals-Departures and Charging-Discharging Period*

In this article we have considered that the batteries of all the vehicles are fully charged when departing from home. It has been also assumed that all PHEVs run solely on electricity until they arrive to university. Assuming that a fully charged PHEV drives s kilometers on electricity, the state of charge (SoC) of a vehicle driven by d kilometers when arriving at university is calculated as:

$$\%SoC = \begin{cases} 100 \cdot \left(\frac{s-d}{s} \right), & d \le s \\ 0, & d > s \end{cases} \quad (1)$$

Let us denote i the i-th electric vehicle belonging to the set $I = \{1,...,I_{EV}\}$ of the PHEVs. In this work, the length of the trip and, consequently, the SoC of the i-th PHEV upon arrival (s_i^0) is calculated using a normal distribution taking as base case (mean) value $\bar{d} = 10$ km [15] and standard deviation σ = 3 km. In this study, two different scenarios of PHEVs fleets have been considered: I_{EV}=10 and I_{EV}=25 PHEVs. The scheduling horizon is divided into a set $N = \{1,...,N_{END}\}$ of $N_{END} = 20$ time slots (having equal duration of 30 minutes). Thus, the duration of a 10 h period is divided into 20 time slots for a more realistic and detailed time analysis. It has been also assumed that all the vehicles arrive at the university at the beginning of the time slot n=1 (8 am) and depart at the end of the time slot $n=N_{END}$ (6 pm). Upon their arrival the PHEVs are immediately available for charging-discharging or they can remain in standby mode.

D. Problem Formulation of the PHEVs Charge-Discharge Control

The objective is to find the optimum time slots during which the PHEVs should charge/discharge in order to minimize the building's energy demand under the current pricing scheme. A charging-discharging schedule of the PHEVs batteries is therefore to be determined in function of the pricing scheme and the current SoC of the batteries. Regardless the charging-discharging schedule during the day, a constraint is imposed which expresses that the SoC of all the batteries is at least 50% (*i.e.* 5.075 kWh) by the time the PHEVs depart (last time slot). This charging level, taking into consideration the selected AER, would allow the PHEVs to drive a distance of around 14 km (=5.075/0.37) solely in electricity mode. This value is higher than the assumed used mean value $\bar{d}$ in Section II-C offering an extra safety margin. In addition, attention should be drawn to the fact that Belgium is a country with high a density population and relatively short distances.

There exist two kinds of loads: fixed and adjustable. In this work, the fixed load is the building load demand and is characterized for each time slot n by the overall energy consumption e_F^n. On the other hand, the adjustable load is the charging load totalized for all the PHEVs ($i=1, ..., I_{EV}$).

In order to model the charging-discharging process of the vehicles, we introduce three sets of variables. First, we consider two sets of binary variables: ξ_i^n and σ_i^n which are defined for every vehicle and every time slot. If the i-th PHEV is charging during the time slot n, ξ_i^n is equal to 1, otherwise it is equal to 0. In a similar way, whether the PHEV is discharging or not, σ_i^n is equal to 1 or 0. The charging and discharging rates are constant and they are both worth 1.92 kW according to the SAE J1772. We denote as c^{EV} and d^{EV} the energy obtained and given from charging and discharging during one time slot respectively. The SoC of the i-th PHEV for the time slot n is represented by the continuous non-negative variable s_i^n. Recall that all the vehicles are characterized by their initial SoC (s_i^0). Hence, the SoC of each PHEV in a time slot depends on its previous time slot and on the charging/discharging rates. It can be estimated according to the following equations and constraints:

$$s_i^n = s_i^0 + \xi_i^n \cdot c^{EV} - \sigma_i^n \cdot d^{EV} \quad \forall i \in I, n = 1 \quad (2)$$

$$s_i^n = s_i^{n-1} + \xi_i^n \cdot c^{EV} - \sigma_i^n \cdot d^{EV} \quad \forall i \in I, \{n \mid n \in N, n > 1\} \quad (3)$$

$$\xi_i^n + \sigma_i^n \le 1 \quad \forall i \in I, \forall n \in N \quad (4)$$

$$s_i^n \le C^{EV} \quad \forall i \in I, \forall n \in N \quad (5)$$

$$s_i^n \ge 50\% \cdot C^{EV} \quad \forall i \in I,\ n = N_{END} \quad (6)$$

Constraint 4 guarantees that in every time slot, PHEVs can be only in charging, discharging or standby mode. The other constraints ensure that the SoC of the PHEVs cannot exceed the maximum battery capacity (see (5)) at any time and that the battery of each PHEV will be charged at least 50% of its total capacity before departure (see (6)). The following constraint establishes the energy balance between the input and output electric power of the system in each time slot:

$$y^n + \sum_{i \in I} \sigma_i^n d^{EV} = e_F^n + \frac{1}{\eta^{EV}} \sum_{i \in I} \xi_i^n c^{EV} \quad (7)$$

where y^n is the energy required from the LV network at each time slot to cover the load demand and the PHEVs charging load. Finally, the objective function to be minimized is:

$$\min \sum_{n \in N} \alpha^n y^n \quad (8)$$

where α^n is the cost of energy absorbed from the grid according to the current pricing scheme at time slot n. A mixed integer linear programming (MILP) model is run in order to schedule the energy usage plan over the time horizon $n = 1, ..., N_{END}$.

E. GGT Problem Formulation

The objective here is to find the optimal integer generation profile to maximize the revenue from the operation of a small sized GGT according to the given pool price scheme. The GGT can only operate in one of the three following possible modes: at low load, high load or off mode. At low load the GGT can generate gen^{min} = 102 kW, while at high load gen^{max} = 204 kW. These values are constant during each time period n. Transitions between the offline and online states of a generator are known as start-up. The start-up, which typically lasts up to a few minutes for a small-sized GGT but can take several hours for a bigger one, is associated with the start-up costs. It is not realistic to assume that, even for a small-sized GGT, it can alternate from off to on state and *vice-versa* without any restrictions. Thus, for a more realistic approach, we have introduced a start-up cost for the operation of the GGT equal to S^{cost} = 20 \$/kWh [16]. The cost of the fuel has been set equal to $fuel^{cost}$ = 0.022 \$/kWh. In the low load state GGT consumes fuel equivalent to f^{min} = 236 kWh/h while in the high load state f^{max} = 472 kWh/h (energy efficiency ≈ 43%). The efficiency of the GGT has been kept constant in both half load and full load state for sake of simplicity. At first glance, such an assumption is not very restrictive since in micro-turbines and small sized gas turbines the difference in efficiency between full load and half load is less than 15% [17]. The operational cost of the fuel for each GGT running state is calculated by multiplying the corresponding fuel energy equivalent with the fuel standard cost. The final revenue r_n of the GGT operation for each time period n is calculated by multiplying the generation in each state (min or max) with the corresponding pool price p_n at time slot n minus the total fuel cost:

$$r_n^{\min} = p_n \cdot gen^{\min} - f^{\min} \cdot fuel^{\cos t} \tag{9}$$

$$r_n^{\max} = p_n \cdot gen^{\max} - f^{\max} \cdot fuel^{\cos t} = 2 \cdot r_n^{\min} \tag{10}$$

The unit of revenue r_n is \$/hr (p_n in \$/kWh, gen^{min} and gen^{max} in kW, f^{min} and f^{max} kWh/h and $fuel^{cost}$ in \$/kWh). All the values have been adjusted for half hour intervals. The available fuel is limited and allows for the generation of maximum 2343 kWh per day. The time horizon is the same with the PHEVs, namely a period of 10 hours split into 20 half-hour intervals ($N=20$). To model the operation of the GGT, we introduce three sets of binary variables: $x_n^{\min}$, $x_n^{\max}$ and x_n^{start} If the GGT is operating on low state at time $n \in N$, $x_n^{\min}$ is equal to 1, otherwise it is equal to 0. To a similar way, if the GGT is operating in high state at time n, then $x_n^{\max}$ is equal to 1, otherwise it is equal to 0. Finally, if the startup cost applies then x_n^{start} is equal to 1, otherwise it is equal to 0. The objective function to be optimized is as follows:

$$\max \sum_{n \in N} r_n^{\min} x_n^{\min} + \sum_{n \in N} r_n^{\max} x_n^{\max} - \sum_{n \in N} x_n^{start} S^{\cos t} \tag{11}$$

The following constraints apply:

$$x_n^{\min} + x_n^{\max} \le 1 \qquad \forall n \in N \tag{12}$$

$$x_n^{\min} - x_{n-1}^{\min} + x_n^{\max} - x_{n-1}^{\max} \le x_n^{start} \qquad \forall n \in N \tag{13}$$

$$\mathrm{Fuel}^{used} \le 2343\ \mathrm{kW}h \tag{14}$$

The first constraint (11) ensures that the GGT can only run in one of the two load states or is off. The second constraint (12) ensures that the startup cost applies only when the GGT goes from an off state to a low or high one and not from a low to high or high to low state.

The operation of the GGT is optimized according to the used pool price scheme. The GGT, instead of injecting the produced energy to the grid, could be used in combination with PHEVs operation to cover the building's energy demand. In this case, if we denote as e_{GGT}^n the energy produced at each time slot n by the GGT, (7) becomes for all n:

$$y^n + \sum_{i \in I} \sigma_i^n d^{EV} + e_{GGT}^n = e_F^n + \frac{1}{\eta^{EV}} \sum_{i \in I} \xi_i^n c^{EV} \tag{15}$$

Both optimization problems were solved successively using the MATLAB© mixed-integer linear programming solver (intlinprog) with the branch and bound algorithm.

III. RESULTS

A. PHEVs Optimized Charging-Discharging Control

In this section the idea is to show how the optimal charging-discharging control of the PHEVs contributes to the minimization of the energy demand and thus of the electricity cost of the building. The charging-discharging times of the PHEVs are decided by the model along with the required energy to cover the building's load. The impact of the PHEVs charging-discharging decisions on the building's energy consumption is illustrated in Fig.3.

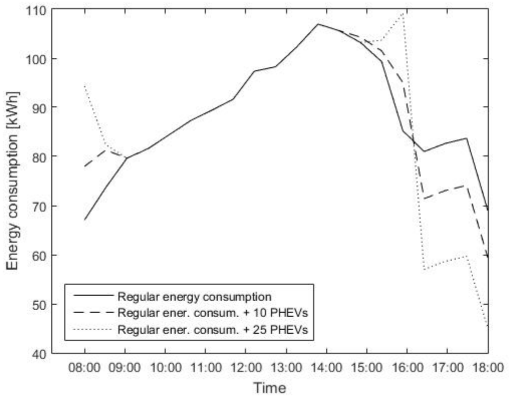

Figure 3 Energy consumption of the university building for coordinated charging-discharging

The objective function was defined so as to minimize the energy consumption of the building, especially when the electricity prices are high. Following this rationale, the PHEVs charge in the early hours when the prices are lower and just before cost peak hours in the afternoon. On the other hand, the PHEVs start discharging when electricity cost reaches its peak contributing to a great extend to the coverage of the building's energy consumption. Between 9 am and 3 pm the PHEVs are in standby mode neither charging nor discharging. In the case of 25 PHEVs, the peak load demand is increased around 4 pm ($n=16$), due to the constraint imposing that all the PHVEs must be delivered at the end of the time horizon with minimum SoC=50%. The increase of the number of the PHEVs leads to significant reduction of the total energy consumption. For instance, during the last time slot ($n=N_{END}$), the total building's consumed energy was reduced 14% in the case of 10 PHEVs and 35% in the case of 25 PHEVs compared to the regular energy demand of the building for the same period.

Fig. 4 depicts the final SoC of all the PHEVs batteries before departing from university.

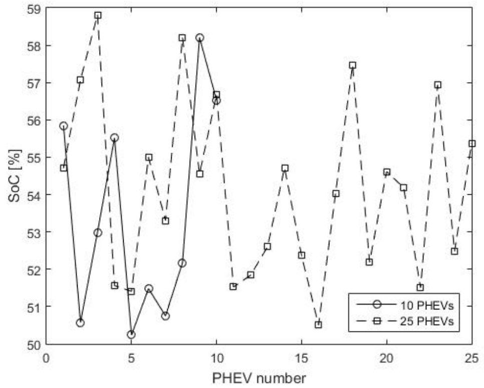

Figure 4 The final SoC for both 10 and 25 PHEVs scenarios

Note that the variability observed in the PHEVs' SoC comes from the randomness of the initial SoC along with the discrete charge/discharge process. The distribution of the charge/discharge slots to the PHEVs is decided by the model aiming at the cost minimization of the building's electricity demand.

B. GGT Optimal Schedule

The GGT operation is optimized according to the used pool price scheme. Fig. 5 shows the optimal operation schedule of the GGT.

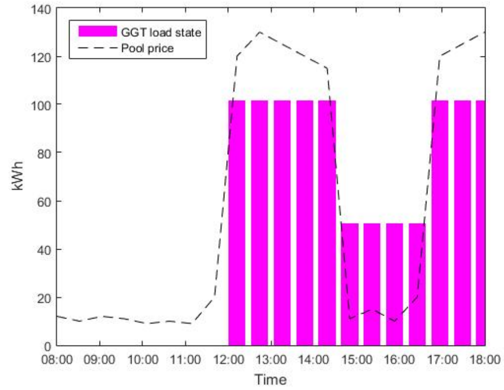

Figure 5 Optimal schedule of the GGT operation

Fig. 5 indicates that the GGT starts its operation when the pool price increases. More specifically, it operates on high load state from around 12 pm until 2.30 pm and from 4.30 pm to 6 pm. It is worth mentioning here that in the meantime, the GGT does not switch to off mode although the pool prices drop substantially. The reason is that, due to the imposed startup cost, it is more economical for the GGT to remain in low state operation during the low pool prices than switch to off mode and then pay the startup cost for restarting its operation. The GGT started only one time, utilized 97% of the available fuel and produced total revenue of $ 68.87 for one day of operation.

C. Combining PHEVs and GGT Operation

In this subsection the combined impact of the GGT operation and the PHEVs charging-discharging process on the building's electricity demand profile is presented. More specifically, we have considered that the produced energy of the GGT (operating according to its optimization schedule as presented in subsection III.B) is not injected to the grid but it is used instead to cover the building's load demand. The impact of the PHEVs charging-discharging process in combination with the GGT operation on the building's energy demand is depicted in Fig. 6 (10 PHEVs) and Fig. 7 (25 PHEVs).

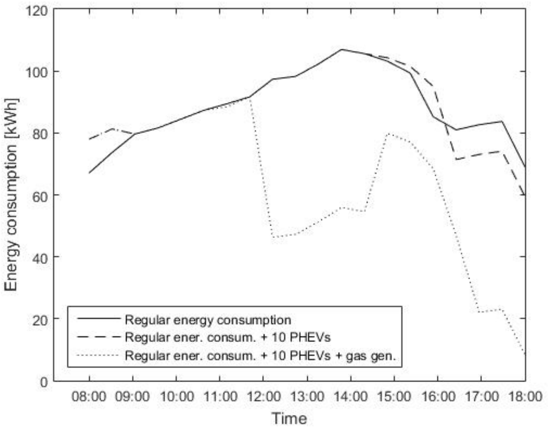

Figure 6 Combined impact of 10 PHEVs and GGT operation on the building's energy consumption

The two figures indicate similar patterns showing that the total energy consumption of the building is significantly decreased mainly during the GGT operation. The fact that the peak of the electricity price tariff coincides with the second peak of the pool price (Fig. 2) plays an important role for the minimization of the total electricity cost of the building as the GGT contributes part of its energy production when electricity is expensive.

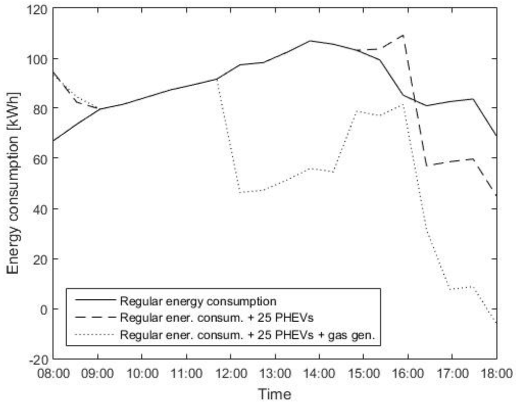

Figure 7 Combined impact of 25 PHEVs and GGT operation on the building's energy consumption

It is worth mentioning here that in the case of 25 PHEVs, the energy consumption becomes negative in the last time slot (5.30 – 6.00 pm). The interpretation of the negative sign is that for this specific time period, the combined operation of the GGT and the PHEVs not only managed to cover the whole building's energy demand at that time period but also had a surplus of energy. Similarly to section III.A, all the PHEVs batteries in both scenarios (10 and 25 PHEVs) are at least 50% charged before departure. Table I shows the total cost of energy for all the simulated scenarios under the current pricing.

TABLE I
TOTAL COST OF ENERGY FOR ALL SCENARIOS ($)

Regular building load	10 PHEVs		25 PHEVs	
	No GGT	GGT serving load	No GGT	GGT serving load
121.9	120.5	83.5	118.5	80.81
-	GGT selling to grid	51.63	GGT selling to grid	49.63

It can be seen in Table I that despite the extra charging load of the PHEVs to the building's energy consumption, the total electricity cost under the optimized charging-discharging process is still lower than the regular load building cost. When the GGT operates to serve the load, a higher decrease of the total electricity cost is observed. On the other hand, if we choose to sell the produced energy of the GGT to the grid and subtract the revenues of the day ($68.87) from the total building energy demand cost (including the PHEVs charging/discharging cost), the total expenses are further reduced. It should be noted though that the results are subject every time to the selected electricity tariffs and the pool prices.

IV. DISCUSSION AND FUTURE RESEARCH

An important remark is that the charging-discharging PHEVs optimal schedule and the optimal schedule operation of the GGT were decided according to two different optimization problems and not a single optimization model. The operation of the GGT was optimized according to the pool price scheme in order to maximize its revenue and not according to the electricity cost tariff so as to exclusively contribute to the minimization of the total building's energy demand and cost. In case of the combined operation of the PHEVs and the GGT, this is not the ideal approach since in reality, we use the GGT based on a schedule that was optimized for selling the produced energy and not using it to cover electricity demand. Thus, a unique MILP formulation comprising both PHEVs and the GGT operation could lead to a better performance in terms of cost minimization and thus, it is a worthy future work step. A single optimization model incorporating both PHEVs and GGT function could allow both possibilities for the GGT: either selling the energy to the grid or serving the building's load.

In this work, only the load of the electric vehicles has been considered as a deferrable load and thus, can be rescheduled according to electricity tariff aiming at overall building energy cost minimization. The main reason that energy demand of the building has not been assumed as deferrable is that not all the energy consumption processes in a building can be deferred and even when this is possible they have to be deferred as a whole. Thus, the main aim of the study was not to optimize the charging/discharging schedule of the PHEVs but rather the total energy required from the grid for the building including the load for the PHEVs. In the same sense, load shifting for achieving peak shaving was not the primary objective of this paper although the results in the case of the GGT contribution indicate a significant reduction of load during peak hours. The investigation though of the peak shaving concept in a similar case is challenging for future investigation.

This method could be generalized for buildings with similar working hours and comparable load but modifications are required for application in residential buildings as in such structures, the typical charging-discharging schedule for the electric vehicles does not coincide with increased building's load requirements and furthermore, there are stricter assumptions on the number of the electric vehicles that can be considered per building.

The type of incentives offered to the electric vehicles owners in order to participate in such schemes is quite important. The building's identity is significant in this case (corporate/private or public). In private/corporate buildings for instance, companies could offer the EVs charging to be free of charge for the owners in exchange of participating in the scheme. In public buildings, the state could offer other kind of discounts/privileges to the participants such as reduced electricity tariffs for their electricity bill or further tax reductions. Furthermore, taking into consideration that the participation in such schemes could reduce the vehicles battery lifetime, an additional incentive for the EVs owners could be the financial co-contribution of the beneficiaries for buying new batteries for the vehicles.

Finally, a very interesting and challenging aspect to be investigated in future research is the integration in the model of the electric vehicles' battery life cycle. Such an addition would allow the study of a long term use of the PHEVs deriving more realistic and useful results for a potential implementation in the real-world of the model in the future.

V. CONCLUSION

This study has examined the effect of a different but finite number of PHEVs on the electricity demand profile of a university building as well as the combined impact of the PHEVs charging-discharging process and the operation of a small-sized gas generator turbine. Analysis showed that the use of the PHEVs batteries as an alternative energy source can significantly contribute to the reduction of the building's energy demand leading to important cost decrease. The utilization of the energy produced by the GGT reduced further the total energy consumption of the building and, consequently, the total electricity cost although results showed it is more cost-effective to sell the GGT produced energy to the grid and deduce the revenue from the total electricity cost. Finally, some discussion about the work done was included and, hence, future lines of research have been identified.

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