Sector Coupling: Optimized Scheduling of Electric Vehicle Charging and Heat Production in Home Energy Systems

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Abstract— **In this paper a mixed-integer optimization approach for the scheduling of electric vehicle charging and heat production in home energy systems is presented. Within the stated linearized optimization problem several equality and inequality constraints have to be fulfilled. First of all the users heat demand has to be covered at every time. In this contribution the heat demand is calculated using a standard load profile approach taken from the natural gas sector. All electric applications in the household are represented by a standard load profile as well which leads to further linear equality constraints. Another assumption is that the only shiftable electric load is the electric vehicle charging. However, the electric vehicle charging is considered as an electric load. Once energy is stored in the car's battery storage system it cannot be fed back into the grid. The optimization framework is able to address several objective functions. To enable a large scale integration of electric mobility peak loads are to be minimized. Within todays legal conditions this "grid-friendly optimization" might not lead to the economic optimum for the house owner as the customer has no incentive to minimize peak loads. A comparison to a second objective function addressing the economic optimum for the house owner issues the costs of the "grid-friendly optimized" scheduling.**

Keywords- electric vehicle charging; mixed-integer optimization; scheduling; sector coupling

I. INTRODUCTION

The expected large scale integration of electric mobility into the power system will lead to numerous challenges. However simultaneous charging of multiple electric vehicles in residential districts requires an enforcement of low-voltage grids. One approach to minimize the needed grid expansion is to minimize peak load demands using flexibility provided by the heating sector. In this contribution combined heat and power plants (µCHP) are in focus. To guarantee a carbon-free operation they can be operated using methane from renewable energy provided by Power-to-Gas applications.

Optimal power flow problems have been widely addressed in literature [3,6,8,9]. To investigate optimal operation of storage devices the original formulations have been extended to dynamic optimal power flow problems (DOPF) [6]. While most optimal power flow investigation focus on transmission system operation DOPF formulations can be applied to electric vehicle charging scheduling on distribution grid level as well [3].

Thereby the energy hub concept introduced in [4] is widely adopted [5,7,8] in investigations on multi-energy systems.

In this contribution a single energy hub is in focus neglecting grid constraints. The energy hub connects the energy loads (power, heat) to the power and gas distribution grids. Therefore this is a multi-energy system. Especially synergy effects in coordinating electric vehicle charging and heat production need to be addressed.

II. MODEL

In this section the model used in the optimization is described. The heating system consists of a µCHP-System, thermal storage and an electric boiler. Furthermore the considered energy hub includes a car charging station and a photovoltaic plant.

A. µCHP-System

In this contribution a simplified static model of a µCHP plant is used since the regarded time span Δt between two simulation steps is 15 minutes. System dynamics are not in focus. The static model is based on data given in the respective data sheet. Three different operating points can be found in TABLE I.

TABLE I. µCHP DATA

EL. POWER OUTPUT [KW]	THERMAL POWER OUTPUT [KW]	GAS CONSUMPTION [KW]
3	9.7	14.8
4.5	12.4	18.9
6	14.9	22.2

It is assumed that the µCHP-plant can be operated in any point between 50% and 100% of its maximum electric power output. The operating points between 50% and 100% are therefore determined by linear approximation.

It is possible to switch the plant on and off whenever it is needed while frequent on/off-switching should be avoided regarding the wear parts of the plant. The switching of the CHP-plant leads to a mixed-integer optimization problem since a binary decision variable needs to be used. This leads to a set of linear equality and inequality constraints. These constraints describe the static model of the µCHP-plant sufficiently.

In addition to the µCHP-plant the heating system is equipped with a thermal storage system. This storage has a certain capacity and a maximum (dis)charging power. To meet the peaks in the houses heat demand an electric boiler with a maximum power is included. This boiler is assumed to be lossless.

The overall heating system is characterized by the following linear equality and inequality constraints:

$$P_{CHP,th}^{t} + P_{PtH}^{t} - P_{sto,th}^{t} = Q_{load,th}^{t} \quad (1)$$

$$P_{CHP,th}^{t} - \mu_{th} \cdot P_{CHP,el}^{t} = 0 \quad (2)$$

$$P_{CHP,gas}^{t} - \mu_{gas} \cdot P_{CHP,el}^{t} = 0 \quad (3)$$

$$E_{Sto,th}^{t} - \Delta t \cdot P_{sto,th}^{t} - E_{Sto,th}^{t-1} = 0 \quad (4)$$

$$P_{CHP,el}^{t} \leq P_{CHP,el,max} \quad (5)$$

$$-P_{CHP,el}^{t} \leq 0 \quad (6)$$

$$CHP_{ON,OFF} \cdot P_{CHP,el,min} - P_{CHP,el}^{t} \leq 0 \quad (7)$$

$$P_{CHP,el}^{t} - CHP_{ON,OFF} \cdot P_{CHP,el,max} \leq 0 \quad (8)$$

$$P_{sto,th}^{t} \leq P_{Sto,th,max} \quad (9)$$

$$-P_{sto,th}^{t} \leq P_{Sto,th,max} \quad (10)$$

$$E_{sto,th}^{t} \leq E_{Sto,th,max} \quad (11)$$

$$-E_{sto,th}^{t} \leq 0 \quad (12)$$

$$P_{PtH}^{t} \leq P_{PtH,max} \quad (13)$$

$$-P_{PtH}^{t} \leq 0 \quad (14)$$

B. *Car charging system*

One of the most important factors in electric vehicle charging scheduling is the determination of so called availability times. In this time span the car is parked at home and so in this time span the car can be charged at the home charging station.

The whole car charging system can also be described by a set of linear equality and inequality constraints. The storage equation (15) connects dis-/charging power and energy stored in the storage. It depends on the previous time step.

$$E_{Sto,car}^{t} - \Delta t \cdot P_{charge}^{t} + \Delta t \cdot P_{discharge}^{t} - E_{Sto,car}^{t-1} = 0 \quad (15)$$

It is required that the storage is fully loaded at the end of the charging times. This is achieved introducing the following equation for this time step τ.

$$E_{Sto,car}^{\tau} = E_{Sto,car,max} \quad (16)$$

The discharging power of the electric vehicle is assumed to be constant in times when the car cannot be charged. This is reasonable since the real driving behaviour is not of importance for grid connection. With this approach the user defined energy is taken from the storage during the non-charging times. In possible charging times the discharge power equals zero and therefore is dependent on the availability.

$$P_{discharge}^{t} = (E_{discharge}/\Delta t_{drive}) \cdot (1 - availability) \quad (17)$$

Several inequality constraints focus the technical bounds. First of all the charging power is limited to a maximum and a minimum value.

$$P_{charge}^{t} \leq P_{charge,max} \quad (18)$$

$$-P_{charge}^{t} \leq 0 \quad (19)$$

The same applies for the technical bounds of the battery storage. The energy stored in the system cannot exceed a certain maximum and should not fall below a minimum value.

$$E_{Sto,car}^{t} \leq E_{Sto,car,max} \quad (20)$$

$$-E_{Sto,car}^{t} \leq -E_{Sto,car,min} \quad (21)$$

C. *Photovoltaic plant and electric load*

The photovoltaic plant is represented by a single equality constraint using a given infeed profile. The same applies for the electric load in the household where a given standard load profile is used.

$$P_{PV,el}^{t} = P_{PV,el,measurement}^{t} \quad (22)$$

$$P_{load,el}^{t} = P_{load,el,measurement}^{t} \quad (23)$$

D. *Energy Hub*

The home energy system consisting of µCHP-plant, thermal storage, PV generator and car charging station can be seen as one energy hub (see Fig. 1). The electric power at the grid connection point of the energy hub is calculated using the following equation:

$$-P_{CHP,el}^{t} + P_{PtH,el}^{t} - P_{PV,el}^{t} + P_{load,el}^{t} - P_{HUB,el}^{t} = 0 \quad (24)$$

This equation is a further linear equality constraint used in the optimization. By introducing this constraint a minimization of the electric power at the grid connection point is possible.

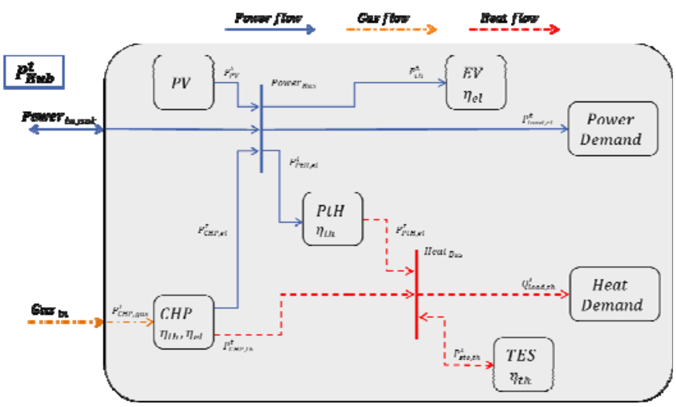

Figure 1. Energy Hub

III. OPTIMIZATION

In this section the mixed-integer optimal power flow problem is stated. This includes the objective function(s) and the constraints introduced in the previous section. The problem is solved using the BONMIN solver [1] with OPTI-Toolbox [2] for MATLAB. This solver uses the Coin-OR Branch and Bound solver CBC as the mixed-integer solver and Interior Point Optimizer (IPOPT) for solving the relaxed problem.

In general the (linear) mixed integer optimization problem has the following form:

$$\min_{x} f(x) \tag{25}$$

Subject to a set of linear in-/equality constraints:

$$Ax \leq b \tag{26}$$

$$A_{eq}x = b_{eq} \tag{27}$$

$$x_{min} \leq x \leq x_{max} \tag{28}$$

$$x_i \in \mathbb{Z}$$

$$x_j \in \{0,1\}$$

$$i \neq j$$

For mixed integer optimization problems the state vector x consists of continuous, binary and integer variables

A. Objective functions

To address the operating cost of the home energy system over a certain horizon T the objective function (29) is minimized. The operating costs consist of cost for gas and power consumption and revenues for power generation of the photovoltaic plant and the µCHP-plant.

$$f(x) = \Delta t \cdot \sum_{t=1}^{T} (C_{gas} \cdot P_{CHP,gas}^{t} - R_{CHP,el} \cdot P_{CHP,el}^{t} + C_{el} \cdot (P_{PtH,el}^{t} + P_{charge,el}^{t} + P_{laod,el}^{t}) - R_{PV,el} \cdot P_{PV,el}^{t}) \tag{29}$$

In contrast to the linear economical optimization a regionalization of energy supply to minimize peak loads is investigated. Therefore the electric power at the grid connection point of the energy hub needs to be minimized. To penalize high peak loads the objective function is quadratic and therefore non-linear:

$$f(x) = \sum_{t=1}^{T} (P_{HUB,el}^{t})^2 \tag{30}$$

This objective function also maximizes the level of self-supply since feeding electricity back into the grid is penalized too by the quadratic formulation. This optimization approach aims at grid relief effects.

IV. CASE STUDY

In the following section the presented optimization approach is applied to four scenarios. The characteristics of the different scenarios are depicted in TABLE II. Winter and summer scenarios are regarded since the heat load demand and the power generation of the photovoltaic plant in summer and winter differ to a great extent. A further distinction has to be made between weekdays and weekends / holiday which affects the availability times of the electric vehicle for charging. Based on the evaluations made in [10] the availability time for residential districts is assumed from 6pm to 6am during the week. On weekends an availability from 0am to 10am and from 17pm on is assumed. All p.u.-values are calculated using a base load of 100 kW.

TABLE II. DEFINITION OF SCENARIOS

Scenario	*Season*	*Day*
1	winter	weekday
2	winter	weekend/holiday
3	summer	weekday
4	summer	weekend/holiday

A. Winter Scenario

A case study for a winter scenario is performed first.

1) Economic Optimization

The results of the economic optimization are shown in Fig. 2 (weekday) and Fig. 3 (weekend). In the winter scenario a reasonably dimensioned µCHP-plant is running at maximum power to provide as much heat as possible. Therefore a flexible use of a reasonably dimensioned µCHP-plant is not possible in winter scenarios. The electric boiler and the thermal energy storage are used to meet the remaining heat load demand.

In both cases the charging station uses the whole availability-time to charge the electric vehicle. The charging power depends on assumptions concerning the state of charge at the beginning of the charging process. While the µCHP is running at its maximum point the simultaneous use of electric boiler and car charging leads to high peak loads.

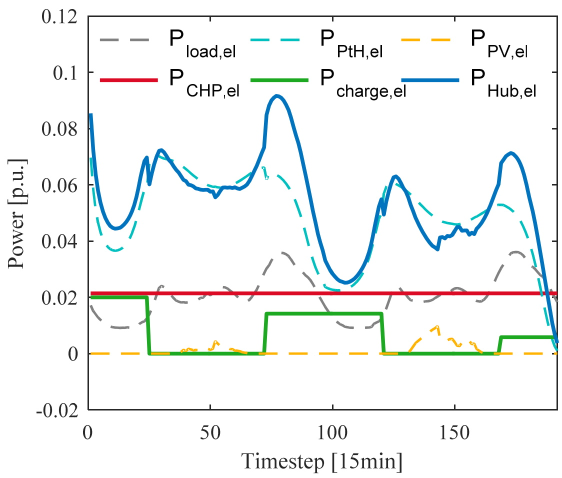

Figure 2. Economic optimization (winter, weekday)

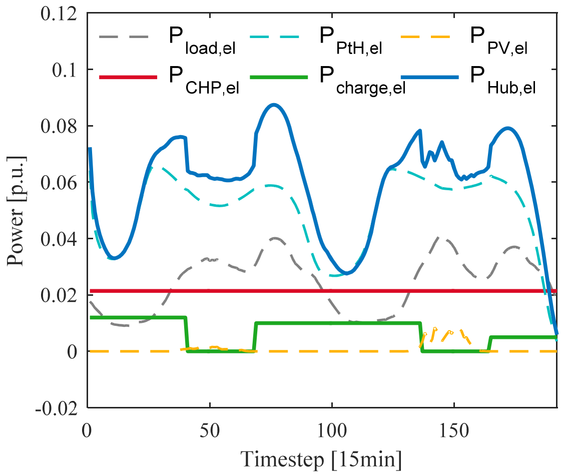

Figure 3. Economic optimization (winter, weekend)

2) *Minimization of peak loads*

In contrast to the economic optimization a minimization of peak loads is performed. Since the µCHP-plant is already operating at its maximum point the flexibility in the hub energy system is the usage of the electric boiler in combination with the thermal storage system.

The results are shown in the following figures:

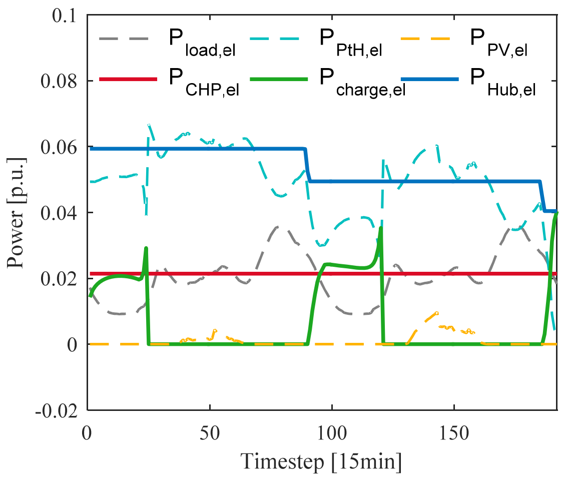

Figure 4. Peak load minimization (winter, weekday)

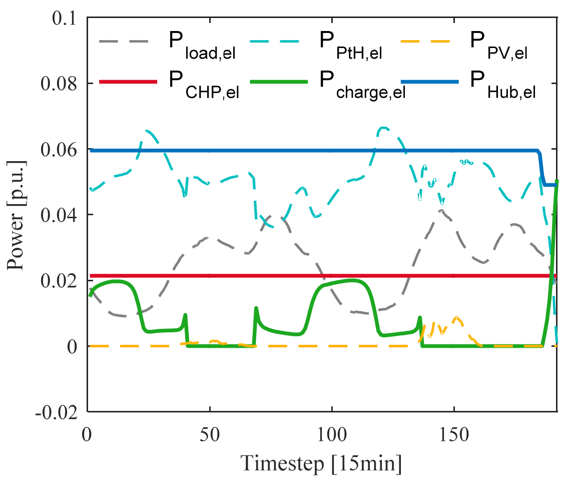

Figure 5. Peak load minimization (winter, weekend)

3) *Comparison*

In TABLE III a comparison of the results for the different optimization goals in winter scenarios is shown. While the costs are the same for both optimization objectives the peak load can be reduced by 31.9 to 35.3%.

TABLE III. WINTER SCENARIOS

Scenario	*Peak load [kW]*	*Average costs [€/day]*
1 (economic)	9.16	85.30
1 (peak load)	5.93	85.30
2 (economic)	8.74	90.15
2 (peak load)	5.95	90.15

B. *Summer Scenario*

In the following section the results for summer scenarios are presented.

1) *Economic Optimization*

The results of the economic optimization in the summer scenario are shown in figure 1 (weekday) and figure 2 (weekend). In the summer scenario the µCHP-plant is used to meet the energy hub power demand. It is therefore running at a lower operating point.

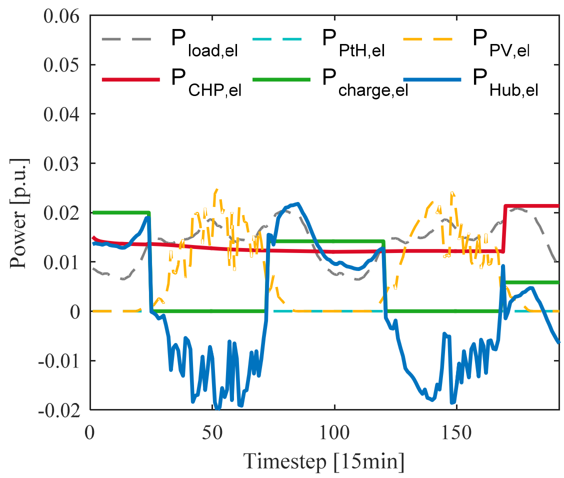

Figure 6. Economic optimization (summer, weekday)

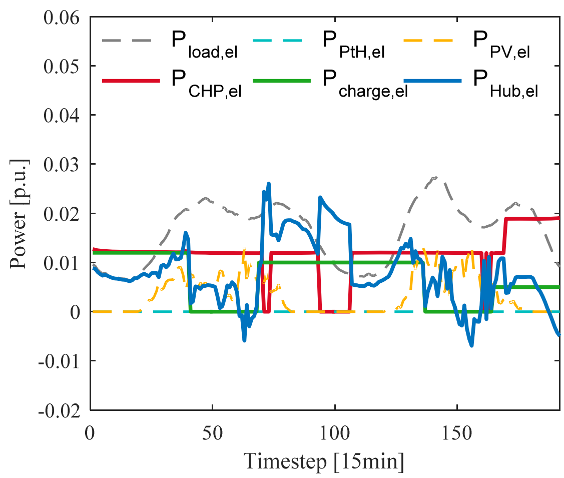

Figure 7. Economic optimization (summer, weekend)

2) Minimization of peak loads

In contrast to the economic optimization a minimization of peak loads is performed. Since the objective function (30) leads to a minimization of the squared hub power the power fed back into the grid is reduced as well. The results of the performed optimization are shown in Fig. 8 and Fig. 9.

In times where the electric vehicle is charged the µCHP-plant is used to cover the electric power demand. The limiting aspect in this case is the thermal demand which is much lower in summer cases.

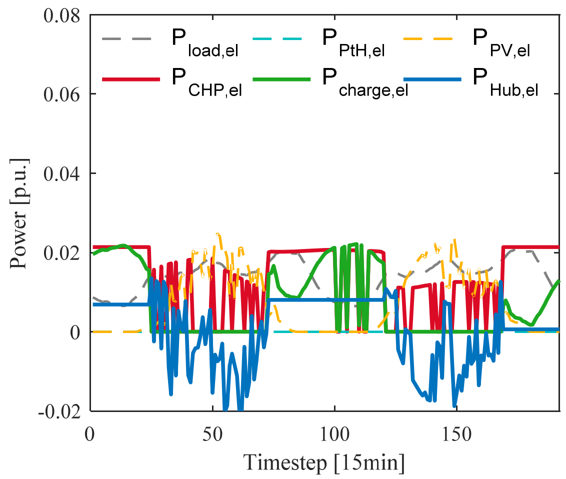

Figure 8. Peak load minimization (summer, weekday)

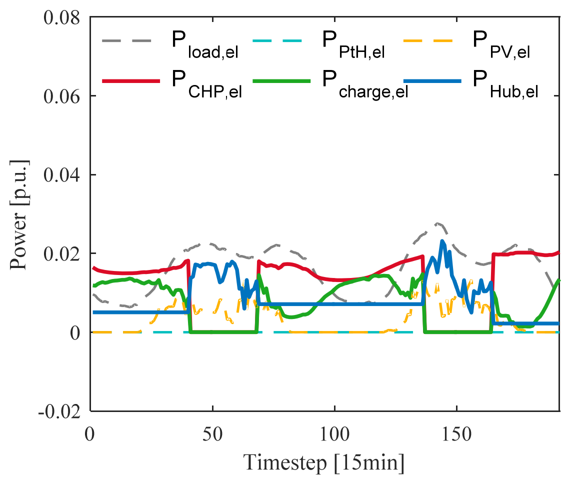

Figure 9. Peak load minimization (summer, weekend)

3) Comparison

In TABLE IV a comparison of the results for the different optimization goals in summer scenarios is shown.

TABLE IV. SUMMER SCENARIOS

Scenario	***Peak load [kW]***	***Average costs [€/day]***
3 (economic)	2.18	7.72
3 (peak load)	1.35	7.93
4 (economic)	2.61	13.59
4 (peak load)	2.31	13.59

Like in the winter scenarios the average costs of energy consumption (almost) stay the same. The minimization of peak loads does not affect the economic benefit of the system-owner. Nevertheless the peak load of the hub can be reduced by 11.5% on weekends to 38.1% on weekdays.

V. CONCLUSION

This paper proposes a mixed integer optimization approach to minimize peak loads caused by electric vehicle charging. By considering multiple energy sectors such as heat and power supply in the optimization framework the energy hub power can be minimized by 11.5 - 38%. As the simulation results show this grid-friendly approach does not lead to significantly higher costs for the energy system operator.

Therefore a capacity prizing approach for electric vehicle home charging systems can lead to lower peak loads in economic optimizations. With a monetary charge of peak loads the economic optimization will lead to the same results as the grid-friendly approach.

In the proposed approach the usage behavior of the electric vehicle or the users demand for power and heat is not compromised.

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